A volcanic hazard assessment of Savo volcano, Solomon Islands

Chapter · November 2016
Cover Photographs:

**Front:** The southern-most pit crater of Yasur Volcano, Tanna Island, Vanuatu taken by Paul Taylor, 28 February 1997 during the workshop fieldtrip. Yasur volcano is perhaps the most accessible active volcano in the world. Since it was first observed by Capt James Cook in the mid-18th century it has been continuously active sometimes resulting in the deaths of observers. Activity has been dominated by mild to moderate Strombolian and Vulcanian type explosive activity. Yasur volcano provides an excellent example of an active volcano that has impacted on traditional communities in the southern part of Tanna Island.

**Back:** A small explosive eruption of the northern-most pit crater of Yasur volcano by Graham Harris.
Volcanic Hazards and Emergency Management in the Southwest Pacific

SPC Technical Bulletin SPC00017

Compiled and edited by Paul W Taylor

Suva, Fiji, 2016
The Pacific Community’s (SPC) Geoscience Division (GSD) began operating on 1 January 2011. GSD was established by transferring the core work programme of the former Pacific Islands Applied Geoscience Commission (SOPAC) to SPC following the decision of Pacific Islands Forum leaders to rationalise the provision of regional services. Part of that process was to transfer and integrate the core work programme of the Pacific Islands Applied Geoscience Commission, or GSD “The Commission” (formally SOPAC) into the SPC. The purpose of establishing SPC Geoscience “The Division” is to ensure the preservation of the identity of the GSD work programme that has built up an excellent reputation, amongst both Members and donor partners over nearly 40 years.

GSD “The Commission” has come a long way since its establishment in 1972, first as a United Nations Development Programme Regional Project, then in 1990 as an independent inter-governmental organisation, and from 2011, to be a new Division in the SPC. Initially, the work programme focused on the assessment of deep-sea minerals and hydrocarbon potential. Over the years, the work programme of GSD expanded to include the assessment of the potential of ocean and onshore mineral resources, coastal protection and management, and geohazard assessment. Over the past decade, its mandate broadened further to include water, wastewater, sanitation, energy, and disaster risk management.

This bulletin, which reflects work conducted by SOPAC when it was a separate organisation, is published by SPC for scientific reference.

Pacific Community
Geoscience Division
Private Mail Bag, GPO Suva, Fiji
Email: spc@spc.int
www.spc.int

DISCLAIMER
While care has been taken in the collection, analysis, and compilation of the data herein, they are supplied on the condition that the Pacific Community shall not be liable for any loss or injury whatsoever arising from the use of the data.
Volcanic risk management is in its infancy in the potentially affected countries of the Southwest (SW) Pacific – Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Past efforts toward developing this capacity to what could be considered an adequate level have been limited to specific scientific studies of individual volcanoes, or island-based volcano emergency planning in selected areas. Historic volcanic disasters in Papua New Guinea, Tonga and Vanuatu, and prehistoric events in all countries, indicate that a volcanic risk management framework is required for the region.

Preliminary work that has already been conducted also indicates that a high degree of volcanic risk is apparent in the SW Pacific, with large populations living on and around the many active volcanoes in each of the countries.

For a number of years, it has been proposed to address this issue by developing an integrated project that would enable countries of the SW Pacific to develop comprehensive volcanic risk management plans. However, efforts have been piecemeal and have not been coordinated at the regional level. The workshop that was conducted in Port Vila, Vanuatu, from 24 to 28 February, 1997, was ‘a small step for the volcanological community as a whole, but a giant leap for the communities of the SW Pacific with a volcanic hazard problem’.

Coordinated by the former South Pacific Applied Geoscience Commission (SOPAC), the workshop offered the first steps toward a regionally coordinated mechanism to reduce the risk from volcanic hazards. It was attended by geoscientists and disaster management officials from Pacific Island countries (PICs) including: Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Technical expertise was provided by representatives from Columbia, Indonesia and New Zealand. Representatives were also present from the Australian Academy of Sciences; the International Association of Volcanology and Chemistry of the Earth’s Interior (IAVCEI); the World Organisation of Volcano Observatories (a Commission of IAVCEI); ORSTOM (Vanuatu, Noumea and France); the United Nations Office for the Coordination of Humanitarian Affairs – South Pacific Program Office; and the United Nations Educational, Scientific and Cultural Organisation (UNESCO). Several observers who had recently completed work in the SW Pacific also participated.

This volume complements the workshop proceedings, ‘Workshop on Volcanic Hazards and Emergency Management in the Southwest Pacific’, published as SOPAC Miscellaneous Report No. 245, and presents the contributions made by workshop participants. It is divided into three sections:

Section 1 includes papers of a more general nature to set the scene, covering issues such as the nature of volcanism in the region (R.W. Johnson); volcanic hazards and human vulnerability (R.J. Blong); a global view of volcanic emergency management (J. Tomblin); and emergency management in the Pacific region (I. Rector).

Section 2 provides papers outlining the current perception of volcanic hazards in the participating countries, including Fiji (A. Tuifagalele); New Zealand (B. Scott and V Neall); Papua New Guinea (B. Talai and I. Itakari); Solomon Islands (T. Toba, D. Tolia and R. Blikli); the Kingdom of Tonga (P.W. Taylor, K.S. Mafi and P. ‘Aho); Vanuatu (M. Lardy, D. Charley and M. Matera, and J. Esu-Wate); and Samoa (P.W. Taylor and F. Sapolu).

Section 3 provides case studies of volcanoes within the region including Rabaul, Papua New Guinea (B. Talai); Ruapehu, New Zealand (B. Scott and V. Neall); Ambae, Vanuatu (P. Wiart and M. Lardy); Niuafo’ou, Kingdom of Tonga (P.W. Taylor); Savo, Solomon Islands (M.G. Petterson, D. Tolia, A. Papabatu, T. Toba and C. Qopoto); and Taveuni, Fiji (S.J. Cronin).

As the compiling editor, it was a pleasure to bring these papers together so they can be used by future researchers who will continue the work of the contributors and workshop participants.

Editing such a volume has not been without its difficulties. The contributors come from diverse backgrounds and a significant degree of review and refinement of papers was required. Because there was also a need to consolidate the topics covered in the volume, a decision was made to include only papers that were directly related to the SW Pacific region. Many other participants provided valuable contributions during the workshop and helped in making it a resounding success. It was a personally rewarding experience to read about and learn from the experiences presented in the papers and all contributors are sincerely thanked for entrusting us with their work.

Paul W Taylor

Compiler and Editor
Chair of the STAR/SOPAC Geohazards Working Group, and
Australian Volcanological Investigations
PO Box 291, PYMBLE NSW 2073, AUSTRALIA
August 2003
# TABLE OF CONTENTS

## INTRODUCTION

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Volcanoes of the South Pacific: Geological Types, Hazard Identification, and a Co-operative Approach to Volcano-Disaster Mitigation</td>
<td>6</td>
</tr>
<tr>
<td>R W Johnson</td>
<td></td>
</tr>
<tr>
<td>Volcanic Hazards, Human Vulnerability and Risk Assessment</td>
<td>30</td>
</tr>
<tr>
<td>R Blong</td>
<td></td>
</tr>
<tr>
<td>A Global Overview of Volcanic Emergency Management</td>
<td>36</td>
</tr>
<tr>
<td>J Tomblin</td>
<td></td>
</tr>
<tr>
<td>Emergency Management in the SOPAC Region</td>
<td>41</td>
</tr>
<tr>
<td>I Rector</td>
<td></td>
</tr>
</tbody>
</table>

## PACIFIC ISLAND COUNTRY PAPERS

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcano - Fiji Situation</td>
<td>50</td>
</tr>
<tr>
<td>A Tuifagalele</td>
<td></td>
</tr>
<tr>
<td>Volcanic Hazards, Surveillance and Emergency Response in New Zealand</td>
<td>53</td>
</tr>
<tr>
<td>B Scott &amp; V Neall</td>
<td></td>
</tr>
<tr>
<td>Volcano Monitoring in Papua New Guinea</td>
<td>63</td>
</tr>
<tr>
<td>B Talai &amp; I Itikarai</td>
<td></td>
</tr>
<tr>
<td>An Overview of Volcanic Hazards and Emergency Management in Solomon Islands</td>
<td>68</td>
</tr>
<tr>
<td>T Toba, D Tolia &amp; R Biliki</td>
<td></td>
</tr>
<tr>
<td>Volcanic Hazards and Their Management in the Kingdom of Tonga</td>
<td>75</td>
</tr>
<tr>
<td>P Taylor, K Mafi &amp; P 'Aho</td>
<td></td>
</tr>
<tr>
<td>Monitoring Systems for a Few of Vanuatu's Volcanoes</td>
<td>87</td>
</tr>
<tr>
<td>M Lardy, D Charley &amp; M Matera</td>
<td></td>
</tr>
<tr>
<td>J Esau Wate</td>
<td></td>
</tr>
<tr>
<td>Volcanic Hazards in Samoa</td>
<td>106</td>
</tr>
<tr>
<td>P Taylor and F Sapolu</td>
<td></td>
</tr>
</tbody>
</table>

## CASE STUDIES

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic Crises Case Histories - Rabaul Volcano, 1983-85, 1994-97</td>
<td>110</td>
</tr>
<tr>
<td>B Talai</td>
<td></td>
</tr>
<tr>
<td>The Volcano Crises at Ruapehu - 1995 and 1996</td>
<td>119</td>
</tr>
<tr>
<td>B Scott &amp; V Neall</td>
<td></td>
</tr>
<tr>
<td>An Example of a Volcanic Crisis in Vanuatu - Aoba (Ambae) Island - 1995</td>
<td>126</td>
</tr>
<tr>
<td>P Wiart &amp; M Lardy</td>
<td></td>
</tr>
<tr>
<td>Nuuafo’ou, Tonga: Volcanic Hazards and the Risk from Future Activity</td>
<td>132</td>
</tr>
<tr>
<td>P Taylor</td>
<td></td>
</tr>
<tr>
<td>A Volcanic Hazard Assessment of Savo Volcano, Solomon Islands, SW Pacific</td>
<td>151</td>
</tr>
<tr>
<td>M G Peterson, D Tolia, A Papabatu, T Toba &amp; C Qopoto</td>
<td></td>
</tr>
<tr>
<td>Is There Volcanic Hazard in Fiji? - Volcanic Geology Investigations on Taveuni</td>
<td>170</td>
</tr>
<tr>
<td>S J Cronin</td>
<td></td>
</tr>
</tbody>
</table>
Contributors

P. 'Aho
National Disaster Management Office
Ministry of Public Works
PO Box 52
NUKUALOFA
KINGDOM OF TONGA

M. Lardy
ORSTOM BP 76
PORT VILA
REPUBLIC OF VANUATU

R. Biko
National Disaster Council
HONIARA
SOLOMON ISLANDS

K. S. Mafi
Ministry of Lands, Survey and Natural Resources
PO Box 5
NUKUALOFA
KINGDOM OF TONGA

R. J. Blong
Natural Hazards Research Centre
(now Risk Frontiers)
MACQUARIE UNIVERSITY NSW 2109
AUSTRALIA

M. Matera
ORSTOM BP 76
PORT VILA
REPUBLIC OF VANUATU

D. Charley
ORSTOM BP 76
PORT VILA
REPUBLIC OF VANUATU

V. E. Neall
Institute of Natural Resources
Massey University
Private Bag 11 222
PALMERSTON NORTH
NEW ZEALAND

S. J. Cronin
Institute of Natural Resources
Massey University
Private Bag 11 222
PALMERSTON NORTH
NEW ZEALAND

A. Papabatu
Ministry of Energy, Water and Mineral Resources
Mines and Minerals Division
PO Box G37
HONIARA
SOLOMON ISLANDS

J. Esau Wate
National Disaster Management Office
Private Mail Bag 014
PORT VILA
REPUBLIC OF VANUATU

M. G. Petterson
British Geological Survey
Keyworth
NOTTINGHAM NG12 5GG
UNITED KINGDOM

F Sapolu
Ministry of Internal Affairs
Government of Samoa
APIA
WESTERN SAMOA

C. Qopoto
Ministry of Energy, Water and Mineral Resources
Mines and Minerals Division
PO Box G37
HONIARA
SOLOMON ISLANDS

I. Itakari
Rabaul Volcanological Observatory
PO Box 386
RABAUL ENBP
PAPUA NEW GUINEA

R. W. Johnson
Australian Geological Survey Organisation
(now Geoscience Australia)
GPO Box 378
CANBERRA ACT 2600
AUSTRALIA

I. Rector
UNDHA - SPPO
(now SOPAC Disaster Management Unit)
3rd Floor, FDB Building
SUVA
REPUBLIC OF FIJI

D. Tolia
Ministry of Energy, Water and Mineral Resources
Mines and Minerals Division
PO Box G37
HONIARA
SOLOMON ISLANDS

B. J. Scott
Waikake Research Centre
Institute of Geological & Nuclear Sciences
Private Bag 2000
TAUPO
NEW ZEALAND

J. Tomblin
PO Box 2639
PILLAR ROCK
ANTIGUA
WEST INDES

B. Talai
Rabaul Volcanological Observatory
PO Box 386
RABAUL ENBP
PAPUA NEW GUINEA
A. Tuifagalele  
Ministry of Regional Development & Multi-Ethnic Affairs  
PO Box 2219  
Government Offices  
SUVA  
REPUBLIC OF FIJI

P. W. Taylor  
Australian Volcanological Investigations  
PO Box 291  
PYMBLE 2073 NSW  
AUSTRALIA

P. A. M. Wiart  
Department of Geography  
University of Cambridge  
CAMBRIDGE CB2 3EN  
UNITED KINGDOM

T. Toba  
Ministry of Energy, Water and Mineral Resources  
Mines and Minerals Division  
PO Box G37  
HONIARA  
SOLOMON ISLANDS

**Editor’s Note:** The contact details for the contributors provided here were those during or shortly after the workshop. Many contributors may have moved on from the roles that they were performing at the time of the workshop and therefore their address details may not be current.

* Contributors that did not participate in the Port Villa workshop but were co-authors of a paper given by a participant or invited to provide a topical paper that was relevant to the aims of the workshop.

* Deceased
INTRODUCTION
ACTIVE VOLCANOES OF THE SOUTH PACIFIC: GEOLOGICAL TYPES, HAZARD IDENTIFICATION, AND VOLCANIC-DISASTER MITIGATION

R. W. Johnson
Geoscience Australia, AUSTRALIA

ABSTRACT
The volcanoes of the South Pacific region occupy a range of tectonic settings but are found mainly in arc-trench systems or above intraplate mantle plumes. 146 volcano systems of Holocene age are identifiable in the South Pacific region, 54 of which are in Papua New Guinea alone. Many of the arc-trench type volcanoes of the region are explosive and have created disasters during prehistoric and modern times. The two most significant disastrous eruptions in recent times took place in 1994-96. Damage losses, totalling hundreds of millions of dollars resulted from the 1994 Rabaul eruption (Papua New Guinea) and from the 1995-96 Ruapehu eruptions (New Zealand). Almost 3000 people were killed in 1951 by the eruption at Lamington volcano, also in Papua New Guinea. Explosive eruptions of a greater scale, such as those at Taupo (New Zealand) in the 2nd Century, Rabaul in the 6th Century, Kuwae (Vanuatu) in the 15th Century, and Long Island (Papua New Guinea) in the 17th century, have not been witnessed in more modern times, yet the potential for such eruptions still exists. More importantly, community vulnerability is increasing as populations grow and developments and investments continue in the volcanically active areas of the region. Volcanic disaster mitigation is possible through (1) improved volcano monitoring, (2) an information-management approach to hazard and risk mapping and assessment, (3) integrated emergency-management procedures, and (4) enhanced public-awareness and education strategies. These improvements should be made in the context of a co-operative regional approach to volcanic emergency management in the South Pacific.

INTRODUCTION
The ‘island-arc’ nations of Papua New Guinea, Solomon Islands, Vanuatu, Tonga, New Zealand, and, to a lesser extent, Fiji are the most volcanically vulnerable countries of the South Pacific, or politically defined region covered by the South Pacific Applied Geoscience Commission (SOPAC) (Figure 1). This is because these countries contain active - and potentially active - explosive-type volcanoes characterised by generally gas-rich, viscous magmas. These volcanoes originated within the geologically complex array of arc-trench systems that dominate the geodynamics of the South Pacific region. In contrast, Samoa, American Samoa, and French Polynesia have active, mantle-plume (“hot spot”) volcanoes, and Australia has low-risk, passive-margin (and hot-spot) eruptive centres. These other volcanoes, although still hazardous to some extent, are less explosive than the volcanoes of the island-arc countries.

Explosively erupted ash, pumice, and gas from major explosive eruptions, and secondary effects, cause losses of life, damage to property and infrastructure, rupturing of critical lifelines, destruction of agricultural lands, and breakdown of the social and cultural fabric of communities. Explosive eruptions from island-arc volcanoes in the SOPAC region can have disastrous consequences that are local, regional, and even global in extent. The 1994 Rabaul eruption, Papua New Guinea, has been the most destructive volcanic eruption in the SOPAC region so far this century (Figure 2), measured in terms of monetary loss (about 300 million PNG kina; Blong & McKee, 1995), and it serves as a salutary lesson in focusing attention on the volcanic vulnerability of SOPAC island-arc countries as a whole. Ruapehu volcano, New Zealand (Figure 3), in 1995-96 caused losses in excess of NZD 150 million to rural, insurance, tourism, and aviation industries (Scott & Neall, this volume). The 1951 eruption at Lamington volcano, also in Papua New Guinea, has been the most consequential this century insofar as lives lost are concerned:
there were almost 3000 deaths caused by the passage of hot pyroclastic surges from a mountain that few had recognised even as a volcano (Taylor, 1958).

The South Pacific region mainly consists of small maritime nations – islands separated, in some cases, by great expanses of ocean. Another feature of volcanoes is their ability to collapse forming large-scale landslides or debris avalanches. Many large volcanoes in the region have the capacity for major, gravitational (debris-avalanche) collapses. Those near the sea may generate destructive tsunamis whose impact may regionally propagate. The region also contains numerous submarine volcanoes. Drifting pumice rafts from submarine volcanoes are a hazard to shipping and to distant coastlines. Thus, volcanic events that start locally can have regional consequences.

There are several questions that need to be dealt with in a consideration of South Pacific volcanism:

- What is the volcanic threat in the SOPAC region?
- What are the different volcanological mitigation needs of each country?
- How well prepared for volcanic hazards is each of the countries and territories in the SOPAC region?
- Have ‘at-risk’ populations been identified?
- Are these populations aware of the volcanic hazards that they face?
- Are there ways in which SOPAC countries can collaborate to establish a network of volcanological emergency-management activities of mutual benefit?
- To what extent can volcanological agencies in volcanically active countries, such as Indonesia and the Philippines, neighbours to the SOPAC region, be part of such a network?
- And finally, and most importantly (for the reasons discussed in section 7): what are the needs of emergency managers in the southwest Pacific?

This plethora of questions created the driving force in organising the international workshop Volcanic Hazards and Emergency Management in the Southwest Pacific, held in Vanuatu from 24-28 February 1997.
Figure 2: Wet ash from Tavurvur volcano, Papua New Guinea fell on Rabaul town in September 1994. It destroyed the main business district, mainly through roof collapses (upper photo), blocking of drainages and roadways (lower photo), and the destruction of power supplies and vegetation cover. Another volcano, Vulcan, was in eruption at about the same time and caused extensive damage, burying some villages and destroying others. Both of these volcanoes are part of the larger Rabaul caldera complex. These two photographs were taken three years after the eruption. Acid rain and scavenging for building materials during these years have caused even further reduction of what was a thriving, modern town.
WORKSHOP AND OVERVIEW

The concept of a workshop on volcanic hazards in the southwest Pacific region had its origins with the World Organisation of Volcano Observatories (WOVO). WOVO is a Commission of the International Association of Volcanology and Chemistry of the Earth’s Interior (IAVCEI) that has strong ties with another IAVCEI Commission for the Mitigation of Volcanic Disasters. Included in the principal aims of WOVO are (1) stimulation of co-operation between scientists working in volcanological observatories and institutions directly involved with volcano monitoring, and (2) facilitation of exchanges of views and experience in volcano monitoring by convening meetings, such as of the type held in Vanuatu. WOVO officials planned the Vanuatu meeting in association with the IAVCEI Secretariat based in Canberra, Australia, and organised and facilitated it using major support from SOPAC.

The workshop had four objectives:

- to review the volcanic threat in the SOPAC region;
- to determine the levels of community awareness of volcanic hazards in the region;
- to review existing volcano-monitoring and emergency-management systems; and
- to permit constructive interaction and dialogue between WOVO members and emergency managers from volcanically active SOPAC countries.

Outcomes of the workshop were (1) a project proposal and work program of enhanced co-ordination in volcano monitoring, volcanic-hazard assessment, and public awareness, and (2) the technical papers presented in this volume.

The purpose of this scene-setting paper is to provide a broad summary review of the tectonic setting, geological-type hazards, and risk implications of volcanoes in the SOPAC region. This review deals with the Holocene volcanoes of the region – that is, those active within the last 10,000 years. The geological setting of the volcanoes is considered first. Then the main volcano types of the region are identified. A characterisation of the volcanoes of the SOPAC region follows on a country-by-country basis, prior to considering volcanic hazards – and disasters caused by them – in the region. A consideration of ways to cope with community vulnerability and volcanic risk, including regional co-operation, completes the review. The development of the paper, therefore, is from initial, purely geoscientific considerations to issues finally directed at public safety and disaster mitigation. The paper is an attempt to complement and extend a previous paper on the volcanism of this region by Latter (1991).
GEOLOGICAL SETTING OF THE VOLCANOES

Volcanoes throughout the world occupy many different kinds of tectonic settings. Most of the active volcanoes of the SOPAC region can be grouped into either of only two main tectonic categories (Figure 1 and 4):

1. Subduction-Zone Related, Island-Arc/Trench Systems Including Marginal Basins of Back-Arc Type

Subduction is the process by which oceanic lithospheric plates disappear down submarine trenches (Figure 4). Their course into the earth's deep interior is tracked by deep earthquakes that define inclined Wadati-Benioff zones. Arc-trench type volcanoes form above these downgoing slabs of oceanic lithosphere, typically as stratovolcanoes and caldera complexes at volcanic 'fronts' 100-150 km landward of the submarine trenches. In addition, back-arc spreading and related volcanism may be caused by (1) subduction-induced upwellings and flow of mantle-wedge material behind the volcanic front, or (2) tectonic extension in the over-riding plate as a consequence of ‘roll-back’ of the downgoing slab. Back-arc basin spreading related to subduction is one mechanism of formation of the many active and inactive ‘marginal basins’ that characterise the geology of the southwest Pacific. Back-arc basin basalts (BABB – their magmas may differentiate, producing rocks of intermediate composition) range from those typical of mid-ocean-ridge basalts (MORB) to those carrying a slight signature of the ‘island-arc’ chemical characteristics more fully developed in volcanic-front lavas. BABB-type volcanoes are submarine, but rarely can be subaerial – for example, the active Niuafo’ou volcano in Tonga (Taylor et al., Taylor, this volume), which is a lava shield reminiscent of classic, ocean-island type volcanoes like on Hawaii, the youngest and largest of the Hawaiian Islands volcanic chain.

2. Mantle Plume (Hot-Spot) Volcanoes

There are excellent examples of volcanic ‘hot spot’ chains similar to those of the Hawaiian Islands within the SOPAC region - especially in Samoa and French Polynesia (see below). Mantle plumes are generally believed to originate at the core/mantle boundary of the earth as hot diapirs of mantle peridotite that rise narrowly to the base of surface tectonic plates and spread out (Figure 4). There, they feed magma to the surface as the plates move over them, forming distinctive age-progressive, hot-spot tracks that help measure absolute motions of the plates themselves (Figure 1). Southward-younging hotspot tracks are found on the floor of the Tasman Sea and in eastern Australia, and there are two active mantle-plume volcanoes in Australian territory on Heard and Macdonald islands in the Southern Ocean outside of the SOPAC region. An active mantle plume also may exist in the St Andrew Strait area of northern Papua New Guinea.

Figure 4: Schematic representation of the two main tectonic settings for volcanoes of the SOPAC region: arc-trench system (including island-arc and back-arc volcanism) and mantle-plume types. Mid-ocean ridge and passive continental-margin types of volcanism are shown on the extreme left and right.
3. Other

Five other tectonic settings can be identified for volcanoes worldwide, and these have representation in the SOPAC region in different degrees.

3.1. Mid-Ocean Ridge

One of the earth’s great mid-ocean-ridge systems, the East Pacific Rise, where oceanic plates are created and separate, defines the eastern and south-eastern margin of the Pacific plate (Figures 1 and 4). This margin swings south-westwards beneath open ocean bereft of island populations, from east of the Galapagos Rift in the eastern Pacific to the Macquarie Ridge south of New Zealand, marking, in broad terms, a geological boundary to the politically defined SOPAC region. Deep ocean-floor volcanism and the production of MORB are believed to characterise much of the length of the Rise, and nowhere along it do volcanoes break sea level. The detailed distribution of volcanoes along the East Pacific Rise is unknown, but the level of volcanic risk to populations in the SOPAC region is vanishingly small.

3.2. Non-Back-Arc Marginal Basins

Not all marginal basins and related volcanoes in the SOPAC region appear to have formed as a result of back-arc extension related to the subduction process (see type 1 above). Some, instead, are small seafloor spreading axes in their own right, analogous (but on a much smaller scale) to the great East Pacific Rise (e.g. Taylor & Karner, 1983). One example is the Woodlark Basin whose eastern end is being subducted beneath the Solomons island arc and whose western end is propagating into the south-eastern end of mainland New Guinea (e.g. Taylor et al., 1995). Active seafloor spreading and submarine MORB production characterise most of the length of the Woodlark Basin. The Coral Sea and Tasman Sea are other examples of marginal basins (now inactive) whose origin seems largely independent of subduction. These ‘non-back-arc’ marginal basins evidently form in response to major tectonic events, affecting the relative motion between the large Indo-Australian and Pacific plates (e.g. Kroenke, 1984). For example, a major reversal in arc polarity of the plate boundary took place in Miocene times, caused by arrival of the Cretaceous Ontong Java Plateau (a vast, oceanic, volcanic plateau) at a northeast-facing subduction zone (e.g. Coleman & Kroenke, 1981). Opening of the Woodlark Basin evidently took place as a response to major re-configuration at the plate boundary.

3.3. Continental Rifts

Large upper-mantle upwellings beneath some continents form major rift valleys and produce large-scale, subaerial, alkaline volcanism, including lavas of, for example, trachyte, phonolite, and comendite composition. The major rift valleys of eastern Africa are classic examples that formed in response to distension (but not splitting and active seafloor spreading) of continental crust. Active rift volcanism of this scale is absent in the SOPAC region, but the aforementioned propagation of the Woodlark Basin into south-eastern New Guinea is a microcosm of it, as continental crust there is being distended (mantine-gneiss domes have formed). Furthermore, small volcanoes in the Dawson Strait area of the D’Entrecasteaux islands off the south-eastern tip of New Guinea are of comenditic composition, analogous to those found in major continental rifts (e.g. Smith, 1976).

3.4. Passive Continental Margin

Continental alkaline and tholeiitic volcanism characterises the largely inactive but extensive Cainozoic volcanism of eastern Australia, as well as (1) the Quaternary and potentially active alkaline volcanism of the Northland-to-Auckland region of New Zealand (North Island), and (2) volcanic islands southeast of South Island, New Zealand, on the Campbell Plateau (Johnson, 1989). The origin of these volcanoes, in large part, remains enigmatic, but a chain of central volcanoes in eastern Australia that include felsic rocks form a mantle-plume related hot-spot track. The remaining basaltic lava fields in eastern Australia are attributed to magmatism related to uplift and heating of the passive margins of continental crust that split to form the Tasman Sea marginal basin 60-80 million years ago. A passive-margin volcanism origin may apply also to the Northland volcanoes, including the potentially active volcanic field in Auckland City.

3.5. Subduction-Zone-Related Continental Margin

Eastwards subduction of the Pacific Ocean floor beneath the South American continent has created the vast length of the Andes mountain chain and its accompanying, largely andesitic, volcanic chains along the western margin of the continent. Continental margin volcanism in this sense is absent from the SOPAC region. However, large felsic caldera systems and andesitic stratovolcanoes characterise the Taupo Volcanic Zone (Figure 5) which represents the southern extension of the largely submarine Tonga-Kermadec island-arc onto thicker, subaerial, continental
crust in North Island (this crust broken off from the eastern side of Australia during formation of the Tasman Sea marginal basin). The subduction-zone-related Taupo Volcanic Zone is, in this sense, a continental-margin province. Arc-trench type volcanoes of the Fly-Highlands province in the highlands region of Papua New Guinea have been built on the northern edge of the Australian continent, including the thermally active volcanoes of Doma Peaks and Yelia. These highlands volcanoes, therefore, are of ‘continental margin’ type, although whether they formed there as a result of contemporaneous subduction is questionable (e.g. Johnson, 1987a).

**EXPLOSIVITY**

The broad identification of two main tectonic settings for the volcanoes of the SOPAC region described in the preceding section (island-arc/trench systems and mantle plumes, categories 1 and 2) corresponds to a fundamental difference in magma type and, therefore, in eruption characteristics. Gas provides the driving force for volcanic eruptions and the two different tectonic and eruption characteristics are related to two separate volcanic gas budgets.

Volcanoes formed above mantle plumes are dominantly lava-flow-producing and basaltic. In contrast, magmas in arc-trench systems typically are explosive, generating extensive airfall and flow deposits, and ranging in composition between basalt, andesite, dacite, and rhyolite. Explosive eruptions are caused by rapid volatile exsolution in depressurised magma which expands, froth-like, but then breaks into particles, producing ash, pumice, and

**Figure 5:** Six rhyolite caldera systems of the Taupo Volcanic Zone (simplified from Wilson et al., 1984, figure 1). Caldera margins mapped from surface geology are shown by the solid lines, whereas the outer limit of the named volcanic centres are shown by the broken lines. The -500 m contour encloses areas of basement rocks that are deeper than 500 metres. Only Taupo is regarded as a Holocene caldera, using the criteria outlined in Table 1. Note, however, that the active volcano Tarawera (site of the disastrous VEI-5 1886 eruption) is part of the Pleistocene Okataina caldera complex, and that other caldera complexes in the Taupo Volcanic Zone cannot be regarded necessarily as extinct.
vesicular blocks (see Section 4). At least some of the volatiles in these magmas probably originate from subducted and hydrated ocean-floor rocks. The explosivity of the magmas is related also to physical properties, such as relatively high viscosity caused by their silica-rich compositions.

These statements on magma characteristics made in relation to the two main tectonic settings are, of course, gross simplifications and there are – as usual in geology – many exceptions. Thus, lava flows are a common constituent of island-arc volcanoes, and indeed are typical for EABB erupted on the seafloor. In addition, hotspot volcanoes can be explosive, particularly where influenced by interactions of magma with groundwater within the volcano. Furthermore, volatiles drive eruptions on mantle-plume islands just as in island arcs although, typically, they produce ‘fire fountains’ of low-viscosity, incandescent, lava lumps and clots that fall back to the ground and reconstitute as lava flows.

Numerous factors determine how a volcano is built up and how many different types of volcano can be formed (section 5). Paramount amongst these are the ‘explosivity’ of eruptions, the proportion of explosive (tephra) versus effusive (lava flows, lava domes) products, and the volume and rate of expulsion of magma at the eruptive vent. Explosivity is particularly important in island-arc volcanoes.

The ‘size’ of an explosive eruption can be described in several ways. Thus, ‘magnitude’ refers to the volume of material produced, ‘intensity’ refers to the emission rate, ‘dispersive power’ is the extent of dispersal, the term ‘violence’ stresses the importance of momentum, and ‘destructive potential’ is the ability to destroy and damage (Walker, 1980). A Volcanic Explosivity Index (VEI) attempts to summarise the ‘size’ of an eruption by using a range of different criteria, but using mainly the volume of material produced, which is easier to measure than factors, such as ‘intensity’ and ‘violence’ (Newhall & Self, 1982). A simple zero-to-eight (0-8) index of increasing explosivity (magnitude) is used in the VEI method, each interval representing an approximate ten-fold increase.

Most explosive eruptions are in the VEI 1-3 categories and are of relatively low impact (Simkin & Siebert, 1994). On the other hand, VEI 4-6 eruptions, while much rarer, are more widespread and serious in their effects. For example, two of the largest historical explosive eruptions in the SOPAC region are the 1951 Lamington eruption in Papua New Guinea and the 1886 Tarawera eruption in New Zealand. These had VEIs of 4 and 5, respectively. Larger eruptions of VEI-6 magnitude (10-100 km³ of tephra) are known from geological studies of volcanoes in the SOPAC region, such as of the tephra deposits of Kuwae volcano in Vanuatu, and of Long Island in Papua New Guinea (see below). No VEI-7 eruptions, comparable with the 1815 Tambora eruption in Indonesia, have been identified in the SOPAC region.

Another outstanding example is the 186 A.D. eruption at Taupo volcano, New Zealand (Figure 5). Its VEI is given as 6+ (Simkin & Siebert, 1994) where the ‘+’ sign signifies an eruption volume in the upper third of the VEI-6 range, therefore, corresponding to eruptions known to be larger than most others in the same range. This is the highest VEI score for any of the eruptions in the SOPAC region listed by Simkin & Siebert (1994). The Taupo eruption produced (in addition to an ignimbrite of 30 km³ volume) a pumice fall deposit of 24 km³ volume but its maximum thickness was less than 1.8 m. This signifies an eruption of extraordinary dispersive power, which has been termed ‘Ultra-Plinian’ on account of this characteristic (Walker 1980).

COMMON LITHO-MORPHOLOGICAL VOLCANO TYPES

The wide range of tectonic settings for the volcanoes of the SOPAC region and the factors that determine how a volcano grows, are reflected in the different types of volcanoes and major structures that have been produced subaerially and on the seafloor. A diversity of types exists in the region, as detailed below:

Stratovolcanoes are the archetypal volcano of arc-trench systems. These are the imposing but, generally simple, steep-sided cones built of alternating lava flows and fragmental deposits that may reach 2-3 km above their base level. Strombolian and vulcanian-type explosive eruptions (see, for example, Macdonald 1972 for definitions of these and other eruption types) of generally low VEI (1-3) characterise the build-up of stratovolcanoes. They commonly produce small volumes of material that build up successively, generally within a few kilometres of the central vent, producing the tall and steep-sided cone, 2300-m high Ulawun volcano on New Britain Papua New Guinea, is a good example. It has been identified by IAVCEI as a Decade Volcano for special study during the International Decade for Natural Disaster Reduction (IDNDR) and, to date, is the only volcano in the SOPAC region to be so designated.
Calderas are collapse depressions on volcanoes that represent the subsidence of the roofs of shallow magma reservoirs. Calderas range in diameter from about 2 to 60 km, but most are less than 25 km. They can have different origins, but many appear to originate by collapse along vertical, inward, or outward-dipping ring faults, even at the same caldera. Others, such as the major calderas of Taupo and Rotorua in New Zealand (Figure 5) simply represent the sagging of reservoir roofs into the underlying magma. The subsidences that cause caldera formation in island arcs invariably are associated with major explosive eruptions (VEI greater than 3). Many of the eruptions are of ‘plinian’ type. These form tall eruption columns of gas, pumice, and ash that may collapse, forming major, pyroclastic flows and laying down deposits of ‘ignimbrite’ (now the international name that originated in New Zealand for rocks laid down by pumiceous pyroclastic flows). Fourteen calderas of Holocene age have been identified in the SOPAC region (see below).

Pyroclastic shields or plateaus develop around calderas characterised by large-volume explosive eruptions (VEI of 4 or more). The shields are made up of extensive deposits of airfall and pyroclastic materials which, unlike those of stratovolcanoes, do not necessarily accumulate in the immediate vicinity of the eruptive centre. Ignimbrites may be of low-aspect ratio – that is, thin (metres or tens of metres) but laterally extensive (tens of kilometres). Indeed, paradoxically, the shields may be so flat and unspectacular in profile that they tend to be underestimated in terms of their past, highly destructive capabilities. Pyroclastic shields and plateaus in the SOPAC region are well developed around the Holocene calderas at Taupo (New Zealand) and Rabaul (Papua New Guinea).

Avalanche amphitheatres are a special type of caldera. They form into an underlying magma reservoir, not by roof collapse, but rather by gravitational collapse along major glide planes within a volcano itself. The collapses remove large sectors of the affected volcano, forming rock slides, then debris avalanches (and then perhaps lahars), that may flow tens of kilometres from the volcano. The avalanches may generate destructive tsunamis if they enter the sea. Large amphitheatre are formed on the volcano that commonly are approximately U-shaped in plan, although others are more arcuate or even controlled by regional, linear, fracture patterns. Large, over-steepened and overgrown stratovolcanoes are candidates for avalanche-amphitheatre formation.

There are many examples of amphitheatre in the SOPAC region. One of the most impressive is at Tinakula volcano in the eastern Solomon Islands.

Lava shields are also low-angle and extensive. However, as the name implies, they are made up mainly of lavas that, because of their large volume and fluidity, are able to flow considerable distances from the source vent. These volcanoes resemble the great oceanic shields of the Hawaiian Islands (and other oceanic islands) and, like them, may have radial rift zones which, themselves, are the sources of lava eruptions. The island-arc volcano of Aoba (Vanuatu) and of Niuafo‘ou (Tonga) also has the distinctive lava-flow dominated shield-like form. Savaii Island, Western Samoa, is another striking example.

Lava cones are steeper than lava shields (although ‘shields’, strictly speaking, are also cones). Their lava flows tend to be smaller in volume and more sluggish than those of lava shields and only rarely extend beyond the foot of the volcano. For example, the activity of Bagana volcano on Bougainville Island, Papua New Guinea, is characterised by the slow effusion of andesitic lavas that flow imperceptibly for years down one side of the volcano until the morphology of the crater rim is changed by explosive eruptions. Flows then start to flow down another part of the cone (e.g. Bultitude, 1979).

Pyroclastic cones are the dominantly fragmental equivalents of lava cones. Basaltic cones typically consist of scoria or cinders, whereas those of more silica-rich compositions consist of pumice, ash, and lava blocks. Pyroclastic cones commonly appear as satellite cones on larger volcanoes, or make up many of the small centres of polygenetic fields. Many of them are monogenetic – that is, formed by ‘once-only’, fairly short-lived (hours to weeks) eruptions. Others, while monogenetic individually, may be clustered together, forming a larger and longer lived complex (for example, the 1878-1994 Vulcan pyroclastic cones at Rabaul, Papua New Guinea).

Polygenetic volcanic fields are areas hundreds or thousands of square kilometres in extent that contain tens or hundreds of small volcanoes – pyroclastic cones, small composite cones, and maars (explosion craters formed by eruptions through wet ground). Volcanic activity, therefore, is not confined to one place (building a large volcano) but rather is distributed widely, constructing many small volcanoes. Auckland City is built over a Quaternary volcanic field, and an extensive field characterises the Quaternary landscape of western Victoria and south-eastern South Australia.

Volcanic complexes are large, composite features made up of a few or several volcanoes that may be of different types, overlap one another, and produce different types of eruptions, although they are all considered to have developed from one general, albeit complex, magmatic system. They may have long histories that are difficult to reconstruct because of the geological complexities and because later events tend to obscure earlier ones. The Rabaul volcanic complex, Papua New Guinea, is a good example. Many plinian/ignimbrite-forming eruptions have taken place there, forming a ‘nest’ of calderas. Deposits of the most recent eruption (about 1400 years ago) are the best exposed and the caldera believed to have formed in association with it has largely obscured earlier collapse.
events. Old stratovolcanoes rim the calderas on the northern and eastern sides of the caldera complex, and intra-
caldera volcanoes include pumice cones, scoria cones, and small stratovolcanoes. There is petrological evidence
for magma mixing and mingling in the presumed, large, magma reservoir that underlies the complex.

The volcanological features described above are largely those of the subaerial volcanoes of the SOPAC region. The
realm of seafloor volcanism is different, especially in deep water which restricts the development of explosive activity.
Information on seafloor volcanism has become available in recent years through numerous marine-geoscience
cruises that have taken place in the SOPAC region. Research vessels routinely employ side-scan sonar equipment,
bottom-tow cameras, and submersibles. These surveys have revealed in the active back-arc basins (for example,
the Lau Basin in Tonga, and the Manus Basin in Papua New Guinea) a range of seafloor volcanic features, including
lava fields, pillow lavas, sheet flows, and hydrothermal vents with the spectacular sulphide chimneys formed by
‘black smokers’ (e.g. Stackelberg, 1985; Both et al., 1986).

CLASSIFYING AND CHARACTERISING
THE VOLCANOES

‘How many active volcanoes are there in your country,’ is a simple enough question, but the answer in not always
easy to provide. This is because the distinction between ‘active/alive’ and ‘dead/extinct’ volcanoes is commonly
made on the basis of historical records, and because ‘historical time’ differs greatly from one volcanic region
to another. It means a few thousand years for the Mediterranean, but only two hundred or so for the SOPAC
region. South Pacific history (as written records) may be short, yet indigenous peoples have carried stories (many
presumably now non-existent) about disastrous eruptions as oral history down through the thousands of years they
have lived in the South Pacific.

There is also uncertainty over the much-used, if not misused, volcanic term of ‘dormant’. Volcanoes that have
produced eruptions in historical time may be termed ‘active’, but a rain-forest covered, eroded, and apparently
‘extinct’ volcano that has long repose periods between eruptions, measured in terms of thousands or even tens of
thousands of years (e.g. Simkin & Siebert, 1984) may appear extinct but, in fact, is still alive and therefore ‘active’.
Drawing the line is difficult in the SOPAC region, as it is elsewhere.

A pragmatic approach in trying to answer the question is simply to use the geological Pleistocene/Holocene
boundary at 10,000 years as the cut-off point for the maximum acceptable age for the latest eruption of a volcano
– that is, an active volcano is one that has produced a magmatic eruption some time during the last 10,000 years.
This time-line is arbitrary to some extent, given that ‘Holocene’ refers to post-glacial time in the northern hemisphere
and given that a few, still active volcanoes may not have been in eruption during the last 10,000 years. However,
the Pleistocene/Holocene boundary is a pragmatic limit, given that it is used in the most comprehensive catalogue
of volcanic eruptions (Simkin & Siebert, 1994, and based on the Volcano Reference File of the Global Volcanism
Program, Smithsonian Institution, Washington D.C., a global database on active volcanoes and their eruptions).

A simple way to classify the Holocene volcanoes of the SOPAC region is by using the following four-fold basis based
on the date of the latest known eruption (Figure 6–8; Simkin & Siebert, 1994):

- recorded eruption between 1900 and 1994,
- recorded eruption up to 1900 AD,
- eruption some time within the Holocene, and
- uncertain Holocene

This classification and the accompanying three maps may give the impression of placing prominence on the most
recently active volcanoes (categories a and b), yet categories c and d may be the more significant, in terms of the
potential for large future eruptions (see below).

A second classification is provided here (Table 1) as a complement to that used in Figures 6 to 8, using the list
of volcanoes provided by the Smithsonian Institution (1992). The classification in Table 1 combines the results of
progressive choices about (1) the basic tectonic type (mantle plume versus others – mainly arc-trench type), (2)
whether the volcano is subaerial or deep-submarine, and (3) one of the following types - polygenetic fields, active
caldera systems, and thermal areas; and then, finally, (4) distinguishes the remaining volcanoes on the basis of
dates and age uncertainties about their Holocene eruptions. This classification was adapted from one used in a
recent 1:10 million scale map of natural hazards in the Pacific Southwest (Johnson, 1995) in which a wide range
of published and unpublished sources were used to classify the volcanoes of the south east Asian and south west
Pacific region.
Figure 6: Holocene volcanoes of New Zealand, Kermadec Islands, Tonga, Samoa, and Fiji (Simkin & Siebert, 1994). Index refers also to Figures 7 and 8.

Figure 7: Holocene volcanoes of Papua New Guinea, Solomon Islands, Vanuatu, and Australia (Simkin & Siebert, 1994).
The Table 1 classification is hardly a precise one as adequate information on many of the volcanoes in the SOPAC region does not exist, particularly geochronological data on many Holocene eruptions. Also, answers arising from the questions for some volcanoes are arbitrary. Furthermore, many volcanoes would classify in more than one group were it not for the ‘progressive question’ format. However, the broad results obtained are sufficiently useful in drawing attention to some of the features of SOPAC volcanoes in general and on a country-by-country basis in particular (Table 2).

146 volcanic systems comprise the general statistics from the analysis for the whole SOPAC region (Table 2). Only 13 of these are mantle-plume types, and only 20 (not including submarine mantle-plume types) are deep-submarine. Deep-submarine volcanoes may be under-represented in the statistics because of the dearth of information about their existence in the still poorly known parts of the Pacific Ocean floor. There are 14 Holocene caldera systems and six polygenetic fields in the region.

Only 21 out of the 146 volcanic systems are in the ‘frequently active’ group (Table 2). The low score for this group however is, in part, an artefact of the ‘progressive question’ format used in Table 1. This is because it is one of the categories remaining after categories 1-5 – which includes some ‘frequently active’ mantle-plume, caldera, and deep-submarine volcanoes – that have been dealt with. Nevertheless, note that the highest score of 31 is for the ‘probable Holocene – no dates’ category (7), reflecting the deficiency of information on many volcanoes in the SOPAC region. Note also, and more importantly, that the total for categories 6-8 is 57. These volcanoes likely carry low perceptions of risk in their local areas because of the dearth of eruptions within community memory. Yet this group of 57 also probably includes volcanoes of long repose intervals but potentially highly explosive character. These may be the eruptive centres capable of producing explosive eruptions of regional, if not global, effect – those of VEI 4 and greater. Finally, note that the 57 does not include the 14 Holocene caldera systems, sites of known large-scale explosive eruptions in the past. Thus, about half of the 146 total is made up of volcanoes which could be regarded as more potentially dangerous than the ‘frequently active’ ones.

Papua New Guinea has 54 volcanic systems identified in Table 2, which is at least twice the total of the other countries, including New Zealand if the “thermal areas (no Holocene volcanism)” group (5) is excluded. The total for Papua New Guinea is similar to that for the Philippines (52), but much less than Indonesia (134), for example. Papua

Figure 8: Holocene volcanoes of French Polynesia, including Antipodes Island (New Zealand (Simkin & Siebert, 1994).
TABLE 1: VOLCANO-SYSTEM CLASSIFICATION GROUPS FOR VOLCANICALLY ACTIVE COUNTRIES OF THE SOPAC REGION

<table>
<thead>
<tr>
<th>Progressive questions on volcano-type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mantle-plume (hotspot) type?</td>
<td>Volcanoes above intraplate mantle plumes that may have formed time-progressive volcanic trails. Move onto the next question if the answer is ‘no’.</td>
</tr>
<tr>
<td>2 Deep-water submarine?</td>
<td>Volcanoes on the ocean floor. Those that have produced ephemeral islands during the Holocene are included in one of the following categories. Move onto the next question if the answer is ‘no’.</td>
</tr>
<tr>
<td>3 Polygenetic field?</td>
<td>Volcanic areas characterised by many (dozens or hundreds) of small eruptive centres (pyroclastic cones, lava domes, maars, etc.) rather than single, major volcanoes. Many individual cones within a field may be extinct but the field as a whole remains active. New cones may form in new places. Move onto the next question if the answer is ‘no’.</td>
</tr>
<tr>
<td>4 Holocene caldera systems (&gt; 5 km)?</td>
<td>Calderas exceeding 5 km in diameter for which there is a known date or other reasonable evidence for their formation during the Holocene. Calderas of unknown age are included here only if they are known, post-caldera, Holocene magmatic eruptions. Calderas of unknown age that do not have post-caldera Holocene magmatic eruptions (but which may have thermal activity) are excluded. Volcanoes within, or on the rim of, known pre-Holocene calderas are classified on one of the other categories. Move onto the next question if the answer is ‘no’.</td>
</tr>
<tr>
<td>5 Thermal areas but no Holocene volcanism?</td>
<td>Thermal areas that do not appear to be associated with Holocene volcanism, although they may be associated with pre-Holocene volcanic rocks. Move onto choosing one of the following categories if the answer is ‘no’.</td>
</tr>
<tr>
<td>6 Uncertain Holocene (Pleistocene)?</td>
<td>Volcanoes that have unlikely, but still possible Holocene status. These are volcanoes of unproven but likely Pleistocene age (or even older). They probably became inactive before the Holocene, but still may retain thermal activity or evidence for Holocene hydrothermal explosions.</td>
</tr>
<tr>
<td>7 Probable Holocene - no dates</td>
<td>No dated magmatic eruptions, but based on volcanoes having geomorphological features, thermal activity, or a general lack of erosion indicative of a notable general ‘youthfulness’. Also includes prominent thermal areas that are associated with only minor volcanoes or volcanic rocks of Holocene age.</td>
</tr>
<tr>
<td>8 Dated Holocene eruptions</td>
<td>Volcanoes known to have been active during the Holocene from oral and written history, or from radiometric dating. This includes volcanoes having had only one post-1850 A.D. eruption. The cut-off date is largely arbitrary, but is convenient in marking greater reporting of volcanic events during developing colonial times in the SOPAC region.</td>
</tr>
<tr>
<td>9 Frequently active</td>
<td>Volcanoes having had two or more magmatic eruptions since 1850 A.D.</td>
</tr>
</tbody>
</table>

TABLE 2: VOLCANO-SYSTEM STATISTICS FOR VOLCANICALLY ACTIVE COUNTRIES OF THE SOPAC REGION

<table>
<thead>
<tr>
<th>Classification number:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Papua New Guinea (542)</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>22</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Solomon Islands (8)</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Vanuatu (19)</td>
<td>-</td>
<td>3</td>
<td>4</td>
<td>-</td>
<td>2</td>
<td>5</td>
<td>-</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Fiji (2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Samoas, and Wallis Island (7)</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tonga (11)</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Kermadec Islands (6)</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>New Zealand (33)</td>
<td>-</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>13</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>French Polynesia (5)</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Australia (1)</td>
<td>(2)</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Totals (146)</td>
<td>13</td>
<td>20</td>
<td>6</td>
<td>14</td>
<td>15</td>
<td>7</td>
<td>31</td>
<td>19</td>
<td>21</td>
</tr>
</tbody>
</table>

1 See Table 1 for classification descriptions (1-9); 2 Country/territory totals given in parentheses.
New Guinea has, by far, the greatest number of ‘probable Holocene – no dates’ (group 7) volcanoes in the SOPAC region, the greatest number (six) of Holocene caldera systems (group 4), and is the only SOPAC country to have all nine of the classification types represented in Table 2. Solomon Islands, in contrast, has eight volcanic systems, including three deep-submarine volcanoes. Kavachi (Figure 9) and Tinakula are its most frequently active volcanoes.

Vanuatu (total 19) has four Holocene caldera systems and five ‘frequently active’ volcanoes including Yasur (Tanna Island) which is one of the most persistently active subaerial volcanoes anywhere in the world (another is Stromboli in Italy). Yasur was seen in activity by the English explorer Captain Cook in 1774 and is thought to have been in more or less continuous strombolian-type eruption ever since, and possibly for hundreds of years before that. Fiji has only two volcanoes identified in Table 2: Taveuni has radiocarbon-dated Holocene eruptions; Koro Island is in the ‘uncertain Holocene’ category.

Samoa, American Samoa, and Wallis Island between them have seven mantle-plume type volcanic systems. Tonga has 11 entries, including four deep-submarine centres. Its most frequently active volcanoes (four) include the well-known Metis Shoal (a pumice-raft producer) and Niuafou’ou Island. There are six volcanoes identified in the Kermadec Islands, two of them deep submarine. Raoul Island is the largest volcano in the Kermadec group.

New Zealand has 33 volcanic systems identified in Table 2, but these include 13 active thermal areas that are not clearly associated with Holocene volcanism. New Zealand has examples of volcanoes in all the groups identified in Table 1, except for the mantle-plume type. Its three ‘frequently active’ volcanoes are Ruapehu, White Island, and Tongariro (Ngauruhoe). New Zealand has more Holocene polygenetic fields (category 3) than any other SOPAC country. Taupo is the only one of the many Quaternary caldera systems in the Taupo Volcanic Zone of New Zealand that classifies as Holocene, using the criteria set out in Table 1. However, this statistic must be treated with considerable caution, as it implies that the risk of future caldera-forming events at the existing Pleistocene calderas in New Zealand is insignificant in the longer term (Figure 5). New Zealand is, in fact, exceptional on global standards in having more high VEI-type volcanoes per 100 km of volcanic chain than does any other part of the world (Simkin & Siebert, 1984).

French Polynesia has five mantle-plume type volcanoes, mainly submarine and mainly in the Society Islands. Australia has two (Big Ben volcano on Heard Island, and centres on the MacDonald Islands), but these are outside of the generally accepted geographic limits of the SOPAC region. Australia, therefore, has only one entry in Table 2 – the polygenetic field of western Victoria and south-eastern South Australia (the ‘Newer Volcanics’).
HAZARD TYPES AND PAST DISASTERS

A geophysical event becomes a hazard when it threatens the lives and livelihoods of people. Volcanic hazards are wide-ranging, and the range of hazard types and relative threats are different from one volcano to another (Crandell et al., 1984; Blong, 1984). Fourteen hazards listed elsewhere (Blong, this volume) include, for explosive volcanoes, tephra falls, pyroclastic flows, pyroclastic surges, and ballistic ejecta. Rafts of floating pumice can be hazardous to shipping and destructive to coastal zones. Interaction of magma with the sea, water of volcanic lakes or groundwater, causes explosive eruptions involving the ‘flashing’ of water to steam, and the chilling, shattering, and comminution of magma.

Lahars (‘mudflows’), debris avalanches and floods from melted snow and ice are also volcanic hazards. Gas, vapour and aerosols can be hazardous at volcanoes, as well as lightning and air shocks during explosive eruptions. Lava flows damage property and destroy arable land. They generally are not life-threatening, although people are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

The nature of ‘secondary’ volcanic hazards has been articulated as follows: ‘lava flows can ignite fires, cold lahars can occur with every reasonably intense rainfall for months or years after the eruption ceases, valleys can become blocked by landslide debris to create lakes that breach on overtopping [or through collapse], chemical leakages from damaged industrial plants or oil storage facilities can pollute land and water’ (Blong, this volume). Secondary hazards also include traffic accidents during evacuations, and health problems in evacuation centres, resulting from volcanic crises. Losses of power, water supply, sewerage systems, communications, and transportation links may also be hazardous phenomena that result from eruptions.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

The nature of ‘secondary’ volcanic hazards has been articulated as follows: ‘lava flows can ignite fires, cold lahars can occur with every reasonably intense rainfall for months or years after the eruption ceases, valleys can become blocked by landslide debris to create lakes that breach on overtopping [or through collapse], chemical leakages from damaged industrial plants or oil storage facilities can pollute land and water’ (Blong, this volume). Secondary hazards also include traffic accidents during evacuations, and health problems in evacuation centres, resulting from volcanic crises. Losses of power, water supply, sewerage systems, communications, and transportation links may also be hazardous phenomena that result from eruptions.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

The nature of ‘secondary’ volcanic hazards has been articulated as follows: ‘lava flows can ignite fires, cold lahars can occur with every reasonably intense rainfall for months or years after the eruption ceases, valleys can become blocked by landslide debris to create lakes that breach on overtopping [or through collapse], chemical leakages from damaged industrial plants or oil storage facilities can pollute land and water’ (Blong, this volume). Secondary hazards also include traffic accidents during evacuations, and health problems in evacuation centres, resulting from volcanic crises. Losses of power, water supply, sewerage systems, communications, and transportation links may also be hazardous phenomena that result from eruptions.

Examples of these types of volcanic hazards are found throughout the SOPAC region, and disasters have been caused as a result of them within historical time. A list of Fatalities and Evacuations caused by volcanic crises is provided by Simkin & Siebert (1994) who list 23 volcanoes as having produced 33 disastrous events (lives lost, settlements damaged, and so forth) in the SOPAC region. Thirteen of the volcanoes and 17 of the events are reported to have been killed by them on Niuafo’ou in Tonga. Volcanic earthquakes and deformation of the ground (faulting, subsidence) on volcanoes can be damaging, and volcanogenic tsunamis of widespread effect may be generated by volcano edifice collapse by pyroclastic flows crashing into water and by large volcanic earthquakes.

The nature of ‘secondary’ volcanic hazards has been articulated as follows: ‘lava flows can ignite fires, cold lahars can occur with every reasonably intense rainfall for months or years after the eruption ceases, valleys can become blocked by landslide debris to create lakes that breach on overtopping [or through collapse], chemical leakages from damaged industrial plants or oil storage facilities can pollute land and water’ (Blong, this volume). Secondary hazards also include traffic accidents during evacuations, and health problems in evacuation centres, resulting from volcanic crises. Losses of power, water supply, sewerage systems, communications, and transportation links may also be hazardous phenomena that result from eruptions.
- An unknown number of coastal villagers – at least several hundred – were killed in 1888 at the western end of New Britain and on adjacent islands when a volcanogenic tsunami from Ritter volcano, Papua New Guinea, ran up to 12-15 m above normal sea level (Cooke, 1981). The tsunami was caused by gravitational collapse of the formerly symmetrical and steep-sided volcanic island of Ritter, producing a debris avalanche and resulting in formation of an avalanche amphitheatre (Johnson, 1987b).

- About 500 people were killed in 1937 by tephra falls and pyroclastic surges from Vulcan volcano at Rabaul, Papua New Guinea, and the town of Rabaul was evacuated temporarily (e.g. Fisher, 1939). Three people were asphyxiated by carbon dioxide gas in 1990 while collecting megapode eggs on the southern side Tavurvur volcano, Rabaul (GVN, 1990). Three people who came to their rescue also perished. Explosive eruptions at Vulcan and Tavurvur volcanoes in 1994 caused the burial by tephra of many villages and destruction of about two-thirds of the modern town of Rabaul (e.g. Blong & McKee, 1995). Damage was estimated to be about PGK 300 million, but there were only five reported deaths (one not directly related to the eruption). International air traffic was diverted, at cost, around the volcano. A major restoration effort is taking place at present in the Rabaul area, following on from the substantial humanitarian relief effort undertaken immediately after the 1994 eruption. The latest caldera-forming and ignimbrite-producing eruption (VEI 6) at Rabaul took place about 1400 years ago.

- Almost 3000 people were killed in 1951 by a VEI-4 explosive eruption at Lamington volcano, Papua New Guinea (Taylor, 1958). Pyroclastic surges swept down the northern flank and destroyed the government station at Higaturu. The death toll of almost 3000 is the highest for any volcanic eruption or, indeed, any natural disaster in the SOPAC region within historical time.

- Two volcanologists were killed in 1979 by a laterally directed phreatic or phreatomagmatic explosion from a vent near the base of Bagiai volcano, Karkar Island, Papua New Guinea (McKee et al., 1981). The island was placed on alert because of the perceived threat of further, possibly catastrophic explosive activity. Extensive evacuation preparations were made, but no evacuations were required.

- Thirteen people were killed on Manam volcano, Papua New Guinea, in December 1996 when pyroclastic flows moved down a major valley on the south-western side of the island, reaching the sea, and destroying inhabited areas (e.g. GVN, 1996). Four radial valleys on Manam had been known for many years to be vulnerable to pyroclastic flows (Figure 10) and had been identified as unsuitable for human habitation. The population of Manam was evacuated in December 1956, prior to major volcanic activity that buried much of the agricultural land on the island and destroyed an evacuated village (Taylor, 1963).

Figure 10: A basaltic pyroclastic flow descends the north-eastern radial valley on Manam volcano, Papua New Guinea, on 17 March 1960 (Taylor, 1963). Ash clouds rise from a fast-flowing, basal, block-and-ash avalanche.
Further information on the impact of eruptions on communities in the SOPAC region can be obtained from the field of archaeology, including the collection of oral history. Five examples of this are as follows:

- French archaeologists referred to the impact of a major volcanic event at a formerly larger landmass, Kuwae, in Vanuatu (e.g. Garanger, 1966, 1972). Oral history refers to Kuwae tilting and breaking into pieces while a large eruption was taking place, killing most of the inhabitants of the island. Present-day Epi and Tongoa are the largest island remnants of the former Kuwae (Figure 11). Subsequent volcanological research has identified the existence of the largely submarine Kuwae caldera — ‘the forgotten caldera’ — and evidence for a VEI-6 explosive eruption in the early 15th century (Monzier et al., 1994; Robin et al., 1994). Human remains in southern Tongoa are associated with pyroclastic-flow deposits from this eruption. Volcanogenic tsunamis of widespread extent may have been generated by this major explosive eruption.

- Legends exist from Aoba volcano, Vanuatu, for an eruption there about 300 years ago that killed many people in the N’dui N’dui area of the island as a result of ‘flood of lava’ (Warden, 1970).

- The effects of a major explosive eruption at Long Island, Papua New Guinea, in the 17th century have been reconstructed (Blong, 1982). This eruption, like the Kuwae one, has been assigned a high-magnitude VEI of 6 (Simkin & Siebert, 1994). Long Island is a coastal volcano but the impact of its effects were widespread in the highlands region of mainland Papua New Guinea where ‘time of darkness’ stories refer to damage to crops and deaths caused by starvation and house collapse. Long Island itself was devastated and, presumably, many people perished (Egloff & Specht, 1982), not only from the direct effects of the eruption (including pyroclastic flows) but also, presumably, further afield from the impact of volcanogenic tsunamis.

- Oral history has been collected, referring to the former existence of Yomba volcano, Papua New Guinea where, today, only a reef exists (Mennis, 1981). The stories are generally consistent that Yomba volcano was distinct from nearby Long Island (see above), that tsunamis and a ‘time of darkness’ followed a Yomba eruption and disappearance of the island, and that people from Yomba escaped to the mainland and to other islands.
Witori and Dakataua are two Holocene caldera complexes on the north-central coast of New Britain, Papua New Guinea, that are near to volcanic sources of obsidian, the formerly valuable trade-and-exchange material. Obsidian was valued on account of its excellent flaking properties and sharp cutting edges. Tephra sequences in the area include the deposits of several large-scale eruptions (up to VEI-6) from the two volcanoes, together with soils that are artefact-bearing (obsidian tools and Lapita pottery) and indicative of repeated occupation of the area, following devastating eruptions (Machida et al., 1996). Both caldera complexes are regarded as active today and are included in the statistics in Table 2 (column 2). Development of an oil-palm industry, logging operations, and the beginnings of an eco-tourism industry, characterise development along this coast today.

This last example highlights the present-day vulnerability to volcanic hazards of just one developing community in the SOPAC region. It serves also to focus on the most important subjects of the international workshop in Vanuatu – that of risk and preparedness.

VULNERABILITY, RISK, AND REGIONAL CO-OPERATION IN VOLCANOLOGY

Living with Volcanoes

Volcanoes are extraordinarily attractive to humankind. Their rich soils encourage agricultural development. Their craters and calderas, where breached by the sea, form superb harbours and, therefore, bases for economic and political (and subsequently military) endeavours. Volcanic materials can be mined and geothermal heat transformed to energy in a resource-demanding world. Isolated volcanic islands have been staging posts throughout maritime human history for the spread of Pacific cultures, many of whose people stayed on as islanders to capitalise on rich, oceanic, fishing grounds. Volcanoes are the homes of deities and spirits to whom homage must be paid in terms of pilgrimages, shrines, and religious rites. They are also the subjects of Hollywood-style disaster movies. Volcanoes are scenically beautiful, attracting nominations as national parks and financial investment in the development of tourism. They are exciting places to be – sources of inspiration when considering the powerful forces of nature, and ideal for adrenalin rushes during downhill skiing where the slopes are steep and snow is plentiful. Volcanoes clearly attract community growth. Yet, as explored briefly in the foregoing, volcanoes are dangerous.

How best, then, can society prepare for the eventuality of volcanic eruptions and mitigate volcanic disasters? The question is not a trivial one. Indeed, it is increasingly important because communities world-wide are becoming more and more vulnerable to the effects of volcanic eruptions as populations increase, development takes place, and investment increases. The question is of considerable concern in volcanic areas of urban development, such as Naples (Italy), Kagoshima (Japan), Quito (Ecuador), Portland (USA), and Mexico City (Mexico). The theme of ‘Cities on Volcanoes’ is a contemporary one (IAVCEI sponsored a meeting with this title in Rome, Italy, in June-July 1998).

Two notable urban areas in the SOPAC region can be added to the above list: (1) Auckland (New Zealand) where the city is built amongst a polygenetic field of small volcanic cones (Figure 12; Allen & Smith, 1994); and Rabaul (Papua New Guinea), where the community continues to wrestle with the choice of re-establishing the town even as volcanic eruptions continue there, and despite having experienced the trauma of damaging, investment-reducing eruptions in 1937 and 1994.

The problem of volcanic vulnerability is not restricted to larger urban areas. Numerous, smaller, individual communities must come to terms with coping with life on volcanoes. This applies particularly to the SOPAC region and its generally small but widely dispersed populations.

There is now widespread agreement internationally that volcanic-disaster mitigation in urban and rural communities must be tackled co-operatively. An emergency manager cannot operate in isolation from an understanding of the way that volcanoes ‘work’. The work of a volcanologist is of little value if results cannot be translated into preventative strategies and tactics at the community level. Co-operative venturing underpinned the spirit of the international workshop in Vanuatu and was translated into discussion and recommendations under the following four headings.
1. Volcano Surveillance

Finding out when eruptions will take place, what kind they will be and, importantly, when they will stop, are the challenges facing volcanologists in the realm of public service. The task is daunting. Yet volcanologists can make general, timely forecasts about these events if (1) a volcano is well monitored, (2) there is a good knowledge of its past eruptive events and resultant effects, (3) the volcanologists themselves are well trained and experienced, and (4) effective working relationships have been established with local authorities, and with the news media.

The extent and effectiveness of volcano surveillance in the SOPAC region are variable but generally ‘below par’, although there are basic capabilities in New Zealand, Papua New Guinea, and Vanuatu. Volcano monitoring worldwide is focused on earthquake detection, on measuring the tilting, extension, and uplift of ground surfaces on volcanoes and, to a lesser extent, on geochemical monitoring of volcanic gases and other fluids. Monitoring is non-existent or inadequate, in practical terms, at several of the dangerous volcanoes mentioned so far in this review. The workshop identified eight volcanoes in five SOPAC countries requiring at least a basic, permanent, seismic-monitoring capability.

Permanent geophysical monitoring is not essential on all active volcanoes of the SOPAC region, particularly in countries where adequate funding simply may not be available, but certainly such monitoring is needed at some critical ones. A basic system in itself need not be expensive, but there are support costs for staff and upkeep that need to be kept in mind. However, early indications of volcano unrest can be noted by people in local communities if an effective public-education program is undertaken. Prompt reporting to local authorities of such signs as felt earthquakes and the appearance of fresh landslips, hotter ground, or warmer crater-lake waters, may be sufficient to trigger the deployment of monitoring equipment from elsewhere in the SOPAC region, on a temporary basis, to an otherwise unmonitored volcano. This, ideally, should be undertaken for the SOPAC region by a regional ‘rapid response’ capability based in one of the SOPAC countries already having some geophysical monitoring capability.

2. Hazard and Risk Management

A volcano may be perceived as threatening to a community, but what exactly is ‘the hazard’? What precisely is ‘vulnerable’? What is the ‘value’ of the vulnerable parts of the community and, therefore, what actually is ‘at risk’? Mapping volcanic hazards is an established and proven process on many volcanoes (e.g. Crandell et al., 1984; Figure 13). In contrast, mapping vulnerability and risk is more difficult, although the challenge is being taken up (e.g. Blong & Aislabie, 1988) with the realisation that many populations are becoming more and more vulnerable.
Preparing communities for the impact of hazards involves answers to the above questions, which can be answered only by adopting an effective information-management approach. Hazard assessments require the acquisition of good topographic, bathymetric, and meteorological data, together with satellite and air-borne imagery, as well as the mapping of volcanic deposits. Vulnerability can be defined from the mapping and assessment of spatially referenced information on population distributions (including demography and make-up of the population), land uses, lifelines and the built environment, and establishing the expected losses from hazards of particular types. Risk maps of use to emergency (and land-use) planners, therefore, can be developed. The amount of collected information can be substantial, but it can be managed effectively through use of appropriate databases and computer tools, such as Geographic Information Systems (GIS); e.g. Granger & Johnson, 1994).

A digital approach to the mapping and assessment of hazards, vulnerability, and risk is being adopted worldwide, including in Australia where the Australian Geological Survey Organisation (AGSO) is undertaking a national geohazards vulnerability of urban areas project (the Cities Project). AGSO is developing a generic risk-analysis approach to geological hazards (Figure 14). GIS and other computer management systems provide an effective means of running ‘scenario analyses’ whereby a volcanic eruption (hazard) of a particular size and type can be ‘inflicted’ on a community of known value and vulnerability. Hazard and vulnerability parameters can be changed to forecast different risks ‘on screen’, so providing decision makers and authorities with an appreciation of the magnitude of the likely disaster, and with mitigation strategies and tactics.

3. Emergency Management Procedures

Emergency management practices cover the totality of crisis events – pre-crisis prevention and preparedness through to post-event response and recovery.

Several countries in the SOPAC region have strengthened their institutional capacities and established emergency management mechanisms. There is a focus now on attempting to provide co-ordinated and timely responses during times of crisis. However, not all of these countries have had the opportunity to develop comprehensive emergency management plans and programs for use in anticipation of and during volcanic crises, or to engage in work related to volcano surveillance, mapping volcanic hazards, and defining volcanic risk. Yet emergency managers are the key link in the chain of co-operation, linking volcanologists, risk assessors and educators with the communities they all serve. This is because emergency managers ultimately are responsible for the preparation of national volcanic emergency plans.
Volcanologists play a special role in prevention and preparedness aspects of emergency management (e.g. UNDRO, 1985; see also papers on this topic in Scarpa & Tilling, 1996). They can undertake critical hazard analyses and give prevention advice on where people should live, farm, and establish their homes and businesses. They can provide important information to planners on building codes (e.g. on ash-fall resistant roof structures) and to engineers on preventative measures, such as the construction of diversion and pocket dams in lahar-threatened areas.

Volcanologists also can play a role in preparedness activities, such as evacuation planning and the practice of evacuations. They can advise how to operate safely when visiting volcanoes (e.g. IAVCEI, 1995a). Their role in emergency management is crucial at times of volcanic crises in providing timely advice to authorities. Volcanologists can help in developing protocols for use when they may have to cope with, for example, an influx of visiting scientists wanting to study an eruption during a crisis (IAVCEI, 1997). Good relationships with the media are crucial at these times and establishing appropriate information-dissemination mechanisms is part of a good preparedness plan (e.g. Peterson, 1988). Finally, volcanologists can provide advice during response and recovery stages when discussions take place on the location of evacuation camps and on resettlement proposals.

4. Education and Awareness

Lives will not be saved and property will not be prepared sufficiently for hazardous impacts if communities in volcanically vulnerable areas are unaware of the hazards they face and the procedures that have been put in place for their own safety and well-being. Knowledge of volcanoes and their hazards can be introduced to children by informed parents at home, by teachers in schools, and by emergency managers in communities. School projects on volcanoes — such as ‘paint a volcano’ competitions — can be organised.

Volcanologists can visit educational institutions, invite people to their observatories, take groups out to volcanoes (when safe) and show them the deposits laid down by previous eruptions. Liaison officers can be used during volcanic crises, particularly to help communicate essential information to the community. Talk-back radio and videos (e.g. IAVCEI 1995b, 1996) are effective means of communication, in addition to the distribution of printed material, such as pamphlets, stickers, and posters. Logos on baseball caps and tee-shirts can be both eye-catching and, therefore, awareness raising (Figure 15).
Few involved in the field of volcanic emergency management — volcanologist, risk assessor, emergency manager, and decision maker — can disengage from the necessity of educating and raising awareness. Education and awareness are the cement of the pieces that connect the different work responsibilities of the volcanologist at one end of the chain and affected people at the other.

CONCLUSIONS

Numerous active volcanoes exist in the SOPAC region and many are a threat to populations, investment and development in the South Pacific region. Volcanic disasters have taken place in the past and will happen again, so long as inadequate mitigation measures are kept in place. Only a few countries are able to sustain adequate volcano-monitoring capabilities of their own, and to undertake additional supporting work, such as mapping of hazard, vulnerability, and risk on volcanoes. A solution to this weakness is the development of regional co-operation and establishment of a volcanic emergency management network.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the work done by Carol Simpson in generating information that forms the basis of Tables 1 and 2. He appreciates, particularly, comments on the draft manuscript made by T.D Jones, M. Leiba, B.J. Scott and P.W. Taylor. This paper is published with the permission of the Executive Director, Australian Geological Survey Organisation, Canberra.

REFERENCES


Petterson, M.G., et.al., this volume.


Scott, B. & V.E. Neall, this volume


Taylor, P.W., et al., this volume. Volcanic Hazards and their Management in the Kingdom of Tonga.


INTRODUCTION

Increased populations, improved lifestyles, the growth of infrastructure – even with stable rates of volcanic hazard occurrences – will result in increased vulnerability and increased risk. Larger concentrations of people and the globalisation of commerce and industry increase the potential for the consequences of volcanic eruptions to be experienced over wider areas than were experienced previously. Despite our inability to do risk assessment and risk management well in the past, all of these influences highlight the need for enhanced efforts now.

This paper considers five aspects of volcanic hazards risk assessment: (1) the physical characteristics of volcanic hazards that influence human and infrastructure vulnerability; (2) relative risks; (3) the relative vulnerability of people; (4) secondary hazards; and (5) probable maximum eruptions.

This paper is a shortened version of Blong (1996).

PHYSICAL CHARACTERISTICS

The first part of the risk assessment process involves identifying the hazards. Table 1 provides a short-hand summary of the physical characteristics of the various volcanic hazards that might occur in any eruption.

It is not easy to make too many generalisations beyond those listed. Rarely do all volcanic hazards occur at all volcanoes, or in all eruptions. Jökulhlaups or glacier burst floods are pretty rare in the tropics. Even lava flows of any magnitude are uncommon in the South Pacific – though the 1905-11 eruption of Matavanu in Western Samoa provides the exception. Not all the properties listed are of equal importance – importance varies with the volcano, the eruption, location in relation to the vent, and with what is at risk.

RELATIVE RISKS

Part of the risk assessment process involves establishing which of the multiplicity of potential volcanic hazards might be important. Here, Papua New Guinea (PNG) volcanoes are taken, as a whole, as an example. VEI~4 eruptions are the focus with the concern, in this example, of damage to buildings. Table 2 sets out a risk assessment process in 6 columns. Column 1 lists the volcanic hazards just discussed. Column 2 provides estimates of the relative frequency of each hazard in PNG VEI~4 eruptions; for example, lava flows that escape from the crater occur in about 15 out of 100 eruptions. This estimate has been made using selective heuristics (i.e., guessing) – it could be improved by using the data in Simkin and Siebert (1994).

Column 3 makes a stab at the average area in km² affected by the hazard, assuming that this particular hazard occurs. It is important to note that the average area affected by tephra falls is deliberately underestimated – 500km² is equivalent only to a circle with a radius of 12-13 km around the vent.

Column 4 estimates the damage to the average building affected by the hazard. Building damage in a volcanic eruption might result from burial, foundation failure, impacts from ballistic ejecta, transport, excessive wall or roof loads, ignition/incineration, racking, collapse, undermining or corrosion. Here, whatever the cause, the aim is simply to estimate the anticipated cost of damage as a percentage of the cost of replacing the whole building. It is assumed
### TABLE 1: PHYSICAL CHARACTERISTICS OF VOLCANIC ERUPTIONS

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Lava flows            | - temperatures above ignition points of many materials  
                        - velocities from a few tens of m/h to 60 km/h  
                        - buoyant effects - can transport objects  
                        - follow topographic depressions  
                        - noxious haze from sustained eruptions |
| Ballistic ejecta      | - 3-5 km radius of vent  
                        - high impact energies  
                        - densities <3 t/m³  
                        - fresh bombs above ignition temperatures of many materials |
| Tephra falls          | - downwind transport velocity <10 to <100 km/h  
                        - exponential decrease in thickness downwind  
                        - can extend 1000 km+ downwind  
                        - material <64 mm diameter at thermal equilibrium  
                        - can produce impenetrable darkness  
                        - compacts to 1/2 initial thickness in a few days  
                        - surface crusting encourages runoff  
                        - abrasive, conductive, magnetic |
| Pyroclastic flows     | - concentrated gas-solid dispersion  
                        - flow velocities up to 160 m/s  
                        - emplacement temperatures <100 to >900°C  
                        - small flows travel 5-10 km down topographic lows  
                        - large flows travel 50-100 km  
                        - large flows climb topographic obstructions |
| Pyroclastic surges    | - low concentration but high kinetic energy  
                        - radius of deposition 10-15 km  
                        - climb topographic obstructions  
                        - emplacement velocities > tens of m/s |
| Lahars                | - generated with rainfalls >10 mm/h  
                        - hot or cold  
                        - increase turbidity and chemical contamination  
                        - erosive  
                        - travel distances up to tens of km  
                        - hazard may continue for months or years after eruption |
| Jokulhlaups           | - can appear with little or no warning  
                        - discharges may be >100,000 m³/s |
| Rock/debris avalanches| - sector collapse, minimum volume 10-20 million m³  
                        - travel distances 20-30 km+  
                        - hot or cold  
                        - emplacement velocities up to 100 m/s  
                        - create topography |
| Earthquakes           | - maximum MMI of 8 or less  
                        - damage limited to small areas  
                        - damage dependent on subgrade conditions |
| Ground deformation    | - damage limited to 15-20 km radius  
                        - subsidence may affect hundreds of km² |
| Tsunamis              | - open ocean travel rate >800 km/h  
                        - exceptional waves to 30 m+  
                        - inundation velocities 1-8 m/s |
| Air shocks            | - up to 15-fold amplification of atmospheric pressure |
| Lightning             | - cloud-to-ground lightning near volcano  
                        - strikes related to quantity of tephra |
| Gases and aerosols    | - water vapour a major component  
                        - SO₂ next most important  
                        - SO₂, H₂S, HF, HCl - corrosive/reactive  
                        - CO₂ in areas of low ground/poor drainage  
                        - pH of associated rainwater may be 4.0-4.5 |
that buildings are distributed evenly around the volcano and across all areas at risk; obviously, this is an unrealistic assumption but it serves the purpose for the risk assessment. Thus, lava flows tend to completely destroy buildings, whereas ballistic ejecta just punch a few holes through the roof and floor, destroy the odd structural member and singe a few bits and pieces - nothing your average handyman could not fix for a mere 30% of the replacement cost of the building.

Column 5 takes the values in Columns 2 to 4, multiplies them together and divides by the lowest non-zero value - in this case, the value for Gases and Aerosols. These numbers are then rounded to emphasise that all of the values here are but rough estimates. Column 6 further rounds these values to provide just crude order of magnitude estimates of relative risk. In Column 6, 1 represents the highest relative risk.

It is easy to be critical of the various values in the columns of Table 2. Most of us would want to change a few of them. That is okay. What Columns 5 and 6 show is that you have to shift the values in Columns 2 to 4 quite a bit in order to alter the orders of magnitude in Column 6.

Column 6 indicates that tephra falls are in a class of their own as far as relative risk goes (for buildings in VEI~4 eruptions in PNG), despite the fact that the area affected by tephra fall (Column 3) was deliberately underestimated. Second order risks include lahars, pyroclastic flows, rock avalanches, pyroclastic surges, ballistic projectiles and lightning strikes. The third and fourth order risks are not of immediate concern.

The relative risk assessment process outlined here is subjective but simple. It could be improved with the application of some hard data - if any is available. It might be further improved by using group expert opinions. As open to criticism as the methodology is, it is worth noting that the process outlined here is a more sophisticated version of the Qualitative Risk Analysis Matrix proposed in the Australia/New Zealand Risk Management Standard (Standards Australia, 1995).

In fact, this process represents a fundamental risk management tool that is easy to adapt to local situations, individual volcanoes, or single eruptions. Similarly, the process can be modified readily so that individual classes of building (commercial or residential, for example), types of lifelines or economic activities are the focus of the relative risk assessment.

### VULNERABILITY OF PEOPLE

The volcanic hazards and physical characteristics outlined in Table 1 obviously have the potential to affect humans in a variety of ways. Those at risk have the opportunity to be buried, crushed, lacerated, fractured, penetrated, asphyxiated or burnt. Astonishingly, few data are available about morbidity and mortality (injuries and deaths) as a result of each of the listed volcanic hazards.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Frequency%</th>
<th>Area affected (km²)</th>
<th>Building damage indexa (%)</th>
<th>Relative risk indexb</th>
<th>Order of Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava flows</td>
<td>15</td>
<td>&lt; 2</td>
<td>100</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Ballistic ejecta</td>
<td>20</td>
<td>2</td>
<td>30</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>Tephra falls</td>
<td>30</td>
<td>500a</td>
<td>20</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Pyroclastic flows</td>
<td>10</td>
<td>20</td>
<td>100</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Pyroclastic surges</td>
<td>&lt; 5</td>
<td>20</td>
<td>100</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>Lahars</td>
<td>25</td>
<td>20</td>
<td>80</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>Jökulhlaups</td>
<td>0</td>
<td>0</td>
<td>80</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Rock avalanches</td>
<td>&lt; 1</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>&lt; 5</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Ground deformation</td>
<td>&lt; 1</td>
<td>20</td>
<td>60</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Tsunami</td>
<td>2</td>
<td>20c</td>
<td>60</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Air shocks</td>
<td>2</td>
<td>100</td>
<td>&lt; 5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Lightning</td>
<td>30</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Gases and aerosols</td>
<td>5</td>
<td>10</td>
<td>&lt; 5</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

a Deliberate underestimate of area affected; b Estimated % average reconstruction cost; c Coastal strip, 1 km wide; d Product of Columns 2-4, divided by the value for Gases and Aerosols (lowest non-zero value) and rounded to provide order of magnitude estimates of relative risk.
However, Blong (1996) provided a broad overview, summarised here in Figure 1 and Table 3. Figure 1 provides cumulative distribution functions for deaths attributed to a range of volcanic hazards in the period 1600-1986. These data are based on a 1987 unpublished version of the Smithsonian Institution Volcano Reference File and will not necessarily be in accord with the data in Blong (Simkin and Siebert, 1994). The list of volcanic hazards used in the construction of Figure 1 and Table 3 do not, unfortunately, agree in toto with those in Table 1. Deaths from ballistic ejecta have been grouped with tephra falls; rock/debris avalanches and pyroclastic surges have been lumped with pyroclastic flows; lahars embrace water floods and jökulhlaups; seismic action combines earthquakes and ground deformation. Indirect deaths include those from starvation and disease in the aftermath of an eruption.

![Figure 1: Cumulative distribution functions for deaths attributed to volcanic hazards in the period 1600-1986 (based on a 1987 version of the Smithsonian volcano reference file (Blong, unpubl.).](image)

**TABLE 3: EXPECTED DEATHS IN FUTURE ERUPTIONS IN WHICH FATALITIES RESULT FROM SPECIFIC VOLCANIC HAZARDS**

<table>
<thead>
<tr>
<th>Hazard</th>
<th>No. of events</th>
<th>Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Lava Flows</td>
<td>12</td>
<td>400</td>
</tr>
<tr>
<td>Tephra falls</td>
<td>38</td>
<td>300</td>
</tr>
<tr>
<td>Pyroclastic flows</td>
<td>37</td>
<td>3600</td>
</tr>
<tr>
<td>Lahars</td>
<td>44</td>
<td>850</td>
</tr>
<tr>
<td>Seismic action</td>
<td>5</td>
<td>50+</td>
</tr>
<tr>
<td>Tsunami</td>
<td>11</td>
<td>2500</td>
</tr>
<tr>
<td>Gases</td>
<td>10</td>
<td>1700</td>
</tr>
<tr>
<td>Indirect</td>
<td>11</td>
<td>260 000</td>
</tr>
</tbody>
</table>

In the 386-year period considered here, volcano-related 564,612 deaths occurred (that we know about), with 76,152 of these fatalities resulting from 20th century eruptions. Indirect deaths and those produced by seven eruptions - Asama (1783), Lakigigar (1783), Unzen (1792), Tambora (1815), Krakatau (1883), Mont Pelee (1902) and Nevado del Ruiz (1985) - dominate the record. The record is unstable in that a single eruption producing 10-20,000 fatalities completely alters the pattern of mortality. For example, prior to the 1985 eruption of Nevado del Ruiz, lahars produced about 12.3% of known eruption-related fatalities this century. When including the deaths in the Armero lahar, this proportion changes to about 39 per cent.

Despite the instabilities and the uncertainties, Figure 1 and Table 3 provide some interesting results. The relatively small number of events on which many of these estimates have been based should be noted. Clearly, from Figure 1, the cumulative curves have not been smoothed.
The 50th Percentile values indicate the median death tolls expected as a result of a specific volcanic hazard, assuming that a hazard kills someone – it is relevant only to those eruptions in which humans die. Due to the under-reporting of small death tolls, this table probably overstates median death tolls. In terms of human vulnerability, given all the data constraints and the caveats already noted, pyroclastic flows and tsunamis appear to be the volcanic hazards producing the largest death tolls per eruption.

Even assuming that deaths in the last four centuries provide an adequate guide to deaths in the future, there is not a lot that can be done with these statistics. Translating global statistics to the local volcano is fraught with difficulty and even regional data sets would provide too few data points to allow sensible interpretation. Nonetheless, Table 3 contains “background information” that should be kept in mind when local assessments of human vulnerability are considered.

LIFELINES

Although we know quite a lot about lifelines in relation to earthquakes and windstorms (e.g. O’Rourke, 1995; Cook and Soltani, 1994; Andrews and Blong, 1996), we do not have a large database of experience, indicating lifeline resiliency and failure in volcanic eruptions.

The significant question seems to be – what is the weakest link in the lifeline? Which bridge, which telephone pole; which transmission tower? In order to develop answers to such questions, we need excellent information about each lifeline, the redundancies built into the network, and the susceptibility of each component or node to damage from each volcanic hazard, working through the physical characteristics one at a time.

At the very least, the sort of preliminary analysis set out in Table 2 could be carried out for each hazard, recognising that the “fragility” of each lifeline component is likely to be different for each hazard. Such analyses have rarely (if ever) been undertaken. These simple elements of risk identification and analysis would seem to be the first steps in risk reduction.

Finally, lifeline interactions must be checked. Does the road-bridge most vulnerable to removal by lahars also carry the water supply pipeline? Will electrical failure also prevent the pumping of water through the reticulation system, and a reduction in fire-suppression capabilities?

SECONDARY HAZARDS

With the multiplicity of volcanic hazards set out in Table 1, who needs more? However, we should recognise that there are more. Lava flows can ignite fires, cold lahars can occur with every reasonably intense rainfall for months or years after the eruption ceases, valleys can become blocked by landslide debris and create lakes that breach on overtopping, and chemical leakages from damaged industrial plants or oil storage facilities can pollute land and water.

Risk assessment needs to recognise secondary hazards or na-tech (natural-technological) hazards and to identify areas of potential collateral damage.

CHARACTERISTIC ERUPTIONS AND PROBABLE MAXIMUM ERUPTIONS

Much of the consideration here has focussed on middle-sized eruptions (VEI~4) – big enough to involve a number of volcanic hazards and to produce a wide range of consequences, yet small enough to be reasonably common.

What eruption magnitudes should we focus on? Should we produce a shiny new version of Table 2 for each vulnerable element for VEI 3, 4, 6, or 8? Can risk assessments, hazard maps or risk reduction measures be developed independently of a consideration of eruption magnitude and character?

Can we identify characteristic eruptions – that is, eruptions of a size and character that seem to be repeated commonly at a volcano? Identification of characteristic eruptions seems to imply that detailed tephrostratigraphic studies have been conducted, producing evidence from which satisfactory conclusions can be drawn. For the
coming eruption, do we have quality geophysical and geochemical data that allows us to confirm or deny that the event will be of a characteristic magnitude? Is there such a thing as a characteristic eruption, any more than there is a characteristic earthquake for a particular fault, or a characteristic cyclone intensity for the Coral Sea?

Most flood hazard maps show the 1/100 year inundation line. Other natural perils often consider events with return periods of 1/100 to 1/1000 years, particularly for insurance purposes. Most wind and earthquake building codes refer to a 10% chance of exceedance in 50 years, about a 1/475-year return period. Most volcanoes erupt less frequently than once in 1/100 years, and many less often than 1/1000 years. A few others erupt continuously for hundreds of years.

Can we identify a Probable Maximum Eruption for a given volcano? Is the answer always VEI~8, because that is where the scale stops? Hydrologists recognise that concepts, such as a Probable Maximum Precipitation or a Probable Maximum Flood relate to return periods that are longer than (i.e. less frequent than once in) 10,000 years. Do Probable Maximum Eruptions relate to similar time periods?

Whatever the answers to these questions, we need to determine whether we can afford to ignore such issues in volcanic hazards risk assessment.

CONCLUSION

Volcanic hazards risk assessment involves identifying both hazards and vulnerabilities. The risk assessment process includes identification of risks, analysis of risks, risk control and risk transfer. The emphasis in this paper has been on risk analysis – in effect, establishing just which volcanic hazards are important for each vulnerable element.

However, risk analysis should not be an end in itself but a prelude to sincere efforts at risk control whereby weak links are eliminated and risks are reduced through control measures such as evacuation, land-use planning, improved buildings codes, redundancy in lifeline systems, hardening of weak nodes, etc. Scenario development and fault tree analysis are vital tools in risk control, but they are only worth while if the risk identifications and risk analysis parts of the assessment process are done well.

Risk transfer is often the final part of the assessment process. Risk transfer commonly involves three players - citizens, insurers, government. All three players have interests in endeavouring to get the other two to assume the risks they do not want. Risk transfer is another story.

Finally, risk assessment has a sense of totality about it. Because risk assessment implies an in-depth understanding of both hazard and vulnerability, it cannot be divorced from a social, political, demographic, cultural, economic milieu. Equally, there is doubt that volcanic hazards risk assessment can be divorced from risk assessment for other natural perils. There may be little point, for example, in strengthening the roof of a building so that it will resist tephra fall if the building is located on a floodplain.

Volcanic hazard risk assessment makes best sense when it is conducted within the framework of integrated natural hazards risk assessment.

REFERENCES


A GLOBAL OVERVIEW OF VOLCANIC EMERGENCY MANAGEMENT

J. Tomblin
ANTIGUA, WEST INDES

THE ELEMENTS OF EMERGENCY MANAGEMENT

Effective management of a volcanic emergency depends primarily upon the extent to which the situation and its particular coordination needs have been foreseen, systematically analysed and planned for in advance, especially by the people in charge and also (at a level of basic understanding and readiness to react) by the population. One of the best ways of improving emergency management is to analyse recent case histories of emergencies where the physical and socio-economic conditions are comparable. By looking carefully at reports of these cases, it is easy to identify which elements of the emergency presented problems, how important each of these problems were, and how procedures can be set up to reduce similar difficulties during future crises.

The responsibilities for ensuring the best possible management of a potential natural disaster rest mainly with two groups of officials: Firstly the scientists, who must establish as clearly as possible the type, magnitude and probability of occurrence of the eruptions that can be expected, and, secondly, the disaster managers, i.e. government officials responsible for the logistical and socio-economic aspects of emergency management. They must establish the criteria and be ready to implement the procedures for taking protective measures which, in most cases, will involve carrying out an evacuation and looking after evacuees. Working in collaboration with the disaster preparedness managers, there should also be land-use planners who steer housing, industrial lifeline services and other aspects of long-term development, as far as possible, from the highest volcanic hazard zones, and engineers who design critical facilities and structures, such as vital medical and communications facilities.

A third vital component of good volcanic emergency management is to ensure close mutual understanding of needs and collaboration between the scientists and disaster managers: for example, a clear understanding by the scientists of the type and format of hazard statements which can be used directly by the emergency managers for determining acceptable risk.

A fourth component of good crisis management, sometimes difficult to establish, is to ensure the fullest and most constructive use of the media as a public information channel.

To illustrate that the above problems are real but, in many cases, not too difficult or costly to correct, the remainder of this paper will highlight certain issues with specific reference to recent experiences of emergency management needs. It will illustrate their causes and consequences, and will propose appropriate corrective measures. Table 1 provides a tabulated summary of the most frequently recurring problems in the author’s and UNDHA’s experience, and indicates how and who should take corrective action.

BASELINE MONITORING

The need to know the typical level of background activity in the form of local seismicity, ground deformation, thermal and chemical regimes of hot spring, lake levels and other similar phenomena is evident, but there are still many high-risk volcanoes where routine measurements of this kind are not carried out. For example, at Ruiz Volcano in Colombia, no scientific monitoring of this kind had been established prior to the onset of the 1985 activity, even though there had been two previous catastrophic eruptions in historical time. On the island of Montserrat in the West Indies, in 1995 seismicity was being monitored, but ground deformation measurements had lapsed several years earlier and most of the survey piers had been destroyed by bush clearing and agricultural activities. These could not be immediately re-established, measuring instruments were faulty, and local scientists were lacking in practice with the methods. As a result, there was less knowledge than there should have been on the volume of
### TABLE 1: VOLCANO-SYSTEM CLASSIFICATION GROUPS FOR VOLCANICALLY ACTIVE COUNTRIES OF THE SOPAC REGION

<table>
<thead>
<tr>
<th>DIFFICULTY</th>
<th>CAUSES</th>
<th>CONSEQUENCES</th>
<th>CORRECTIVE MEASURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inadequate baseline monitoring prior to new crisis</td>
<td>Low capacity and commitment of scientists</td>
<td>Difficult to evaluate magnitude of impending eruption</td>
</tr>
<tr>
<td>2</td>
<td>Absence of up-to-date hazard maps</td>
<td>Low interest and initiative of local scientists</td>
<td>No satisfactory basis for risk evaluation and emergency planning</td>
</tr>
<tr>
<td>3</td>
<td>Slowness to deploy local crisis monitoring resources</td>
<td>Local scientists poorly organised and funded. Low recognition of risks</td>
<td>Valuable time lost in assessing the gravity of the emerging crisis</td>
</tr>
<tr>
<td>4</td>
<td>Delays in clarifying needs and best sources for external assistance</td>
<td>Lack of proper contingency planning and appropriate contacts by local scientists</td>
<td>External assistance slow to arrive, not well matched to local conditions and needs</td>
</tr>
<tr>
<td>5</td>
<td>Bad collaboration between local monitoring teams or between locals and externals</td>
<td>Professional rivalries and jealousies, or personal publicity-seeking</td>
<td>Authorities receive differing opinions and are confused</td>
</tr>
<tr>
<td>6</td>
<td>Scientists fail to reach consensus on future hazards</td>
<td>Lack of consultation. Unwillingness to compromise. Poor leadership</td>
<td>Authorities lack clear technical guidance</td>
</tr>
<tr>
<td>7</td>
<td>Inadequate statistical basis for quantifying hazards</td>
<td>Global historical case histories not properly reviewed and utilised</td>
<td>Hazard statements may be misleading</td>
</tr>
<tr>
<td>8</td>
<td>Excessive emphasis on worst case scenarios</td>
<td>People tend to focus on the most spectacular of any range of possibilities</td>
<td>The media further emphasise worst case scenarios. Result is undue public anxiety</td>
</tr>
<tr>
<td>9</td>
<td>Lack of clarity on who decides whether or not to evacuate</td>
<td>Improper hazard quantification by scientists</td>
<td>Scientists may be tempted or invited to give opinions on subjects beyond their professional expertise</td>
</tr>
<tr>
<td>10</td>
<td>Senior public officials not fully aware of volcanic hazards and risks</td>
<td>No recent major eruptions to stimulate concern</td>
<td>Low recognition of possible future losses</td>
</tr>
<tr>
<td>11</td>
<td>Development planning rarely oriented to minimise volcanic risks</td>
<td>Nature and scale of potential eruption losses not recognised</td>
<td>Vulnerability increases much faster then necessary</td>
</tr>
<tr>
<td>12</td>
<td>Incomplete emergency management plans</td>
<td>Poor knowledge or application of relevant planning procedures</td>
<td>Delays and bad decisions in response to emergency</td>
</tr>
<tr>
<td>13</td>
<td>Officials cited in the plan are not fully conscious of their duties</td>
<td>Poor training or motivation</td>
<td>Plan is not properly followed Coordination suffers</td>
</tr>
<tr>
<td>14</td>
<td>Criteria for calling an evacuation not clearly defined</td>
<td>Procedures not sufficiently clear or well-practised</td>
<td>Valuable time with training and to identify where duties are badly allocated</td>
</tr>
<tr>
<td>15</td>
<td>Population not fully aware of alert and evacuation routines</td>
<td>Need more simulation exercises</td>
<td>Existing plans will not work properly</td>
</tr>
<tr>
<td>16</td>
<td>Part of the population may refuse to evacuate</td>
<td>People not fully aware of risks</td>
<td>Evacuations will be more difficult to carry out</td>
</tr>
</tbody>
</table>
magma in moving below the volcano, hence no upper limit could be placed on the magnitude of a future eruption. At Rabaul in 1994, telemetered ground deformation instruments were faulty and this contributed to delaying the scientists’ declaration of the hazard level until it was almost too late to evacuate the large population at risk.

HAZARD MAPS

Reliable hazard maps based on careful field reconstructions of past eruptions are fundamental to all aspects of risk evaluation. The needs, outlined in Table 1, are self-evident. Any major new construction in the higher hazard zones around a volcano should be seized on as an opportunity to justify a new cycle of review of hazards, in the light of new exposures of volcanic strata and based on the latest global experience of interpreting their significance. Where good hazard maps do not exist at the beginning of a new crisis, they must be prepared urgently. This was done successfully during the two-month precursory period at Pinatubo Volcano in 1991. It did not happen as quickly as required during the 11 months of precursors to the Ruiz disaster, and insufficient time was left for emergency planning to be completed.

EXTERNAL MONITORING ASSISTANCE

In many developing countries, there may be local staff and equipment to carry out baseline monitoring at the more dangerous volcanoes, but often there are not enough instruments and additional manpower to deal with an emerging crisis. In order to cope efficiently with a crisis, there should be standing arrangements with external specialists who are already well-acquainted with the local scientists and with local physical, socio-economic and political conditions. In certain developing countries, a permanent linkage and regular collaboration (including joint field missions) exists between the local and one or more external specialist groups. It is best if the latter visit regularly to help with baseline measurements for which local capacity may be lacking. This ensures prompt and relevant assistance whenever a new emergency arises, and is an important aspect of good management and contingency planning by the scientists. This happened very efficiently at Pinatubo in 1991. By contrast, it was a painfully slow process at Ruiz Volcano in 1985, due in part to difficulties of internal coordination between the poorly experienced local scientific groups. At Montserrat in 1995, there was no clear contingency plan for calling up external assistance, resulting in delays in obtaining qualified help of the kind needed.

COLLABORATION AND CONSENSUS AMONG THE SCIENTISTS

The success of scientific monitoring and interpretation during a volcanic emergency depends not only on the skills of individuals, but also on the coordination of their efforts through good leadership into clear and simple hazard statements, representing the best consensus of what may often be divergent opinions on the rate of escalation and maximum extent of an eruption. Difficulties of this kind were particularly acute during the emergency of 1976 in the French West Indian territory of Guadeloupe. Further details on this eruption and similar management problems are cited in the United Nations Disaster Relief Coordinator-United Nations Educational, Scientific and Cultural Organisation) (UNDRR-UNESCO) manual entitled Volcanic Emergency Management (Anon., 1985). Suitable corrective measures are proposed in this manual, and more briefly in Table 1 of the present paper.

QUANTIFICATION OF HAZARDS

During the heat of a volcanic emergency, scientific teams typically find themselves obliged to take one of two alternative courses in giving advice to the crisis management authorities. They must either quantify the various hazards by giving probabilities such as a 1 in 20 chance of pyroclastic flows hitting the capital town during the remaining course of the eruption, and a 1 in 80 chance of this occurring with less than 12 hours of recognisable precursors. Alternatively, the scientists will be expected to recommend whether and when to evacuate one or more of the hazard zones. It may not always be evident to the scientists concerned that the decision to evacuate involves a delicate equation: on one side is the need to avoid loss or injury (e.g. by evacuating), and on the other side is the need to minimise socio-economic disruption (e.g. by not evacuating). Whilst volcanologists are the best qualified
to quantify the hazard (acknowledging that this is only a crude and not a precise estimate), it is very doubtful, and might even be challenged in a court of law, whether they are sufficiently well-informed on the socio-economic factors to decide, or even to recommend to the political authorities, where to place the limit of acceptable risk. This issue is a crucial one that, in many countries, has not been thought out, in advance of the next crisis as carefully and calmly as it deserves.

If it is accepted by the scientists that they must give quantified hazard estimates, they should take steps to inform themselves as fully as possible about all relevant regional and global precursor sequences, so that the "horse-racing odds" that they provide for different eruption scenarios are based upon the best possible synthesis of the behaviour of all other comparable volcanoes. The writer is attempting, on his own account, to develop and update analyses of this kind that he began more than twenty years ago. It would be very useful for World Organisation of Volcano Observatories (WOVO) and United National Educational, Scientific and Cultural Organisation (UNESCO) to help coordinate a larger-scale effort to search out and synthesise all relevant worldwide data.

At present, (for example recently in Montserrat), quantified estimates by scientists on the probable future course of the eruption have, in the case of many individuals, been given "off the top of their head", rather than being based on real historical data and worldwide averages.

**AWARENESS AMONG PUBLIC OFFICIALS**

One of the key factors in stimulating attention to the logistical aspects of pre-emergency planning is the extent to which senior government officials are aware of volcanic risks, and are motivated to give the subject the attention it deserves. For example, at Ruiz Volcano in 1985, too many other burning issues remained higher on the agenda of senior government authorities. Earlier historical volcanic disasters had been long forgotten, even in the areas devastated. The capital, Bogota was far from the hazard zones, and no scientists in Colombia had dedicated themselves to investigating volcanic hazards, using modern methods. In the areas devastated by Ruiz Volcano in 1595 and 1845, and particularly the town of Armero where 22,000 people were buried by the mudflows of 1985, urban development had taken no account of volcanic hazards. The same applied in Montserrat, where the capital Plymouth was built immediately at the foot of the volcano with little development in the more distant safe zones of the island, even after significant volcanic alerts in 1933 and 1966. Similarly, the choice of the site of Rabaul and its continued growth as the provincial capital, even after the moderately destructive eruption of 1937, is an example of misguided development planning.

**STATUS OF EMERGENCY MANAGEMENT PLANS**

Incomplete or outdated logistical plans, or the poor knowledge of such plans by the responsible officials and the population at risk, obviously lead to delays and bad decisions in responding to an emergency. Items 12-14 of Table 1 review the typical difficulties encountered and the corrective measures required. For each volcano, specific plans are needed for each of the more likely eruption scenarios, and these should be practised and updated at regular intervals. If the criteria for calling an evacuation and the procedures for implementing it are widely agreed and known, it will be carried out much more efficiently. The case of the successful evacuation of Rabaul under difficult conditions in September 1994 illustrates the value of holding regular (in this case, annual) public information and practice sessions. Such activities help to keep the whole population aware of risks and of how they can reduce them. Simulations (item 15 of Table 1) also help to identify which particular tasks are least likely to be completed and require more careful planning.

Finally, the question often arises as to whether an evacuation should be imposed “at gun-point” by the authorities, or whether those people who do not wish to move from the high-hazard zones should be allowed to stay. This poses a difficult dilemma for the authorities. Forced evacuations create unpleasant confrontations but, on the positive side, reduce the risk of looting in the evacuated zone, as well as the risks that rescuers may feel obliged to take if destructive activity affects an incompletely evacuated area. What is important is not which alternative is chosen, but that the preferred policy is clearly established before the next crisis, so that it can be applied without hesitation.
CONCLUSIONS

It should be clear, from the issues that have been raised in this paper, that systematic pre-emergency investigations and planning are critical to the successful management of a volcanic crisis, and that there are numerous problems that are better to discuss in public as a means of seeking consensus in advance of any crisis.

Experience shows that there is no unique set of best solutions. Different cultures and political regimes will favour different alternatives. The purpose of this paper is, therefore, not to prescribe specific options, but rather to trigger a process of orderly analysis, decision-making and planning for volcanic emergency management within each high-risk community.

REFERENCES

EMERGENCY MANAGEMENT IN THE SOPAC REGION

I. Rector

United Nations Department of Humanitarian Affairs – South Pacific Programme Office, FIJI

INTRODUCTION

This paper will focus on emergency management from a regional perspective, and will be based on the approach adopted by the South Pacific Disaster Reduction Programme (SPDRP) – in-country technical assistance and training component. A brief outline of the background and an overview of the major objectives and project components of the SPDRP will be provided.

THE SOUTH PACIFIC DISASTER REDUCTION PROGRAMME

The SPDRP is a four-year programme that is scheduled to wind down its major in-country support programmes at the end of 1997. Core funding has been provided by UNDP, although significant contributions have also been made by the Australian (AUSAID), New Zealand, French, British and US governments.

The major objectives of the SPDRP are to:

• improve the capacity of countries to mitigate, prepare for, respond to natural hazards through institutional strengthening and community-based disaster management programmes;
• provide governments with applicable technical support materials for use in disaster management and provide training to enable them to effectively use these materials; and
• achieve an acceptable and sustainable level of co-ordination and collaboration among participating countries, donors and other regional projects.

The project component involves in-country, mitigation, regional training (USAID/OFDA), information management, regional support material and regional co-ordination.

DISASTER MANAGEMENT

At this stage, this discussion will briefly expand the focus to the broader issue of disaster management, given that any effective emergency response capability should flow from a broader and more integrated disaster management programme.

Over the past decade, a number of disaster management programmes have been implemented. Many of these have been linked to training, whilst others have been focused on developing national disaster plans. The effectiveness of some of these programmes was short lived. It is believed that the major reason was due to activities being addressed as single-issue items, rather than as part of a larger disaster management programme. More alarmingly, many governments held the view that disaster management and disaster relief are one in the same and, as such, were something that were implemented only when a cyclone struck. Hence the low levels of support for the National Disaster Management Offices (NDMO).

There are probably a number of reasons why disaster management has been viewed in this context. The frequency of events and the manner in which disaster management is marketed are two significant factors.
These issues will not be elaborated on; however, as noted previously, effective emergency management systems come from even more effective disaster management programmes. However, a great deal of emphasis still needs to be placed on promoting and soliciting support for disaster management, not only at the highest political and policy levels, but also within the more receptive departmental and Non-Government Organisation (NGO) levels. During the past twelve months, the SPDRP has introduced two significant strategies that have started to change the perception of disaster management, and has resulted in increased support from government and NGO sectors.

The first strategy focused on how disaster management was presented, and is felt that this is essential to clearly differentiate between disaster management as the “ongoing design development and implementation of programmes and activities” to that of emergency response, “which is the implementation of procedures and actions – when a cyclone or other hazard is threatening”.

Figure 1 is somewhat different to the traditional “cycle”, which has or is being used to provide a diagrammatic overview of disaster management. Over the past nine months, the in-country workshops and briefings have focused on presenting disaster management as “the business we are in”. Within that business are a number of interactive sections that work on vulnerability reduction and strengthening of coping capacities of countries. The cycle has also been removed from within the business and has been linked to the event or situation, be that an emergency or disaster. This is more appropriate for the South Pacific Region and reflects the real situation, which sees a disaster or major emergency as the triggering factor for new programmes, major reviews and amendments, etc. By presenting disaster management in this form, those activities in support of sustainable development (95 per cent of the time) can be distinguished from those activities in response to a threat or disaster situation (5 per cent of the time). This is a critical “first hurdle” as the recognition of disaster management and its benefits to government development programmes will undoubtedly gauge the level of ongoing support from governments.

Figure 1: The Disaster Management Cycle.
The second strategy has been the formation of national disaster management working groups (Figure 2). These groups are managed by the NDMO/Focal Point, and comprise middle to senior level representatives of government, NGO, Red Cross and, in some countries, selected private industry who work together on one consolidated disaster management programme. In many cases, these groups are sub-divided into smaller groups to address specific programme activities. For example, in Tonga and Vanuatu, the sub groups are mitigation, planning and education and awareness.

![Organisation structure for Institutional Strengthening.](image)

**Figure 2: Organisation structure for Institutional Strengthening.**

The immediate benefits from this strategy have been:

- a reliable support base for NDMOs and/or Focal Points;
- a strengthening of government and NGO links;
- improved communication between departments and, in particular, between the technical and non-technical services;
- greater understanding of roles and responsibilities;
- better co-ordination of resources;
- more complimentary organisational planning; and
- more effective education and awareness programming through to the communities.

The involvement of NGOs further serves to ensure that the community interests are incorporated into plans, procedures, policy and warning systems. The success, however, is very much determined by the drive of the NDMO/Focal Points.

An overview of the in-country process for the development of emergency management systems (Figure 3) will now be provided. Although this process is used in all countries, its application varies according to country requirements or situations.

There are no specifically adapted training courses or material to support the in-country programmes, although several planning modules are being drafted with the assistance of Emergency Management Australia (EMA). The process is, therefore, relying on the development process to serve as the learning tool. However, it should be appreciated this has its limitations, particularly as technical support visits cannot be conducted on the frequency
required for this to be an effective approach. SPDRP’s approach is to work with national working groups during visits, and then to set a programme of activities until the next visit. The process that will now be outlined has its advantages, in that it assists countries in programming, and by way of identifying the links between each stage, can facilitate the identification of pre-requisite activities and training needs.

NATIONAL DISASTER MANAGEMENT PLANS

It must be stressed that with National Disaster Management Plans, the emphasis is on management and not disasters. The plans are designed on a uniform format, which makes it easier to follow and understand not only what disaster management is all about, but also how it is being addressed in a country. In the smaller countries, operational procedures are included as annexes, as the requirement for specific support plans is not appropriate.

The key issues that are included in these plans are:

- policy;
- concepts;
- organisational structure;
- management systems and mechanisms for addressing the programme components of mitigation, preparedness, response and recovery;
- roles and responsibilities as they apply to the national programme; and
- standard or uniform issues (control, National Emergency Operation Center (NEOC), media policy, international assistance policy, etc.)

The key to success is the development and annual review of national disaster management programmes. Without this process in place, interest for disaster management will soon diminish.
OPERATIONAL SUPPORT PLANS

These plans are hazard specific and contain information, which will facilitate an effective response to a hazard. Examples of such plans include those for; cyclones, earthquakes, aircraft emergencies, oil spills, sea search and rescue and volcanic eruptions.

Information contained within the operational support plans include:

- policy;
- details of the hazards and associated characteristics, and where developed hazard mapping;
- specific or key roles and responsibilities;
- operational procedures;
- warning and community alerting systems;
- evacuation centres; and so on.

The majority of these plans have been modelled on the cyclone threat, however, in Vanuatu, a great deal of progress has been made on the development of the Ambae volcano plan. This process has been achieved through the combined efforts of the National Disaster Management Office, ORSTOM (Office of Scientific and Technical Research Overseas), the working group members, and the SPDRP that has supported the task from the beginning. Country officials are now coming to the realisation that as the plan nears completion, the work is just beginning with briefings, donor meetings and other time-consuming programme activities that all need attention. Fortunately, the government official responsible for disaster management in Vanuatu has had an extensive management and operations background, where Vanuatu would be struggling otherwise. The development of the Ambae volcano plan and operational procedures has brought home the reality of just how complex such an operation is and, at present, it is considered that many of the disaster management officials of the region would find it difficult to manage without appropriate training.

ORGANISATIONAL AND VILLAGE LEVEL PLANS

Organisational and village plans are among the most important as without them reliable and effective response by organisations and communities cannot be assured. The plans are based upon allocated roles and responsibilities and are structured on plans and procedures (the when and how factors). These plans should complement and support national and operational support plan requirements.

The development of organisational and village plans is a process that requires the most urgent and consolidated support. The SPDRP is not in a position to address this task through to completion.

EDUCATION AND AWARENESS

The SPDRP has completed an education and awareness manual, which has been designed to train national working group members and others on the development of effective education and awareness programmes. As part of this, two in-country courses have been completed (Tonga and Vanuatu) and, by the end of 1997, it is anticipated that many of the remaining countries will have received similar training.

The aim of this process is to show members of the working groups that education and awareness is more than posters and pamphlets, and that programmes should be designed on a wide range of issues including the following:

- hazards and their characteristics;
- policy issues;
- plans and operational procedures; and
- mitigation and preparedness issues.

They can also be generic or specific in nature.
Although attempts have been made to increase the capacity of countries to design and develop education and awareness programmes on an ongoing basis, the problem that many are facing is not having someone who has artistic skills to reflect their ideas on paper. In Vanuatu, the education and awareness programme for Ambae is being developed around a series of visits, briefings, community meetings, pamphlets and other strategies. The target audience also varies with a great deal also to be programmed for the surrounding islands.

CONCLUSION

The logical process that is being used by SPDRP addresses the minimum requirements that countries should strive to meet. It will require the combined efforts of government, NGOs and technical services.

When referring to hazards and disasters, the difference associated with the influencing factors of vulnerability and coping capacities is often considered. It is of concern that national disaster management structures are quite vulnerable, and their coping capacities varied.

The project document that will result from this workshop must stress the importance of professional skills development training, which targets not only planning issues, but provides a better understanding of the hazard and associated characteristics. This will also need to be followed up by regular in-country technical support programmes so that the reinforcement process can continue to improve knowledge and skill levels.

As a final comment, attention is drawn to two programmes (one is a reality and one yet to be commenced), which are or may be implemented over the next year or two.

1. The European Union (EU) tropical cyclone warning upgrade project. In September 1996, the EU launched its cyclone warning upgrade project for EU/ACP countries. Whilst the major emphasis of the project is directed towards improving the meteorological services of the region, two of the three project objectives are complimentary to existing SPDRP in-country activities, ie.

- to strengthen the communications between meteorological services, NDMOs and the public; and
- to ensure warning users understand the information contained in tropical cyclone warnings, and are aware of the appropriate actions to take.

The strategies for addressing both of these objectives are, firstly, a natural progression on existing SPDRP in-country activities, and will facilitate the continuation of the reinforcement phase, and secondly, the activities will automatically address the institutional strengthening process, which will benefit issues related to the development of emergency management systems for other hazards, such as volcanoes and earthquakes.

2. The Regional Disaster Management Framework (project proposal). In 1995, the SPDRP initiated discussion with EMA and AUSAID on the development of a framework for the long-term support for disaster management in the South Pacific. This framework has now been developed to the stage whereby a project document can be formulated. The timing of this process to completion is the unknown factor, however, it is hoped for a mid to late 1998 implementation of all or some of the project components. The ongoing strengthening of disaster management capacities will be the major focus of the framework, and this will have considerable linkages to improving emergency management capacities.

It is seen that both of these proposals are closely linked to the expected outcome of this workshop.
PACIFIC ISLAND COUNTRY PAPERS
INTRODUCTION

The geography of the main island of Viti Levu suggests the existence of a mature geological environment for a considerable period of time. However, many of the other islands in the Fiji Group appear to have experienced volcanic activity in the recent past but no periods of activity have been reported.

This paper outlines the perceptions of volcanic hazards on the Fiji Islands and provides an outline of the level of preparedness that currently exists. It will also provide evidence to suggest that eruptive activity may have occurred on several of the outer islands in the recent past.

VOLCANIC HAZARDS

Compared to the volcanically active neighbouring countries of Papua New Guinea, Solomon Islands, Vanuatu, Tonga and Western Samoa, the risks from volcanic hazards in Fiji is perceived to be low.

The possibility of a volcanic eruption occurring in the future cannot be dismissed as geological records indicate that eruptions may have occurred less than 500,000 years ago on some islands such as Naigani, Yatewa Kalou, Rarantita, Mago and Nabukelevu (Kadavu) islands to name a few. With the exception of Nabukelevu, the above eruptive centres have produced alkaline-olivine basalts or hawaiites. Recent eruptions were probably relatively small and quiet rather than those eruptions witnessed at the Hawaiian, Papua New Guinea and Vanuatu volcanoes. An eruption at a new centre could perhaps cause loss of life and damage to property, however, most likely on a smaller scale.

The province of Kadavu and associated islands have been built from volcanic products of various compositions. The general trend in age and composition indicates that the development of volcanic centres has proceeded from northeast to southwest with the products being of a more acidic composition in the younger volcanoes. Any possible eruption in the area of western Kadavu (on land) could be explosive with widespread falls of ash and ejecta causing damage to properties and perhaps loss of life. This is, however, mere speculation as there is no indication that future activity may occur in the western region of Kadavu within the next few hundreds, thousands or more years.

Potentials for volcanic activity from localities on Taveuni Island, located at the northern zone of Fiji cannot be eliminated (Cronin, 2015). Recent volcanic deposits from the southern part of the island have been dated at 10,000 to 20,000 years. An occupation site located under a thin layer of volcanic ash was found in the same area of the Navolivoli cone and charcoal from the sight has been dated at 250 BC to 50 AD. Archaeological evidence in the Vuna area has indicated that at least 650 years has elapsed since the last eruption in the area. Archaeological excavations at Navolivoli in Vuna reveal that 3-5 eruptions took place in the period between 250 BC and 1320 AD. This may have been the last cycle of activity and therefore, present conditions may indicate that no further activity may occur for many centuries or even millenniums.

HISTORICAL ACTIVITY

During historical times, Fiji has only been affected by volcanic eruptions in Tonga and Vanuatu. Ash from an eruption at one of the volcanic centres in Vanuatu in 1968 reached Fiji and affected the visibility in central Viti Levu to a
maximum of 2 km. This instance of such an amount of ash to blanket Viti Levu and the rest of Fiji appears to be uncommon.

Volcanic eruptions in Tonga are common and many produce pumice that eventually reach parts of Fiji. Recent cases where significant quantities of pumice have been witnessed in Fiji waters have included the Metis Shoal eruptions of 1967-1968, northern Tonga in 1973 and another eruption of Metis Shoal in 1979 which resulted in the formation of Lateiki Island. The large rafts of pumice produced during these eruptions affected much of the Fiji coast, disturbing the ecology and disrupting shipping services. Very little has been done to minimise the harmful effects of pumice generated from Tongan volcanoes.

Volcanic hazards and volcanic risk in Fiji can therefore be divided into three categories:

- hazards from eruptions at newly formed volcanic centres in Fiji;
- hazards resulting from eruptions at known recent volcanoes in Fiji; and
- hazards resulting from eruptions outside Fiji.

VOLCANO SURVEILLANCE

The low to negligible risk of volcanic activity in Fiji may be the reason for the lack of the establishment of a proper surveillance or monitoring system by the Fiji Government. Although Fijian waters are frequently affected by pumice rafts from neighbouring Tonga, setting up a monitoring system would be uneconomical. The presence of pumice rafts moving towards Fiji is usually reported by pilots of aircraft or by ships transiting the region. Air Pacific, Fiji’s national carrier, has yet to raise the issue of the effect of ash clouds produced during volcanic eruptions from neighbouring countries on its regional operations. The reality is that Air Pacific could be severely affected by ash clouds produced during such activity.

The Mineral Resources Department maintains a seismograph on Taveuni that could also record volcano-seismic activity that may occur.

PUBLIC AWARENESS & STRATEGIES

No public awareness materials have been published or released regarding volcanic eruptions. The absence of such materials is indicative of low risks of volcanic hazards in Fiji. Fiji, however, is affected by other hazards such as cyclones, floods, etc. for which the Fiji Government has established mechanisms to counter their effects.

Fiji’s annual National Disaster Awareness Week is the focal point for the government to increase public awareness of the effects of certain hazards on the community. Although the use of the media has been effective over the years, people can become complacent and ignore such programs. Some sectors of the population, however, have to learn the painful way when tragedy strikes, simply because of their ignorance and complacency. The Fiji Government is assisted by the Red Cross and other Non-Governmental Organisations to further public awareness programmes, provided for the community. Printed materials, such as brochures, posters, billboards and flyers have been instrumental in providing awareness to the community.

ALERT LEVELS, EMERGENCY EVACUATION PLANS, AND VOLCANOLOGIST EMERGENCY MANAGER LINKS

There are no established alert levels for volcanic eruptions in Fiji, neither have emergency evacuation plans been prepared for any localities. As mentioned previously, this is solely due to the low risk from volcanic hazards in Fiji. Developing and establishing measures in the absence of a threat or very low risks is not only considered uneconomical but also unnecessary. The situation, however, may change in future but no plans are at place.
On the other hand, the National Disaster Management Plan that has been developed in regard to prevalent hazards in the country spells out unilaterally who are the responsible organisations during emergency operations and their respective roles. Once an emergency is declared by the Minister responsible for disaster management, the resources of government are pooled to combat the situation prevailing. Within Fiji’s emergency framework, the National Disaster Management Council receives reports and recommendations from the Emergency Committee and takes appropriate actions at the national level. Divisional and district controllers are responsible for taking control of emergency operations at their respective levels. Overall, the National Disaster Controller oversees the emergency operation at the national level with the National Emergency Operation Centre coordinating all activities.

REFERENCES


VOLCANIC HAZARDS, SURVEILLANCE AND EMERGENCY RESPONSE IN NEW ZEALAND

B. J. Scott† and V. E. Neall‡

† Institute of Geological & Nuclear Sciences, NEW ZEALAND
‡ Massey University, NEW ZEALAND

VOLCANISM IN NEW ZEALAND

The New Zealand region lies astride the boundary between two of the largest tectonic plates on Earth. Thus it is characterised by a high density of active volcanoes and a high frequency of eruptive activity. New Zealand’s active or potentially active volcanoes are found throughout the North Island, North of latitude 40°S (Figure 1), and offshore to the north in the Kermadec Islands.

Three major types of volcano are found:

Volcanic Fields

These are dominated by basaltic volcanism, with eruptions from Rangitoto Island in Auckland, the most recent activity between 500 - 1200 years ago. The Auckland, Whangarei and Bay of Islands volcanic fields are characterised by many small eruptions over a wide geographic area. All eruptions appear monogenetic.

Figure 1: Location map showing the major volcanoes and volcanic fields in New Zealand.
Cone Volcanoes

Cone volcanoes, such as Egmont and Ruapehu, are characterised by a succession of small-moderate andesitic eruptions from essentially the same place over a long period of time (100 - 250,000 years). The products of successive eruptions accumulate close to the vents to form large cones that reach 2-3000 m above sea level.

Caldera Volcanoes

Caldera volcanism in New Zealand is concentrated into the central portion of the Taupo Volcanic Zone, being characterised by large-scale rhyolitic eruptions (Wilson et al., 1984). Resurgent volcanism is variable at these centres; some are almost completely infilled with lava domes (eg. Okataina), while others like Rotorua and Taupo have experienced little resurgence.

Many oceanic volcanoes occur to the northeast, west of the Tonga - Kermadec Trench. The three major volcanoes (Raoul, Macauley and Curtis) differ from typical subduction volcanism as they have erupted substantial amounts of dacite and basalt, rather than andesite. Summit and submarine calderas are a prominent feature.

NEW ZEALAND VOLCANIC HAZARDS

Volcanic events do not occur as frequently in New Zealand as seismic or storm events so perhaps they do not attract quite the same public attention. That was until 1995, when Ruapehu’s eruptions brought the impact of volcanic activity on the North Island into high profile. The potential of volcanic eruptions to inflict massive and widespread damage to life and property at infrequent intervals, represent a major natural hazard that could paralyse the North Island’s economic livelihood.

The general occurrence of volcanic activity within New Zealand over the last 2 million years is reasonably well documented, except that the absolute timing of numerous eruptive deposits is still incomplete.

Major published overviews summarising this work include those of Dibble et al., (1985), Latter (1985), Gregory & Watters (1986), Houghton et al., (1988) and Scott et al., (1995). However, the amount of specific information on each individual volcanic centre is variable and much unpublished detailed information needs to be made publicly available.

This section reviews the information available on the volcanic hazards associated with the 10 major volcanic centres, of about 20 centres recognised in the New Zealand region, and discusses the potential hazards and current availability of information.

When discussing volcanic hazards, we use the term HAZARD for the natural event having a probability of occurrence in a given period of time and RISK when something of human value is at stake.

RISK = HAZARD x VALUE x VULNERABILITY

A further distinction that needs to be made when discussing volcanic risk is the difference between volcanic hazards analysis and volcanic monitoring (or surveillance). Volcanic hazards analysis involves reconstructing the past volcanic activity at a centre to reveal the past volcanic behaviour. This record is used to interpret the potential hazards in any future eruption from that centre. Volcanic monitoring involves numerous techniques, from geophysics, geodesy, geochemistry and direct observation to detect signs of impending volcanic or geothermal activity.

The Institute of Geological and Nuclear Sciences and the New Zealand universities have expended considerable effort in the last two decades in these two areas of research because:

1. Most volcanic eruptions tend to follow past eruptive behaviour at the same centre, although there have been exceptions; and
2. To quote Williams and McBirney (1979) “Given an adequate monitoring system, there is no reason why any volcanic eruption should occur without recognisable premonitory phenomena. The techniques now available, though only empirical, are adequate to warn of an impending eruption, if not in terms of its precise nature and timing, at least as an event that is likely to occur within a reasonable time.”
Now to the specific volcanic centres, beginning in the north and moving clockwise.

In the far north, the volcanoes of the Kermadec Islands have the potential to disrupt the major Pan-Pacific air and sea routes to New Zealand (Latter et al., 1992). In particular, these comprise Raoul Island in the far north, which last erupted in 1964; Macauley Island, which lies on the margin of a large undersea caldera volcano and Curtis Island, which is currently the most rapidly rising piece of land in New Zealand.

On the main North Island there are two volcanic fields in Northland – the Bay of Islands Kaikohe field, last thought to have erupted between 1200 and 1900 years ago near Waitangi, and the Whangarei field, where eruptions ceased about 30,000 years ago.

The Auckland Volcanic Field comprises at least 48 eruption centres in a 360 km² area. The eruptions have been of basaltic magma producing lava flows, scoria cones and in interaction with groundwater, explosion craters (Smith and Allen, 1993). Each centre seems to have comprised just one eruptive episode and there is no general agreement as to whether the pattern of vents is ordered with respect to time or whether it is random. Most hazards have been confined to a radius of 1-4 km from each vent but the adjoining high population density elevates the risk considerably (Cassidy et al., 1986). Return periods have been calculated of 2-4,000 years for the explosion craters and 1-4,000 years for scoria cones in the Auckland field (Dibble et al., 1985). More than NZD 3600 million of property could be at risk in a future eruption. The Auckland volcano - seismic network now has four seismographs.

Mayor Island is an unusual composition rhyolite. It probably last erupted less than 1000 years ago and has produced eruptions up to 10 km³ in volume. Despite its isolated location, one of the major hazards could be tsunamis along the Bay of Plenty coastline. One is referred to the papers by Buck (1985) and Houghton et al., (1992, 1994) for a more detailed account of the potential hazards.

White Island is an active andesite volcano that has erupted many times this century. Rarely has ash reached the mainland but of major concern is the potential in a larger scale eruption for seawater to enter the magma chamber through the horse-shoe shaped crater, forming an explosive eruption (Cole, 1986; Nairn, 1987; Nairn et al., 1991). An investigation into the potential of tsunami hazards in this region has been the subject of research by De Lange (1983). More than NZD 25 million worth of property is at risk. Ash eruptions have an average return period of about five years. Regular surveillance includes ground deformation, magnetic intensity, gas collection and seismic monitoring; see Scott et al., (1995) for details.

Okataina Volcanic Centre is a rhyolite centre responsible for some of the largest volcanic eruptions in New Zealand during the last two million years, some exceeding 50 km³ volume (Nairn, 1991). The frequency of eruptions and current geothermal activity indicate this centre is a highly likely location for future volcanic activity constituting a major volcanic risk to the Central North Island. Any renewal of activity here, the last being just over 100 years ago, would have major disruptive effects on habitation, tourism and forestry of the region. A return period of 2,200 years is calculated for the rhyolite eruptions, in which more than NZD 3100 million of property could be at risk. Regular surveillance includes a volcano-seismic network, lake levelling and crater lake calorimetry at Waimangu.

Rotorua Volcanic Centre has not erupted in the last 30,000 years but major rhyolite eruptions up to 100 km³ emanated from here in the last 200,000 years. The major geothermal systems associated with this centre have been responsible for small hydrothermal explosions that are of short-term risk to Rotorua City and outlying residential area. A volcano-seismic network records local earthquakes.

Maroa Volcanic Centre is the least well known of the volcanic centres in this review (Wilson et al., 1986). Located to the north-west of Wairakei, it comprises 70 rhyolite domes of unknown age, the last eruption having occurred about 14,000 years ago.

Taupō Volcanic Centre has been New Zealand’s most violent volcano in recent times (Wilson, 1993). Four major destructive rhyolite eruptions in the last 3500 years culminated in one of the largest historical eruptions in the world (over the last 7,000 years). The widespread damage that resulted from these eruptions enveloped 90 km radius from Lake Taupō, with large volumes of airfall pumice carried further downwind to northern Hawkes Bay and substantial volumes of water-borne pumice sweeping throughout the entire catchments of the Waikato, Wanganui, Rangitikei, Ngaruroro and Mohaka Rivers, inundating low-lying land in Hamilton, Wanganui and around Hastings. Earlier larger eruptions from Taupo have reached 200 km³ volume and whilst infrequent have constituted the largest eruptions in New Zealand over the last 2 million years, the ash being well preserved in peat of the Chatham Islands and in deep sea cores obtained from thousands of kilometres away in the South Pacific. Whilst scientific articles on the individual Taupō-sourced eruptions are published (Wilson, 1993), an overall volcanic hazards appraisal is not readily available, except for the precis in Dibble et al., (1985). Major pumice eruptions have a return period varying from 900 to 2,500 years with more than NZD 1,000 million worth of property at risk. Regular surveillance includes lake levelling and a volcano-seismic network.
Tongariro Volcanic Centre is an andesite volcano massif with numerous vents. The most southern is Ngauruhoe, the most recently active vent, which last erupted in 1975 AD. Eruptions from this centre are much less voluminous than Taupo, averaging less than 1 km$^3$. Regular surveillance includes geodetic measurements, gas sampling and seismic monitoring.

Ruapehu Volcanic Centre with its former hot acidic crater lake has been the site for numerous eruptions in the last 150 years. Like Tongariro, Ruapehu is an andesitic volcano with low volume eruptions each totalling less that 1 km$^3$ volume. However, of major hazard is the formation of lahars (volcanic debris flows), generated by eruption through the crater lake, collapse of the lake walls or from melting of snow and ice, which have formed major lahars in the Whangaehu and Whakapapa catchments in particular (Houghton et al., 1987; Neall et al., 1995). Not only did lahars cause the loss of 151 lives in the Tangiwai Disaster of 1953, but they also provide the major danger to skiers on the upper slopes of Mount Ruapehu in winter time when up to 10,000 people may be enjoying themselves above the 1,500 m altitude. A volcanic hazard map is available of Tongariro National Park at 1:100,000 scale broadly outlining the major lahar routes (Latter, 1987). Seismicity at Ruapehu is monitored at the Chateau Observatory. Since 1984, a lahar warning scheme has been operational on Mount Ruapehu based on the principle of automatic detection of seismicity under the volcano followed by instrumental damage close to the crater lake recording volcanic damage by terminating its signal (Hurst, 1986). This system failed to work in 1995 and is currently being redesigned. Gauges for lahar detection exist on a number of the major rivers for warning Railways Corporation and Electricorp. Small volume (6 x 10$^5$ m$^3$) lahars have a return period of 17.5 years; larger scale lahars (2 x 10$^8$ m$^3$) have a 5,000 year return period. The Ruapehu 1995 and 1996 eruptions are discussed in more detail separately.

Egmont Volcano is like Ruapehu, andesitic, being located in a central position with respect to the Taranaki region. It has a long history of numerous small volume pumice and ash eruptions, with a return period of about 200 years, but of major hazard have been the repetitive collapses of sections of the cone, resulting in major landslides, with return periods of between 500 and 8,000 years depending on magnitude. These produced massive lahars that swept to beyond the present coastline, building the region above sea level. The greatest threat from lahars is to the east and to the west of the volcano (Neall and Alloway, 1991). Zones of risk are identified on a 1:100,000 volcanic hazard map (Neall, 1982) and recently updated (Neall and Alloway, 1996). Note that this map applies only to ground hugging volcanic events and not airfall deposits. Based on the record of past eruptive behaviour Latter (1985) considers Egmont to be the highest risk volcano in New Zealand for an eruption of about 107 m$^3$ magnitude. A volcano-seismic monitoring network has now been installed around Egmont.

**VOLCANO SURVEILLANCE**

Two scales of monitoring are required for active volcanoes. The first is background monitoring between crises using a limited number of fixed instruments or sampling points. The key is to strike a balance between cost and the need for accurate and reliable data. The second scale is the monitoring in the event of a crisis. Volcano surveillance is based on the assumption that movement of magma will occur beneath and/or into a volcano before any significant eruption can start. Four primary techniques are used in New Zealand;

- volcano-seismic networks;
- ground-surface deformation;
- chemistry of gases and fluids; and
- crater lake calorimetry.

Earthquakes commonly provide the first indication of volcanic unrest. Today there are five operational volcano-seismic networks (Figure 2) about New Zealand’s volcanoes. Three are operated by GNS in the Taupo Volcanic Zone, while the other two are operated by Regional Councils in conjunction with GNS. These are about Egmont volcano and the Auckland Volcanic Field (Figure 2). A single direct-write seismograph is also operated at Raoul Island, historically our most active volcano. Four of the volcano-seismic networks have dedicated computer-based automatic location systems, which can provide near-real time epicentral information. Real-time volcanic tremor analysis systems have also been developed by GNS (Hurst, 1985) and are installed on the frequently active volcanoes.

Geodetic measurements are used to monitor changes of the ground-surface as magma moves within a volcano. Techniques used by GNS include measuring distances with electronic distance measuring equipment (EDM), while ground tilting measurements are made by precise levelling and using some of the volcanic lakes as large scale spirit levels. At White Island, a precise levelling network is used across the main crater floor. In recent years detailed large-scale horizontal control surveys have been made, and in some cases repeated, across the Taupo Fault Belt and about the caldera volcanoes. Since 1991, we have used global positioning systems (GPS) to make
these measurements. Regular EDM measurements were made about Ruapehu’s crater lake, but did not show any significant changes before the recent eruptions.

Changes in volcanic gas chemistry, the rate of gas emission (e.g. SO₂) from active vents and the chemistry of crater lakes and hot springs, can be used to detect changes in the behaviour of a volcano or its associated geothermal system. Chemical work has concentrated on the gas chemistry at White Island; fumaroles at Red and Central craters, and Ketetahi on Mt Tongariro; the summit crater of Ngauruhoe and the waters of Ruapehu’s former crater lake. Samples from the crater lake from Raoul Island are also regularly analysed. More recently GNS purchased a correlation spectrometer (COSPEC) to enable it to accurately monitor the gas emitted from New Zealand’s volcanoes.

Crater lakes in particular are valuable indicators of the status of a volcanic system. Changes in groundwater, lake levels, rates of steam flow and the temperatures of such waters often give evidence of unrest within a volcano. Crater lakes at Raoul Island, Waimangu (Okataina Volcanic Centre) and Ruapehu are monitored. The water level of Green Lake (Raoul Island) rose more than 6 m before the 1964 eruption started, and also rose over 1 m in 1993 following an earthquake swarm. Calorimetry of a lake can provide an insight into the volcanic or geothermal system feeding the lake (Scott, 1992; Hurst et al., 1991).

PUBLIC AWARENESS STRATEGIES

The eruption of Mt St Helens in 1980 had the effect of totally changing New Zealand’s civil defence attitude to volcanic risk. Now, a volcanic eruption had occurred nearby to a built-up western technological society. Initially New Zealand’s reaction was to prepare unpublished reports on the likelihood and the potential impacts of future potential
volcanic activity at seven major volcanic centres. These reports became the foundations of a public awareness exercise championed by the National Civil Defence Volcanic Hazards Working Group created in 1989. Known as the ‘yellow books’, they contain scientifically factual information about the volcanic history of selected volcanoes and are available free from the New Zealand civil defence organisation. All appear in the reference list to this paper.

Supporting this Civil Defence initiative were a number of scientific publications that complemented this thrust towards public dissemination of volcanic hazards information. These included:

1. The first detailed 1:100,000 volcanic hazards map in New Zealand of Egmont Volcano (Neall, 1982), recently updated and completed with newly available information (Neall and Alloway, 1996).

2. An overall review of volcanic hazards in New Zealand prepared in response to a UNESCO initiative (Dibble and Neall, 1984; Dibble et al., 1985).

3. An assessment of volcanic risk on and from Mayor Island (Buck, 1985).


5. A 1:100,000 volcanic hazards map for Tongariro National Park (Latter, 1987) and a complementary volcanic hazards assessment for Ruapehu (Houghton et al., 1987).

6. The production of a video by the New Zealand Geological Survey on volcanism in New Zealand entitled Ruamoko’s Heritage. This was specifically designed for school children together with an associated information pamphlet.


In the meantime, the Ministry of Civil Defence began to raise the profile of volcanic hazards and volcanic risk to New Zealand. In the late 1980’s the potential to expand volcanic seismic monitoring networks at our volcanoes received considerable impetus from the Ministry’s publicity efforts. This culminated in a Volcanic Hazards Awareness Year named Nga Puia from 1991-92. During the Year, a major civil defence volcanic exercise took place with a 2-month lead time followed by a symposium with local government and industry representatives. As part of the exercise, a system of alert levels was developed for the first time. Nationally distributed pamphlets, displays and videos all promoted an awareness of volcanic hazards and the need for preparedness.

One regional council has published its own volcanic contingency plan. With the recently released Egmont Volcanic Hazards Map, the Taranaki Regional Council has released evacuation plans based on zones of risk around the volcano. Associated with release of the plan are pamphlets delivered to each household describing the volcanic hazards and evacuation zones. Staff give public lectures to voluntary organisations and spend considerable time with schools giving a summarised version in the form of a bookmark to children. A teacher’s volcanic hazard kit has been distributed to each school in the region.

A second region that has begun to address volcanic risk as a local issue is the Bay of Plenty (BoP). Currently, BoP Regional Council has commissioned an IGNS report on the impact of two eruption scenarios from the Okataina Volcanic Centre on the population and infrastructure of the BoP region (Johnston and Nairn, 1993) and a hazard assessment of Edgecumbe Volcano. Auckland has begun draughting a volcanic contingency plan and Environment Waikato has commissioned an assessment of volcanic hazards in the Waikato region.

A major public awareness initiative was the opening of the Taupo Observatory in 1993 when IGNS began a major public relations launch. Visitor numbers have totalled 100,000/year.

The year 1995 commemorated the 50th anniversary of the 1945 eruptions of Mt Ruapehu when the crater lake last disappeared by displacement of a lava dome. A number of public awareness strategies were organised for this anniversary, including newsletters, public and school presentations, new publications and numerous civil defence exercises at the district and regional level.

A special issue of the Ministry of Civil Defence magazine Tephra was published on volcanic hazards which coincided with the reawakening of Ruapehu in September 1995. Another novel initiative in 1996 has been the release of a CD-ROM, produced for educational use (sponsored by Clear) about volcanic hazards.

With the 1995/96 eruptions at Mt Ruapehu, new public awareness strategies emerged. Usually each day during the eruptive period, the Institute of Geological and Nuclear Sciences released scientific reports to the Ministry of Civil Defence, other responding agencies and the media. These reports became the basis for a toll-free telephone number where anyone could ring for additional information. The success of this service is seen where it seems to have satisfied a demand from the public for accurate up-to-date information on the volcanic situation. Additional reports and a live video-watch were also available on the Internet.
In dealing with the media throughout the entire crisis, one message was clear – by making all relevant scientific information available to the public, there was no resultant adverse publicity from information being withheld. The public are now sufficiently well informed with numerous avenues for obtaining news that one cannot afford not to be up front and informative as possible. The only problematic experience was when news media in certain other countries greatly exaggerated the scale of the events in New Zealand.

**VOLCANIC ALERTS – EMERGENCY RESPONSE**

**New Zealand Civil Defence Setting**

The current Civil Defence Act (1983) moved New Zealand’s Civil Defence efforts to a position where regional councils and territorial authorities made better provision of their functions in relation to civil defence. A three-tiered structure was created with a national Ministry charged with the role of planning and general execution of civil defence measures. Regional government are required to enable civil defence measures to be carried out during a state of national or regional emergency, while the local territorial districts have similar requirements relating to their local setting.

Presently, the role and position of civil defence in New Zealand are being reviewed in the context of an all hazards approach (Teagle, 1995).

**National Civil Defence Plan – Volcanic Impacts**

Under the conditions of the Civil Defence Act (1983), a National Civil Defence Plan has been prepared and specifies the measures to be undertaken, the functions to be exercised by departments, organisations, local authorities, regional councils, and territorial authorities, whether in preparation for possible emergencies or during or following such emergencies. Only in November 1994 was an annexe added to the national plan specifically directed at volcanic impacts.

The new annexe describes the special case of volcanic hazards and its implications for civil defence plans. The annexe was produced by consultants, following a period of consultation with regional and local governments, the ministry and the scientific community involved in volcano studies. It clearly recognises how aspects of volcano crises differ from more traditional hazards like flooding, especially the “uncertainty as to the likelihood or timing of the eruption,” the need for civil defence action before there is an emergency, and the prolonged nature of volcano crises. Unfortunately, these important factors are poorly appreciated by national, regional and local governments, departments, industry and the public at large. As discussed later, the 1995 Ruapehu eruption has helped change this situation.

Also incorporated into the annexe is a table of Scientific Alert Levels that provides a standard reporting format on the status of volcanic activity at any New Zealand volcano and provides a key to warning systems set up by the National Civil Defence Plan. The annexe also summarises the responsibilities of the ministry, regional councils, territorial authorities, and the Institute of Geological and Nuclear Sciences (GNS). The latter are the principal providers of a volcano surveillance capability in New Zealand, and are responsible for issuing and updating the scientific alert levels.

Following the first signs of unrest at Ruapehu volcano in December 1994, the first science alert bulletins were issued by GNS and the first test of volcanic contingency planning in New Zealand was underway. Although a pass mark may have been awarded for systems and procedures, the table of scientific alert levels (Table 1) in particular, did not measure up. The short-falls and remedies are discussed below.

**Scientific Alert Levels**

In November 1994, amendments to the National Civil Defence Plan introduced the volcanic impact’s annexe to the plan and amended the existing warning systems to incorporate volcanoes. The warning systems introduced three levels of public statement; starting with Information Bulletins at alert levels 1 to 2, a Watch Bulletin at alert level 3, and Warning Bulletins at alert levels 4 and 5. These are issued by Civil Defence.
The November 1994 Table of scientific alert levels (Table 1) was based on 5 levels, and did not consider the large range of different volcanic systems, being biased to the concept of a reawakening volcano.

**TABLE 1: SCIENTIFIC Alert LEVELS (August 1995)**

<table>
<thead>
<tr>
<th>Frequently Active Cone Volcanoes</th>
<th>Reawakening Volcanoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Island, Tongariro, Ngauruhoe, Ruapehu</td>
<td>Kermedec's, Northland, Auckland, Mayor Island, Rotorua, Okataina, Taupo, Taranaki</td>
</tr>
<tr>
<td><strong>Scientific Interpretation</strong></td>
<td><strong>Phenomena Observed</strong></td>
</tr>
<tr>
<td>Usual dormant, intra-eruption or quiescent state.</td>
<td>Typical background surface activity; seismicity, deformation and heat flow at low levels</td>
</tr>
<tr>
<td>Minor phreatic activity</td>
<td>Departure from typical background surface activity.</td>
</tr>
<tr>
<td>Significant change in level or style of ongoing eruptive activity.</td>
<td>Increase from low level of eruptive activity, accompanied by changes to monitored indicators.</td>
</tr>
<tr>
<td>Significant local eruption in progress.</td>
<td>Increased vigour of ongoing activity and monitored indicators.</td>
</tr>
<tr>
<td>Hazardous local eruption in progress.</td>
<td>Significant change to ongoing activity and monitoring indicators.</td>
</tr>
<tr>
<td>Hazardous large volcanic eruption in progress.</td>
<td>Destruction within the Permanent Danger (red) Zone. Significant risk over wider areas.</td>
</tr>
</tbody>
</table>

As precursory activity at the crater lake, Mt Ruapehu escalated and declined during the early months of 1995, various alert bulletins were issued. Short-falls within this Table became apparent and effort was directed to amending it. The amended table of scientific alert levels (Table 1) was tabled in July and approved as operative on 30 August 1995. This new Table clearly distinguishes between “frequently active cone volcanoes” and other volcanic systems that are dormant. These are a significant mix of both volcano systems in New Zealand.

The revised table of scientific alert levels is based on six levels, with the new addition being “zero”. Zero provides somewhere to start from or return to during a crisis. The other significant improvement is the clear separation of the descriptions for frequently active cones from other volcano systems, i.e. generally calderas or volcanic fields. The new Table allows for a clear progression from quiescence to hazardous eruption in progress for either class of volcano system. The distinction between level 3 (significant local eruption in progress) and level 4 (hazardous local eruption in progress) was particularly important during the enhanced phase of activity at Mt Ruapehu. The Table is designed for an escalating scenario only, and addresses the current status of a volcano. It tries to avoid prediction and time connotations. These factors were part of the design parameters.

The Volcanology programme of the Institute of Geological and Nuclear Sciences is charged with the responsibility of setting the alert levels, via the national CD plan. This is achieved via a series of Scientific Alert Bulletins, and Media Bulletins that are released on an as needed basis. These bulletins are widely distributed. An aspect of the 1995 Ruapehu eruption was the use of the Internet to keep people informed (Williams, 1996). There are other products like ashfall predictions and specific advice for aviation, health, energy and transport agencies.
REFERENCES


VOLCANO MONITORING IN PAPUA NEW GUINEA

B. Talai and I. Itikarai

Rabaul Volcanological Observatory, PAPUA NEW GUINEA

INTRODUCTION

Rabaul Volcano Observatory (RVO) is a government body responsible for monitoring the activity of 14 active and 22 dormant volcanoes in Papua New Guinea (PNG). It has therefore the role to advise the Government through the National Disaster and Emergency Services on the activity of the monitored volcanoes and those that show signs of renewed activity. It also has the role of issuing warnings, whenever possible, of impending eruptions. RVO also bears additional tasks of involving itself in volcano disaster prevention and mitigation, risk assessment and in the preparation or revision of volcano emergency plans for volcanoes that pose threats to population.

Regular monitoring of volcanoes in PNG began as a result of the disastrous Rabaul eruption in 1937. The eruption killed over 500 people. A permanent observatory was established at Rabaul in 1940 but was destroyed during the WWII. It was re-established after the war in 1950.

Since 1950, the Volcanological Observatory has set up an extensive surveillance network of various monitoring techniques throughout PNG which provides the means for providing warning of impending eruptions. The result is that in 1997, 13 out of 36 (about one third) of PNG’s active and dormant volcanoes were being monitored to some degree.

Following the Rabaul eruption in 1994 a request was made to AIDAB (now AusAID) to up-grade volcano monitoring at Rabaul and other active volcanoes in PNG. The request was approved and later contracted to the Australian Geological Survey Organisation (AGSO – now Geoscience Australia) for implementation. The final implementation documents were signed in May 1996, between AusAID and AGSO allowing work to begin on five selected dangerous volcanoes; Rabaul, Manam, Karkar, Ulawun and Lamington. The implementation program will be assisted by RVO.

SCOPE OF VOLCANO SURVEILLANCE IN PNG

The present volcano monitoring network in PNG consists of a central observatory located at Rabaul and 6 outstation observatories at Manam, Karkar, Langila, Ulawun, Lamington and Esa’a’ala (Figure 1). The central observatory is manned by full-time officers, while 5 of the outstation observatories are manned by part-time observers. Manam has a full-time observer. These observatories serve the interests of more than 200,000 people living on and/or near the active and dormant volcanoes.

Except for the main observatory at Rabaul, all the outstation volcanoes are equipped with a single seismic station. Only Manam is also equipped with a water-tube tiltmeter. Manam, Karkar and Ulawun have arrays of levelling, dry-tilt, EDM and gravity stations. These are re-occupied about once a year or when renewed activity is reported. In Rabaul, a dense network of several methods of volcano monitoring is in use. Details on these are given in the next section.

The data from outstation observatories are relayed to the RVO on a daily basis using a network of VHF radios. This allows the scientific staff at the RVO to keep abreast of the activity at each of the volcanoes.

The other active and potentially active volcanoes are visited only when volcanic emergencies arise. In these circumstances, officers with extra equipment from the RVO can be despatched to the sites at short notice within 24 - 48 hours.

Current staffing at the central observatory consists of 5 volcanologists, 2 seismologists, 1 surveyor, 4 electronic technicians, 3 senior technical officers, 2 typists and 1 clerk.
METHODS OF VOLCANO MONITORING IN PNG

Several methods of volcano monitoring are used in PNG. These include: visual observation; volcano seismicity; ground deformation; and geochemical.

1. Visual Observation

Visual observation is probably the oldest and cheapest method in volcano monitoring. It is cheap in that there is no need for expensive equipment. The basic requirement needed in applying this technique is a clear line of site between the observation post and the summit. Observations can however be done from other vantage points also.

Nowadays information gathered from visual observations plays a very important role for correlation with instrumental data.

2. Volcano seismology

In PNG, seismographic equipment specifically designed for volcano monitoring came into operation in 1967 following the establishment of the Rabaul Harbour Network consisting of 5 seismic stations. The network used radio telemetry allowing seismic signals to be recorded at the observatory. The network has since grown in number and prior to the September 1994 eruption, consisted of 13 stations. There was a period between 1985 and 1990 when 3-component stations were operated. All the stations were equipped with short-period seismometers. An Omori seismograph having two horizontal components with a very gain was also operated. The Omori seismograph was used during the war by the Japanese army to monitor the eruption at Tavurvur.

The seismic data telemetered to the Observatory were recorded on a 16 mm film (Teledne-Geotech Develocorder) and heat sensitive papers (Teledne-Geotech Helicorders). The 3-component stations were recorded on an analog magnetic tape. Routine computer locations were done for all earthquakes recorded on 5 or more stations.

During the September 1994 eruption, about 80% of the Rabaul Harbour Network was destroyed by ash fallout and vandals. Only three stations remained. Three weeks into the eruption, the USGS Volcanic Disaster Assistance Program (VDAP) team came to the assistance of RVO with a seismic array of 8 stations. The array was set up in two weeks and together with the remaining 3 seismic stations of RVO, seismic monitoring was up and running again. The new set-up incorporated a real-time digital data acquisition system that was a great leap forward from the old analogue system. It greatly improved the post-data processing.
The current network will be expanded in 1997 with the installation of 4 new stations outside the boundaries of the Rabaul caldera. The expansion will be done as part of the PNG-Australia Volcanological Service Support (VSS) Project funded by AusAID and contracted to the Australian Geological Survey Organisation (AGSO).

At the 6 out-station observatories, seismic monitoring was done using an in-house built single-component vertical seismograph and recorded on either a smoked paper or an ink-pen drum. In September and October 1996, under the PNG-Australia VSS Project, the old equipment (about 20 years old) for four of the high volcanic-risk volcanoes (Manam, Karkar, Ulawun and Mount Lamington) were replaced with 4 new single-component vertical seismographs (Kelunji Drum Recorder).

3. Ground Deformation

Tilt

Tiltmeters were first introduced in PNG to measure ground deformation after the 1937 eruptions in Rabaul. It was introduced to the out-station observatories after the war.

Bubble tiltmeters. The first tiltmeters used for volcano monitoring were a pair of 50 cm bubble tiltmeters, similar to a carpenter’s level. The instrument can provide fairly reliable result when installed in a stable environment, usually in underground vaults where temperature variations are low. Although this type of tiltmeters are eventually phased out (only one left at Karkar), they have provided valuable data.

Water-tube-tiltmeters were introduced at Rabaul and other observatories (Manam, Esa’ala and Lamington) in 1966. The instrument consists of 2-pairs of sealed pots filled with water and connected by two flexible plastic tubes about 2 cm in diameter. The two pair of pots are aligned at right angles to each other and bolted onto a concrete pier. Like the bubble tiltmeters, the water-tube tiltmeters should be operated in stable environment where temperature variations are low. At present, there are 4 water-tube-tiltmeters operating in underground vaults in Rabaul. The unit at Esa’ala was discontinued.

Dry tiltmetry is a method that was developed in Hawaii. It was introduced in Rabaul in 1982 prior to the 1983-1985 Seismo-Ground Deformational Crisis. The technique was later extended to Manam, Karkar and Ulawun volcanoes.

The system involves field measurements of an established array of three benchmarks set in generally flat ground in a triangle configuration. Measurements are done using a levelling instrument set in the middle of the setup and readings taken on an invar rod placed on top of each benchmark.

Before the 1994 eruptions, the dry tilt network at Rabaul consisted of 25 stations. The post-eruption network has only 14 stations. At Manam Volcano there are 4 dry tilt stations. Karkar and Ulawun have 7 and 4, respectively.

In Rabaul, the measurements were done on a weekly basis for stations located on prime locations near the source of deformation. Stations further away from the deformation source were read once a month.

Electronic tiltmetry was introduced at Rabaul during the crisis period mentioned above by the United States Geological Survey (USGS). Seven (7) electronic tiltmeter stations were installed with VHF radio links to the Observatory and data was recorded on computers. The system was abandoned after a few years of operation due to continuous breakdown in instruments or telemetry.

During the initial two weeks of the 1994 Rabaul eruption, the USGS re-installed 3 new electronic tilt stations. There are plans under the VSS program for these type of electronic tiltmeters to be installed on four other volcanoes; Manam, Karkar, Ulawun and Lamington.

Levelling and Gravity

Levelling at Rabaul began in 1937 when an 8-km level line between Rabaul Town and the southern tip of Matupit Island was established. This line was re-occupied at intervals of 3 to 27 months between 1973 and 1983. After late-1983 the line was measured on a more regular (monthly) basis. Over the years the levelling line extended to the northern, eastern, western and southern sides of the caldera. These sections were levelled annually. Just before the eruption, in 1994, the total levelling line was about 30 km long. About a third of this was destroyed during the eruption. The sections destroyed are between Matupit and Rabaul Town and a portion of the western section near Vulcan. The destroyed sections were re-established recently resulting in resumption of monthly level measurements.

Two other volcanoes, Karkar and Manam, have a levelling line of 1 km each established in 1980 and 1991 respectively. These networks re-occupied annually pending availability of funds.
In conjunction with the levelling program, a network of 43 gravity stations was established. Gravity readings are done on a monthly basis using a LaCoste and Romberg gravimeter. Due to problems with the gravimeter, readings were discontinued in 1993.

Gravity stations are also present at Karkar (12), Manam (4) and Ulawun (3).

**Electronic Distance Measurements (EDM)**

Thirty-one (31) EDM lines across the Rabaul caldera from 2-base stations on the caldera rim were established in late-1983 by the USGS. A Keuffel and Esser Ranger V-A laser instrument was used to do the measurements. This used to be done in weekly intervals between late-1983 and 1985, but was later reduced to two per month. The method was discontinued following the destruction of a lot of the reflectors during the 1994 eruption.

EDM networks were also set up at Karkar (8 lines) and Ulawun (6) in 1986 and Manam (10) in 1987. This network was re-occupied annually.

**Global Positioning by Satellite (GPS)**

This is the latest ground deformation technique introduced at Rabaul in 1996 under the Australian-PNG VSS Project and will hopefully be used at other volcanoes in the country. It is still in its infant stages but there is a lot of anticipation that the network will get rolling by the latter part of this year. Current plans for the network are to have a base station and 3 other permanent stations within the Rabaul caldera. This set-up will provide real-time monitoring of the Rabaul volcano. A rover GPS unit will allow measurements to be done at distances beyond the limits of the caldera.

**Sea Level Measurements**

The technique of sea level monitoring was set up in 1981. The technique uses a crude concept of levelling but in an offshore environment. Vertical measurements are done between a fixed point placed in wrecks, bunkers, rocks or any other structure in the sea and the sea level. Although accurate to only 2 cm it has shown good results for long-term deformations. At present there are about 40 sites around the caldera that are re-occupied about once a fortnight.

**4. Temperature Measurements**

Temperature measurements in geothermal areas on volcanoes started after the Rabaul 1937 eruption at Rabaul and later on the other volcanoes in the country. This parameter was a very good precursor to the eruption in 1941. Temperature measurements at hot springs, fumarolic areas and other hot spots are done on a weekly to monthly basis in Rabaul and occasionally on other volcanoes.

Temperature measurements are done using a mercury-in-glass maximum thermometer or thermocouples.

**5. Geochemistry**

A program of regular collection and analysis of gas condensates and thermal waters was carried out in the 1970s in Rabaul and later on other volcanoes, but owing to difficulties of collection of gas condensate and the variable activity of some fumaroles, only the collection of thermal water was continued. In 1983, a correlation spectrometer (COSPEC) was introduced in Rabaul and other volcanoes to monitor the flux of SO2 in volcanic plumes.

A new program of geochemical monitoring was introduced at Rabaul in 1996 under the PNG - Australian VSS Project.

**Correlation Spectrometer (COSPEC)**

The correlation spectrometer was introduced at Rabaul in September 1983 for a brief period of time and later at Bagana, Ulawun, Langila and Manam volcanoes. The instrument was on loan from the USGS and later returned. However, in 1995, the Canadian Government donated a COSPEC to RVO that has since been used at Rabaul on a daily basis. It was deployed at Ulawun for two days in October 1996. There are plans for the instrument to be deployed at other volcanoes in the country.
Soil Gas, Gas Condensate and Geothermal Water Monitoring

Under the PNG-Australian VSS Project a new program for geochemical monitoring in Rabaul was recently re-established. The method will be extended to other volcanoes in the future. The program is more-or-less a continuation and expansion of the work begun in 1989 by a visiting graduate geochemist. He re-visited in November 1995, to continue the program with RVO assistance. In November 1996 he was contracted by AusAID to set up a proper on-going geochemical monitoring program. The program is still in its infant stage. It involves: volcanic gas monitoring, hot spring gas monitoring, hydro chemical monitoring and diffuse soil degassing monitoring.

FUTURE PLANS

Eruption prediction or more appropriately eruption forecasting is still a difficult task to carry out, even in the more advanced countries where volcano monitoring is done using very sophisticated methods and equipment. The best one can do is to work with the aim of minimising the risk factor from volcanic eruptions. This goal can be achieved by taking an aggressive approach in the following areas:

+ provide continuous monitoring;
+ produce good and efficient emergency plans;
+ produce good and efficient evacuation plans; and
+ close collaboration and cooperation amongst all relevant bodies in implementing the emergency and evacuation plans.

In PNG, eruption forecasting is far from perfect. There is still room for improvements and to a good vibrant monitoring setup is ideal in achieving this. With the ongoing PNG-Australian VSS Project that began in May 1996, it is anticipated that 5 of the most dangerous volcanoes (in terms of risk factor) out of the 14 active volcanoes in PNG will be equipped with additional monitoring techniques to enhance the chances of forecasting volcanic eruptions. One major aspect of the Project plans is to relay data from the 5 active volcanoes to the central volcanological observatory at Rabaul in near real-time, therefore allowing near real-time monitoring of these volcanoes from Rabaul.

SELECTED READING


AN OVERVIEW OF VOLCANIC HAZARDS AND EMERGENCY MANAGEMENT IN THE SOLOMON ISLANDS

T. Toba, D. Tolia and R. Biliki

1 Ministry of Energy, Water and Mineral Resources, SOLOMON ISLANDS
2 National Disaster Council, SOLOMON ISLANDS

INTRODUCTION

The aim of this paper is to outline the volcanic hazards in the Solomon Islands and the objectives and implications of the relevant government authorities in the event of a volcanic disaster.

Geography

The Solomon Islands lie between latitude 155° and 168° East, longitude 5° and 13° South. It is a widely scattered archipelago of mountainous islands and low lying coral atolls, stretching some 1666.8 km² in a south-easterly direction from Bougainville in Papua New Guinea to Santa Cruz Islands bordering the Republic of Vanuatu. The total land area is approximately 28,369 km² and total sea area is approximately 1,632,964 km².

Climate

The climate is tropical; temperatures range from 25°C to 31°C. The islands are almost entirely covered with dense jungle. The rainfall in the mountainous areas is heavy, and measures in hundreds of millimetre per year. On occasions, severe hurricanes affect the Central and Western Solomons. The north-westerly monsoon season is one of calm, punctuated by north-westerly “blows” between November and April. May to November marks the season of the Southeast Trade Winds and the fine weather, although rain also occurs during this period.

Geological Setting

The Solomon Islands occupy a northwest trending submarine rise between 5° and 12° South and comprise seven major islands of which Bougainville is the largest. With the advent of the theory of plate tectonics, a number of plates and sub-plates were proposed for the Melanesian region (Le Pichon, 1968; Johnson and Molnar, 1972; Curtis, 1973; Denham, 1975). In the Solomon Islands, three plates have been defined: the Pacific, the Indian, and the Solomon Sea Plates (Figure 1), although other configurations have been proposed by Curtis (1973). The Solomon Islands have been divided into geological entities or provinces by Coleman (1966).

The Solomon Islands consists of a double chain of islands that are located above the collision zone where the Indo-Australian Plate is being subducted beneath the Pacific Plate. This makes it more prone to geological related hazards such as earthquakes, volcanic eruptions, landslides, tsunamis and flooding.

The archipelago is divided into four geological provinces: (1) the Northern Atoll Province; (2) the Pacific Province; (3) the Central Province, and (4) the Volcanic Province. The islands of most interest in terms of volcanic hazards are located within the Volcanic Province. Most of the volcanic activity is of Plio-Pleistocene age with periods of activity continuing at the centres of Tinakula, Savo, Simbo, Kavachi and a number of submarine volcanoes, including the Coleman and Kana Keoki seamounts, and the Cook volcano.
VOLCANOES OF THE SOLOMON ISLANDS

Previous Work

Little work has been done on the volcanoes in terms of volcanological studies except few personal observations made by interested individuals who have been recorded as memoirs or reports written by them. Fisher (1957), formerly Chief Geologist with the Bureau of Mineral Resources in Australia, completed a preliminary study of the Melanesian volcanoes. Work carried out by Taylor (1976), concentrated on the volcanoes that exhibited Pelean-type eruptive activity. Despite these pioneering studies, little follow-up work has been undertaken except for that carried out by the Geological Survey Division of the Solomon Island Ministry of Energy, Water and Mineral Resources, which is responsible for the surveillance of the active volcanoes. Currently there are four active volcanoes in the Solomon Islands that include Tinakula, Savo, Kavachi and Simbo. The only recent hazard assessment work undertaken on the currently active volcanoes was carried out by seconded British Geological Survey staff (Dr Mike Petterson) on Savo.

Tinakula

Tinakula is a cone-shaped startovolcano (Figure 2) located in the Santa Cruz group of islands in the eastern Solomons at latitude 10.3° South and longitude 165.3° East. Hughes (1975) reported Tinakula to be active in 1595 as observed by the Spanish explorer Alvaro de Mendana. The last reported large eruption was in 1985. Tinakula, however, is in a state of high activity, erupting andesitic ash almost continuously.
Figure 2: Tinakula volcano, April 2002 (photo by D. Tolia). Note the landslide scarps that have been formed on the NW flanks of the volcano.

Savo

Savo Island is located some 35 km northwest of Honiara. It is the surface expression of a stratovolcano, with only the top one third visible above sea level (Figure 3). Savo has been dormant for around 100 years. There are historical records which describe two eruptions from Savo; one description is from 1568 when the Spanish explorer Alvaro de Mendana visited Solomon Islands, and a second report describes a ten year eruption during the 1830s and 1840s with steam emissions continuing until the 1880s. One recently determined radiocarbon age date indicates volcanic activity may have occurred between 1600 and 1700.

Figure 3: Vertical aerial photograph of Savo island on a scale of 1:40,000. The crater region has been outlined and the recent lava dome is readily distinguished in the centre of the crater.
Recent studies of the oral history from Savo have shown that two other eruptions are recorded, one of which appears to have been extremely destructive. The oral history also records a particularly destructive mudflow. Available evidence suggests that Savo is periodically active with repose periods of between about 100 and 300 (est) years. Further studies are required to gain a greater understanding of the frequency of eruptions.

An outline of Savo volcano is given by Petterson et.al (this volume).

Kavachi

A submarine volcano located approximately 25 km South of Vangunu Island in the Western Solomons at latitude 9.40 South and longitude 157.9° East. According to historical records, Kavachi has erupted 6 times in the last 30 years (Johnson and Tuni, 1987). Kavachi often forms a temporary island (Figure 4) during its eruptive phases which occur every 4-8 years.

Figure 4: The ephemeral island formed during a period of subaerial activity of Kavachi volcano between May and September 1991 (photo by M. Hawkins).

Simbo

This volcano has no recorded eruptions in historical times and is currently in a fumarolic or solfataric phase of activity. This is the second highest volcano that poses some risk to the population apart from Savo. In one instance, a minor emergency occurred as a result of increased steam emission and sulphur fire (possibly man-made) within the crater in February 1993. This event caused concern among the population. Because of the number of inhabitants, that were approximately 2000-3000, this volcano also deserves further investigation to establish the magnitude and frequency of pre-historic eruptions. Investigation of the traditional oral history should provide details of historical volcanic eruptions.
VOLCANIC HAZARDS

Tinakula

This island was once populated but its population have been evacuated and relocated elsewhere within the Solomon Islands; however, they sometimes return for subsistence purposes. Although Tinakula is highly active, erupting volcanic ash almost every week, it does not pose a major risk to any population. In the event of a major eruption; the adjacent island of Santa Cruz is likely to be affected by ashfall. Its effects, however, will depend on the prevailing winds.

Savo

The important factor to consider is the eruptive style of Savo. Studies of the recent tephra deposits reveal that Savo consistently erupts acid andesitic to dacitic block rich ash flows, with related pyroclastic airfall and surge activity. These eruptions are potentially highly dangerous. A good example of an eruption of this type comes from the island of Martinique in the Caribbean where, in 1902, the Mont Pelee volcano erupted wiping out the town of St Pierre, killing 29,000 people. The eruptive activity that has occurred on Savo is of Pelean-type that is named after the aforementioned volcanic episode. The little available evidence from written and oral historical accounts suggests that some eruptions have led to significant loss of life. An evaluation of the volcanic hazards of Savo is given by Petterson et.al (this volume).

Kavachi

Kavachi is a submarine volcano, posing risks, particularly to surrounding marine ecosystems. Typically Surtseyan-type explosive activity occurs which is a hazard to the maritime shipping. It, however, currently does not pose a serious threat to any population. Recent activity was reported by a Solomon Airlines pilot on 16-19 January 1997.

Simbo

Simbo is of concern to the relevant government and responsible authorities because of its high population and the presence of a potentially active volcano. If an eruption was to occur the population would be at great risk considering the size of the island and the location of the vent. Further studies are required to gain better understanding of the style of eruption of this volcano since no records of activity are known.

MONITORING AND SURVEILLANCE

It is of great importance to any volcanic hazard mitigation project that a volcano is adequately monitored on a regular basis and that early warning signs of an imminent eruption are recognised at the earliest opportunity.

The Solomon Islands Geological Survey is part of the World Wide Standard Seismological Network (WWSSN) headed by the United States Geological Survey (USGS). At the Geological Survey’s headquarters in Honiara, an IRIS digital system is currently being set up to monitor seismic activity of the region. This system is, however, concentrated on the regional seismic activity. Problems have been encountered in the setting up of an effective network to monitor volcanoes within the Solomon Islands due to both financial and technical reasons. Because of these, the Geological Survey has concentrated on Savo volcano due to its proximity to the main urban and development centres.

At the present time, one 3 component seismometer has been installed on Savo, (telemetered) which has been provided in conjunction with an Israel microseismic zoning project set up in late-1996. There is one direct radio link between one village on Savo and Honiara. The Savo seismometer is only intermittently operational which is another problem with regards to the present level of volcanic monitoring. The only other monitoring undertaken at the present time is the collection of fumarole temperatures at regular intervals.
EMERGENCY MANAGEMENT IN THE SOLOMON ISLANDS

National Emergency Management Authority

The National Disaster Council (NDC) is the overall authority responsible for all disaster related activities in the Solomon Islands. The NDC was established in 1987 by the Solomon Islands Government with wide powers to deal with all disaster related emergencies. It comprises nine members represented by the Permanent Secretaries of key government ministries including the Commissioner of Police.

The NDC Act 1989 provides for the legal instruments for exercising control and co-ordination of national resources during emergencies. Under the NDC Act 1989, Provincial Disaster Committees have been established in each province of the country, providing direct links between national and province levels.

The National Disaster Management Office (NDMO) has been established to look after the affairs of the NDC and provides for day to day operations of NDC.

Emergency Co-ordination Control

During an emergency, the NDC Central Control Group (CCG) which comprises the Commissioner of Police, Superintendent of the Marine Department and the Director of Civil Aviation, co-ordinates all national and other resources and assumes operational control during emergencies. The Director of the NDMO provides the linkages to the NDC for the CCG. The NDC through the CCG is linked to the police operations, the National Reconnaissance and Surveillance Force and the Search and Rescue Unit of the Marine Department. The CCG is also linked to departments specialising in specific hazards mostly through warning and monitoring systems. Such technical departments are co-opted into the emergency operations.

ALERT SYSTEMS AND EVACUATION PLANS

Currently, there is no standard warning and alert system specifically for volcano threats linked to the National Disaster Plan (NDP). There is, however, one for Savo volcano which is outdated and needs a complete review and to be linked to the NDP. Some work has been done to review the 1967 Savo Evacuation Plan in 1992 but it has not been completed. An attempt to get some assistance from the South Pacific Disaster Reduction Program office in Suva, to develop an evacuation plan to replace the outdated plan and a Public Awareness programme for Savo volcano seemed not to be prioritised.

PUBLIC AWARENESS STRATEGIES

The NDMO assumes the primary role for the dissemination of information to the community. Technical departments are also involved in public awareness programs. Channels of dissemination of public awareness and information is limited to radio broadcast programme and publications only. The NDMO has developed a public awareness strategy that is yet to be fully implemented because of the shortfall in available resources.

Currently the NDMO concentrates on implementing the daily radio program that consists of Radio Spots and 5-minute talks on specific hazards, preparedness measures and response arrangements. The public awareness strategy adopted is an integrated approach, involving a wide selection of departments and non-government organisations, covering a range of topics and attempting to make use of other channels of communication.
REFERENCES


Petterson, M.G, Tolia, D. Papabatu, A. Toba, T. Qopoto, C. A Volcanic Hazard Assessment of Savo Volcano, Solomon Islands, SW Pacific. This volume.


Volcanic Hazards and Their Management in the Kingdom of Tonga

P. W. Taylor 1, K. S. Mafi 2 and P. ‘Aho 3

1 Australian Volcanological Investigations, AUSTRALIA
2 Ministry of Lands, Survey and Natural Resources, KINGDOM OF TONGA
3 National Disaster Management Office, KINGDOM OF TONGA

Abstract

Throughout its geological development, the Kingdom of Tonga has been affected by volcanic activity with records describing eruptions dating from the early 19th century. The volcanoes of the Tofua Volcanic Arc (TVA), including Tofua, Metis Shoal, Home Reef, Late, Fonualei and other submarine centres have experienced periods of both explosive and effusive activity. The remote back-arc volcano of Niuafo’ou, the Kingdom’s most active volcano, has experienced at least 10 eruptions since 1800. Although many of the eruptions have been minor events, several have caused some concern. The loss of life or personal injuries have been minimal, but many of the hazards occurring during the eruptions, including lava flows, tephra fall and volcanic gases have caused damage to both crops and villages, affecting the livelihood of the population. A number of the volcanoes have been studied, but reports have provided only brief details of their development. Sadly, little information is available concerning the processes occurring and no hazard assessments, except for Metis Shoal, have been undertaken. Although many of the Tongan volcanoes have been frequently active, no volcano surveillance program has been established. In general terms, the population’s awareness of volcanism and its effects are low. Although a National Disaster Plan has been developed, much is still needed to provide an adequate and effective mechanism for managing a volcano emergency, particularly in terms of the development of operational support plans and strategies to increase the population’s awareness.

Introduction

The Kingdom of Tonga is located in the SW Pacific between Fiji, Samoa and the Kermedec Islands (Figure 1). Although the Kingdom covers a total area of approximately 500,000 km², the 150 islands occupy a total land area of only about 1.5% of the total area (697 km²).

The Kingdom consists of three geologically separate island types. First, the eastern chain consists of raised coralline islands located on the Tonga Platform between latitudes 18.5° and 21.5° S, which includes ‘Eua and the Tongatapu, Ha’apai and Vava’u groups. Secondly, the Tofua Volcanic Arc (TVA) consists of a series of volcanic islands located on a NNE-SSW trending submarine ridge between latitudes 14.5° and 26° S. Lying about 50 km to the west of the Tonga Platform, the TVA comprises the islands of ‘Ata, Hunga Tonga, Hunga Ha’apai, Tofua, Kao, Late, Toku, Fonualei, and the northern outliers of Niuatoputapu and Tafahi. It also includes the periodically active submarine volcanoes of Falcon Island, Metis Shoal, Home Reef and Curacoa Reef. The third, is the remote volcanic island of Niuafo’ou, located within the northern part of the Lau Basin some 450 km NNW of Tongatapu at latitude 15°36’ S and longitude 175°38’ W.

This paper will be to summarise what is known about the types of volcanoes, their activity and the hazards that have occurred during reported eruptions or that can be expected to occur during future activity. Furthermore, aspects of the management of the volcanic hazards will be discussed and also an outline of surveillance programs, public awareness and strategies, alert levels, emergency evacuation plans and links between scientists and emergency managers will be provided. The paper will conclude by giving a summary of the current state of volcanic hazard evaluation within the Kingdom, an outline of the major problems encountered by scientists working in the Kingdom.
and provide a series of recommendations for the future needs of the Kingdom with respect to volcanic hazards and their management.

**THE VOLCANOES**

Geologically, the Kingdom of Tonga forms part of the active Tonga/Kermedec/Lau arc - backarc - remnant arc complex where volcanism has been occurring since, at least, the Miocene. Since the formation of the Lau Basin, between 2 - 5 Ma, volcanism has been confined to two locations within the Kingdom, along the TVA and within the Lau Basin itself.

The eruptive activity that is occurring along the TVA is predominantly explosive in character but effusive phases also occur at the subaerial and submarine centres. Richards (1962) and Simkin and Seibert (1994) have provided a detailed list of the historic eruptive activity reported in known active centres within the Kingdom.
There are at least 10 of the known centres which have recorded eruptive activity (Table 1). Recent subaerial activity has resulted in the development of typically conical structures, composed of interbedded pyroclastic material and lava (eg. Tafahi, Late, Kao and Tofua), while periods of submarine activity have formed pyroclastic cones (eg. Falcon Island, early 1920s and 1930s; Home Reef, 1984) or lava domes (eg. Metis Shoal, 1995). Furthermore, several other centres have undergone periods of caldera formation and enlargement during their development, eg. Hunga Tonga, Hunga Ha’apai, Tofua and Fonualei. An unknown number of other submarine centres present along the arc that has not yet reached the surface and for which eruptive activity has not been reported. Two centres, Kao and Tafahi, for which records of activity are not known, but because of their youthful form are considered to be dormant. Three islands of volcanic origin, ‘Ata, Toku and Niuatoputapu are highly eroded remnants and are considered to be extinct.

**TABLE 1: SUMMARY OF REPORTED ERUPTIVE ACTIVITY AT THE CENTRES OF THE TOFUÁ VOLCANIC ARC.**

*(After Taylor and Ewert, 1997)*

<table>
<thead>
<tr>
<th>Name of Volcano</th>
<th>Volcano Type</th>
<th>Reported Periods of Activity</th>
<th>Hazards</th>
<th>Effects of Reported Eruptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnamed volcano I</td>
<td>submarine</td>
<td>2</td>
<td>tephra fall; ballistic ejecta; pumice rafts</td>
<td>No details known</td>
</tr>
<tr>
<td>Unnamed volcano III</td>
<td>submarine</td>
<td>2</td>
<td>no details known</td>
<td>No details known</td>
</tr>
<tr>
<td>Hunga Tonga and Hunga Ha’apai</td>
<td>remnants of large stratovolcano with a submerged caldera</td>
<td>3</td>
<td>tephra fall; ballistic ejecta; formation of shoals; fumarolic gases</td>
<td>No details known</td>
</tr>
<tr>
<td>Falcon Island</td>
<td>submarine with eruptions forming subaerial pyroclastic cones</td>
<td>at least 6</td>
<td>tephra fall; ballistic ejecta; formation of shoals/islands; fumarolic gases</td>
<td>During periods of activity pumice rafts have affected large areas to the NW and W of the volcano.</td>
</tr>
<tr>
<td>Tofua</td>
<td>subaerial stratovolcano with caldera</td>
<td>at least 5</td>
<td>tephra fall; ballistic ejecta; lava flows; pyroclastic flows?; fumarolic gases</td>
<td>Inhabitants evacuated to Kotu Is following the 1854 eruption. Destruction of vegetation.</td>
</tr>
<tr>
<td>Metis Shoal</td>
<td>submarine with eruptions forming subaerial pyroclastic cones or lava domes</td>
<td>at least 6</td>
<td>tephra fall; ballistic ejecta; lava flows (dome formation); volcanic gases (laze/ vog); formation of shoals/islands; pumice rafts</td>
<td>Pumice rafts have affected shipping in the region; warning to aircraft issued during 1995 activity.</td>
</tr>
<tr>
<td>Home Reef</td>
<td>submarine with eruptions forming subaerial pyroclastic cones</td>
<td>at least 3</td>
<td>tephra fall; ballistic ejecta; fumarolic gases; formation of shoals/islands; pumice rafts</td>
<td>Haze reported to be widespread in region of volcano during the 1984 eruption. Pumice rafts produced affected coastal areas of SE Fiji, disrupting Suva harbour for a period of time</td>
</tr>
<tr>
<td>Late</td>
<td>subaerial stratovolcano with summit crater</td>
<td>at least 2</td>
<td>tephra fall; ballistic ejecta; lava flows; fumarolic gases</td>
<td>Destruction of vegetation.</td>
</tr>
<tr>
<td>Fonualei</td>
<td>subaerial stratovolcano with remnant caldera and summit crater</td>
<td>at least 6</td>
<td>tephra fall; ballistic ejecta; lava flows; fumarolic gases</td>
<td>Ashfall from 1847 eruption fell on ships 900 km to the NE, destroyed crops on Vava’u, inhabitants of Toku evacuated to Vava’u</td>
</tr>
<tr>
<td>Curacoa</td>
<td>submarine</td>
<td>3</td>
<td>tephra fall; ballistic ejecta?; formation of shoals; pumice rafts</td>
<td>Pumice rafts produced during 1973 eruption affected shipping over a large region to the NW and W of the volcano.</td>
</tr>
</tbody>
</table>
The activity that is occurring at Niuafo'ou is distinct from that of the arc volcanoes in that it is typically effusive in character with only minor explosive phases. Since Niuafo'ou was first visited by Europeans during the mid-1600s, at least 10 periods of activity have been reported (Table 2), making it the Kingdom's most active volcanic centre. The frequent eruptions of Niuafo'ou have produced a broad lava shield capped by the remnants of a stratocone. A caldera, 4 km in diameter, has been formed and subsequently enlarged during recent periods of activity, e.g. the 1886 eruption.

It should also be noted that it is also probable that undetected submarine activity is also occurring along the active spreading centres (Hawkins and Helu 1986; Hawkins 1995) and at seamounts within the Lau Basin.

**TABLE 2: HISTORIC ERUPTIONS OF NIUAFO'OU - THERE CHARACTER, LOCATION AND EFFECTS**

(After Taylor 1991; Simkin and Seibert 1994)

<table>
<thead>
<tr>
<th>Eruption</th>
<th>Character</th>
<th>Location and Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1814</td>
<td>Explosive</td>
<td>Within the caldera, location unknown; effects unknown.</td>
</tr>
<tr>
<td>1840?</td>
<td>?</td>
<td>Location unknown; may have been a mistaken report of the 1853 eruption.</td>
</tr>
<tr>
<td>1853</td>
<td>Effusive</td>
<td>SW flank; 'Ahau village destroyed, an unknown number (25 est.) of natives were killed, arable land destroyed.</td>
</tr>
<tr>
<td>1867</td>
<td>Effusive</td>
<td>SSW flank; arable land destroyed</td>
</tr>
<tr>
<td>1886</td>
<td>Explosive</td>
<td>Within the caldera, NE side behind the village of Mata'aho; tephra deposit buried buildings and destroyed crops and other vegetation, casualties may have occurred following this eruption.</td>
</tr>
<tr>
<td>1912</td>
<td>Effusive</td>
<td>W flank, south of Futu village; arable land destroyed.</td>
</tr>
<tr>
<td>1929</td>
<td>Effusive</td>
<td>W flank; Futu village and arable land destroyed.</td>
</tr>
<tr>
<td>1935-36</td>
<td>Effusive</td>
<td>S flank; Petani village threatened, relocated as a result of eruption; arable land destroyed.</td>
</tr>
<tr>
<td>1943</td>
<td>Effusive</td>
<td>SW flank; most of Island’s crops destroyed, arable land destroyed.</td>
</tr>
<tr>
<td>1946</td>
<td>Effusive</td>
<td>N flank; Angaha village destroyed, island completely evacuated December 1946 not being resettled until 1958.</td>
</tr>
<tr>
<td>Intermittent</td>
<td>Fumarolic</td>
<td>Hot springs and H₂S issuing at Vai Kona, springs not active 1958, active December 1982-January 1983, active August 1984; no adverse effects have been reported by the population.</td>
</tr>
<tr>
<td>1985</td>
<td>Explosive?</td>
<td>Earthquake swarm 21-22 March, 250 metre crack/ fissure near Fata'ulu village, small pumice/ scoria raft present on caldera lake; minor damage may have occurred in several villages.</td>
</tr>
</tbody>
</table>

**THE HAZARDS**

As volcanic activity has played a major role in the geological development of Tonga, the hazards associated with the eruptions have had a direct effect on the population. Although it is beyond the scope of this paper to give a detailed appraisal of volcanic hazards, it is, however, pertinent to summarise the hazards that have been reported during eruptions in the Kingdom and outline their effects (Table 3).

The most common hazard that has occurred during periods of activity within the Kingdom has been tephra falls. As the majority of the eruptions that have occurred along the TVA have been explosive, considerable quantities of tephra has been ejected into the atmosphere. Tephra columns have frequently been dispersed in a northwesterly direction under the influence of the dominant Southeast Trade Wind circulation. Due to the variability of the winds, particularly during the wet season, tephra has also been dispersed in an easterly direction. Tephra from the 1847 eruption of Fonualei fell on ships 500-600 km to the northeast and caused damaged to crops in the Vava'u Group (Brodie 1970). During the 1995 eruption at Metis Shoal, notams were issued to aircraft transiting the region warning of the possible threat from tephra (Anon. 1995). Following soil surveys of the major island groups of Tongatapu, Ha'apai and Vava'u, conducted during the 1960s, it was concluded that tephra fall deposits are a major parent material for the soil development throughout the Kingdom. In the case of Niuafo'ou, periods of explosive activity have also occurred. Extensive tephra deposits produced during these eruptions have caused considerable damage to crops and buildings, with many of the population experiencing acute respiratory problems as a result of inhalation of the tephra (Taylor 1991). The most recent tephra-producing eruption that has occurred on Niuafo'ou was during 1886 which blanketed the island with a deposit that varied in depth from a few centimetres to in excess of six metres. The ejection of ballistic projectiles has also been noted during eruptions at the arc volcanoes (Taylor and Ewart, 1997) and during explosive activity on Niuafo'ou (Taylor 1991).
Lava flows produced during eruptions of Niuafo’ou have been voluminous and fluid pahoehoe flows, commonly moving considerable distances (> 1 km) from the vents. Lava flows are the most common hazard that have occurred on Niuafo’ou and have resulted in considerable damage to vegetation and buildings and the loss of life (Taylor 1991; this volume). Flows produced during the 1867, 1929 and 1943 eruptions destroyed large amounts of arable land and crops. During the 1946 eruption, the village of Angaha was partially destroyed by lava flows. These flows ultimately contributed to the evacuation of the island and the subsequent abandonment of the site of Angaha following the island’s resettlement in 1958. The 1853 eruption resulted in the destruction of ‘Ahau village and the reported deaths of up to 80 Niuafo’ouans. In contrast to Niuafo’ou, flows produced at the TVA centres are more viscous, commonly aa, and move only short distances (< several hundred metres) or have been confined to the vent areas, e.g. lava domes. Lava of this nature was produced during the 1939 eruption of Fonualei moved through breaches in the caldera wall and reached the ocean at several localities (Brodie 1970), while Bryan et al., (1972) noted the presence of a small lava dome within the crater of the central cone. During the 1995 Metis Shoal eruption, Scott (1995) reported that a subaerial lava dome with an estimated volume 3 x 10^6 m^3 was produced, the active northeast lobe being extruded at an estimated 1-2 x 10^5 m^3 per day.

One of the hazards causing some concern during the frequent submarine eruptions along the arc has been the production of pumice rafts. Although the rafts have not caused significant damage near to their source, they have caused considerable disruption on surrounding islands and to shipping transiting the region. A period of submarine activity that occurred at Curacoa Reef during 1973 (Simkin and Onyeagocha 1973) produced extensive pumice rafts that caused considerable disruption to shipping transiting northwest of the centre. Furthermore, during the 1984 eruption of Home Reef, pumice rafts moved toward the northwest and affected coastal areas of Fiji, causing a major disruption to Suva harbour for a number of days (Ryan 1986). Ryan also noted that aside from the obvious detrimental effects, there were also benefits, the pumice was collected and used as a valuable resource in the construction industry. A recent survey of Lifuka, Ha’apai Group (Taylor, in prep) suggests that the stranding of large amounts of pumice has occurred along the coastal zone of many of the eastern island groups following recent eruptions along the TVA.

Although the production of volcanic gases during eruptions has been of concern for some time, it was not until observations of the 1995 effusive eruption of Metis Shoal that the potential risk in Tonga was noted. Scott (1995) noted that the corrosive acid rain/fume (laze and vog) plumes produced were considered to pose a considerable

---

**TABLE 3: SUMMARY OF VOLCANIC HAZARDS FOR THE KINGDOM OF TONGA OUTLINING DETAILS OF PROBABLE WARNING PERIODS, CAPACITY AND LIKELIHOOD TO CAUSE DAMAGE, INJURY OR DEATH AND PROBABLE LOCATION FOR EACH HAZARD TYPE AND ITS EFFECTS**

(After Blong 1984)

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Probable Warning Period</th>
<th>Capacity for Damage/Injury</th>
<th>Likelihood for Injury/Death</th>
<th>Probable Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tephra falls</td>
<td>Minutes to hours</td>
<td>Moderate-high</td>
<td>Low-moderate</td>
<td>Proximal; north, west and south quadrants at greater risk due to dominant southeast trade winds</td>
</tr>
<tr>
<td>Ballistic projectiles</td>
<td>Seconds</td>
<td>Extreme</td>
<td>High</td>
<td>Proximal; within several km of the vent; dependent on vent location</td>
</tr>
<tr>
<td>Lightning</td>
<td>None to seconds</td>
<td>Moderate-high</td>
<td>Very high</td>
<td>Proximal; entire island</td>
</tr>
<tr>
<td>Pumice rafts</td>
<td>Days to months</td>
<td>Usually low</td>
<td>Low</td>
<td>Proximal to distal; dependent on prevailing currents</td>
</tr>
<tr>
<td>Lava flows</td>
<td>Minutes to hours</td>
<td>High</td>
<td>Moderate-high</td>
<td>Proximal; within craters/calderas or outer flanks</td>
</tr>
<tr>
<td>Volcanic gases and acid rains</td>
<td>Minutes to hours</td>
<td>Low-moderate</td>
<td>Usually low</td>
<td>Proximal to distal; dependent on vent location and prevailing winds</td>
</tr>
<tr>
<td>Pyroclastic surges</td>
<td>Seconds</td>
<td>Extreme</td>
<td>Moderate-high</td>
<td>Proximal; entire island or within the caldera</td>
</tr>
<tr>
<td>Edifice collapse - Tsunami</td>
<td>Minutes to days</td>
<td>High</td>
<td>Moderate-high</td>
<td>Proximal to distal; Coastal areas of volcano and surrounding islands; commonly on a regional scale</td>
</tr>
<tr>
<td>Seismicity</td>
<td>None</td>
<td>High</td>
<td>Moderate-high</td>
<td>Proximal to distal; entire island; effects are dependent on magnitude of the event/s; large magnitude events may be felt on surrounding islands</td>
</tr>
<tr>
<td>Ground deformation</td>
<td>Minutes to days</td>
<td>Moderate</td>
<td>Low</td>
<td>Proximal; flanks of the island</td>
</tr>
</tbody>
</table>
risk. Scott further noted that the crew of the Tongan Navy vessel VOEA experienced the effects of the HCl-based laze during a visit to the site of activity on 20-21 June 1995. During subsequent visits on 25 and 28 June 1995, SO$_2$-based vog was noted. Taylor (in prep.) has suggested that HCl and SO$_2$-based laze and vog plumes may have caused the almost total destruction of the vegetation on Niuafo’ou during the 1943 eruption. It should also be noted that other gas phases, including CO$_2$, may also pose a risk during periods of activity.

Because of the predominance of oceanic centres, future activity may result in major edifice collapse. Although major structural failure has not been reported during historic eruptions, the morphology of several of the centres, eg. Hunga Tonga and Hunga Ha’apai, suggests that periods of collapse may have occurred in the past. Bryan et al., (1972) suggested that these islands are the remnant of a once much larger stratovolcano that was destroyed during prehistoric times. A direct consequence of the displacement of water occurring during the collapse of the edifice is the possibility that tsunamis were generated and that coastal areas of the surrounding islands may be at risk from inundation by the sea waves generated.

The occurrence of pyroclastic flows or surges have not been reported during recent eruptions. Given, however, the submarine nature of many of the centres along the TVA, e.g. Falcon Island, Metis Shoal and Home Reef, it is reasonable to suggest that base surges may certainly have occurred but not been observed. This phenomenon may occur during the initial stages of activity during vent emergence or when water has accessed the vent area during the later stages of an eruption, following the formation of a subaerial cone. Proximal localities would be at risk from this phenomenon. Although surges were not observed during the 1886 eruption of Niuafo’ou, recent surveys of the resultant pyroclastic deposits (Taylor 1991), suggest that base surges occurred during the initial stages of the eruption. The effects of these surges, however, appear to have been confined to within the central caldera.

It should also be noted that other hazards, including lightning, seismicity and ground deformation occurring during eruptions are considered to pose a potential threat. Scott (1995) further considered that the formation of shoals during submarine eruptions also needs to be considered as a potential hazard, particularly to shipping transiting the region.

**VOLCANO SURVEILLANCE**

Currently there is no dedicated or continuous surveillance of any of the active or potentially active centres within the Kingdom. The permanent deployment of equipment dedicated to the monitoring of volcano-related seismicity has not been undertaken and no long-term records are maintained in the Kingdom.

During the periods of activity that have occurred, surveillance techniques of a temporary nature have been used, including the photographic and video records of the phenomenon, deployment of sonar transponders to record the acoustic signature of the activity, etc. Although observations of the eruptions have occurred, they have not been continuous, with only infrequent visits to the site of activity being conducted. Recent periods of activity have been initially reported by commercial aircraft or shipping transiting the area.

Taking the case of the 1995 eruption at Metis Shoal, the volcanic activity was reported by passing commercial shipping on 9 June. The first sea borne visit to the site was by a local tour operator on 14 June during which a video record of the phenomena was produced. Official Tongan Government sea-borne visits took place on 20 - 21 June (Kautoke 1995), 28 June (Scott 1995) and 24 July (Hon. Fakafanua 1995). An overflight by the Royal New Zealand Air Force, with a New Zealand volcanologist as a member of the crew, occurred on 25 June (Scott 1995). Although Scott (1995) recommended that there was a need for regular and detailed observations of the site, following the 24 July visit, no further observations have been conducted.

**PUBLIC AWARENESS/STRATEGIES**

The matter of public awareness of volcanism and its effects always causes concern when planning strategies for hazard preparedness. Although no formal surveys have been conducted, it is noted that for volcanism in general terms, the awareness of the population is low. It is, however, only increased when an eruption is reported or in progress due to the local knowledge of the activity and the reports that appear in the local press. Little or nothing is known or understood by the population about the effects of a major eruption. With respect to Niuafo’ou, the Kingdom’s most active volcano and the most densely populated, Taylor (1991; 1994; this volume) has noted that the situation is somewhat different. The awareness of Niuafo’ouans concerning the likelihood of volcanic activity occurring is much higher, but the awareness of the effects and implications of an eruption is low.
The Government of Tonga has indicated that the following strategies be considered to raise the general level of awareness of the population and to the minimise the effects of volcanic activity:

- The design and implementation of media broadcasts outlining the effects of activity.
- The development and dissemination of printed materials (in both Tongan and English) addressing the effects of volcanic hazards.
- The development of public education programs, including the presentation of briefing sessions to village and other community units, the preparation of displays and visits to schools.
- The development of appropriate land use zoning and building codes for areas likely to be affected by activity.
- The consideration of the use of protective clothing during periods of activity to reduce the likelihood of personal injury.

**ALERT LEVELS, EMERGENCY EVACUATION PLANS AND VOLCANOLOGIST/ EMERGENCY MANAGER LINKS**

As an initiative to reduce the losses resulting from natural disasters, the Tongan National Disaster Management Office in conjunction with the UNDHA-South Pacific Disaster Reduction Program (now the Disaster Reduction Programme of the SOPAC Division of SPC) has developed the National Disaster Plan (Kingdom of Tonga 1997). This plan, which is in its final form, has yet to be accepted by the Tongan Cabinet. The plan outlines an organisational infrastructure (Figure 2) and the management processes to be considered during an emergency on a national level. The plan does not consider specific hazards, except for volcanic eruptions and the required alert levels (Table 4) that may occur within the Kingdom.

![Organisational infrastructure for the disaster management organisation in the Kingdom of Tonga (After Draft National Disaster Plan, 1996)](image)

Although the plan highlights the need for the preparation of evacuation plans, at this stage none have been prepared for either the inhabited or high risk volcanoes. Because of the potential for volcanic activity to occur on Niuafo’ou in the future (Taylor 1994; Taylor this volume), an operational support plan for the island has been prepared (Taylor, 1998).

Presently no full time or dedicated personnel with volcanological training or experience have been given the responsibility for volcanological matters within the Kingdom.
TABLE 4: STAGES OF ALERT FOR VOLCANIC ERUPTIONS
(After Kingdom of Tonga - Draft National Disaster Plan, Jan 1996)

<table>
<thead>
<tr>
<th>Alert Stage</th>
<th>Phenomena Observed</th>
<th>Time to Expected Eruption</th>
<th>Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Abnormal seismic activity; some ground deformation; fumarole temperature increases.</td>
<td>Months or years</td>
<td>Inform all responsible officials. Review and revision of emergency plans.</td>
</tr>
<tr>
<td>II (Yellow)</td>
<td>Significant increase in localised seismic activity, rate of deformation, etc.</td>
<td>Weeks or months</td>
<td>Ensure readiness of personnel and equipment for possible evacuation.</td>
</tr>
<tr>
<td>III (Orange)</td>
<td>Dramatic increase in the above anomalies; locally felt earthquakes. Mild eruptive activity may be occurring.</td>
<td>Days or weeks</td>
<td>Public announcements of possible emergency and of measures being taken to deal with it. Mobilisation of personnel and equipment for possible evacuation. Deployment of temporary protective measures against hazards occurring.</td>
</tr>
<tr>
<td>IV (Red)</td>
<td>Protracted seismic tremor; increase in the intensity of the eruptive activity.</td>
<td>Hours or days</td>
<td>Evacuation of population from the zones that are likely to be affected by the hazards.</td>
</tr>
</tbody>
</table>

Due to the lack of volcanological expertise in the Kingdom, no formal links between scientists and emergency managers have been formalised. During periods of activity, however, the Tongan Government requests the assistance of a country with volcanological expertise. In the case of the 1995 eruption of Metis Shoal, the New Zealand Government provided assistance in the form of aerial surveillance by an aircraft during a scheduled maritime patrol. Furthermore, an experienced volcanologist was made available to conduct a sea-borne visit to the site of eruption to provide a preliminary evaluation of the hazards.

THE STATE OF VOLCANO RESEARCH IN TONGA

The Tofua Arc volcanoes
Since the early 1960s a number of preliminary studies have been conducted on several of the Tofua Arc volcanoes (Table 5). The studies have described individual eruptions as well as documenting the geology of individual or groups of volcanoes. The geology of Hunga Tonga, Hunga Ha’apai, Late and Fonualei was briefly described by Bryan et al., (1972) and Melson and Bryan (1976). Tofua has been investigated by Bauer (1970) and Baker et al., (1971). Other works by Hoffmeister et al., (1929), Melson et al., (1970) and Latter (1976) have described a number of the submarine eruptions, including those at Falcon Island, Metis Shoal and Curacoa Reef that have occurred during the last 70 years. The majority of the studies mentioned above are in most respects descriptive and do not consider the processes occurring at the centres or assess the hazards. More recently, however, Scott (1995) provided a comprehensive discussion of the eruptive history and an assessment of the hazards associated with the 1995 eruptive activity at Metis Shoal. There is a need for further, more comprehensive studies to be conducted of the majority of the centres of the TVA, which should define the processes occurring and then assess the hazards. This study is currently in progress as part of a project partially funded by the Australian Co-ordination Committee for IDNDR (Taylor and Ewart, 1997).

Niuafo’ou
As noted earlier, the island of Niuafo’ou is the most active and heavily populated of the Kingdom’s volcanoes. Infrequent visits for the purposes of studying the geology have occurred since the early 1800s. Jagger (1931) and Macdonald (1948) provided details of the geology and descriptions of the eruptions that had occurred to the mid-1940s. Taylor (1991) has presented the most detailed and comprehensive study of the island’s development and volcanological history. An evaluation of the volcanic hazards has been presented by Taylor, (1994; Taylor, this volume). Because of the potential for volcanic activity to occur (see Table 5) on the island in the future, an operational support plan has been prepared (Taylor, 1998).
### TABLE 5: STATUS OF HAZARD EVALUATION FOR ACTIVE OR POTENTIALLY ACTIVE VOLCANOES IN THE KINGDOM OF TONGA

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Geology and / or Map</th>
<th>Topographic Map</th>
<th>Bathymetric Survey</th>
<th>Aerial Photography</th>
<th>Volcano Monitoring</th>
<th>Hazard Assessment</th>
<th>Emergency Evacuation Procedures</th>
<th>Major References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submarine volcano I</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Submarine volcano II</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Hunga Tonga and Hunga Halapai</td>
<td>Yes (needs revision)</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Bryan et al., (1972); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Falcon Island</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>Hoffmeister et al., (1929); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Tutu</td>
<td>Yes (needs revision)</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Baker et al., (1971); Bauer (1970); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Kao</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Bryan et al., (1972); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Metis Shoal</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>Yes (preliminary)</td>
<td>N/A</td>
<td>Melson et al., (1970); Woodall (1979); Scott (1995); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Home Reef</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>Anonymous (1984a, b); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Late</td>
<td>Yes (needs revision)</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>In preparation</td>
<td>No</td>
<td>Bryan et al., (1972); Melson et al., (1976); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Fonualei</td>
<td>Yes (needs revision)</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>In preparation</td>
<td>No</td>
<td>Bryan et al., (1972); Melson et al., (1976); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Tafahi</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Curacoa</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>Latter (1976); Simkin and Onyeogocha (unpub data); Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Submarine centres</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>N/A</td>
<td>Taylor and Ewart (1997)</td>
</tr>
<tr>
<td>Niuafo’ou</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes (preliminary)</td>
<td>In preparation</td>
<td>Jaggar (1931); MacDonald (1948); Rogers (1981); Taylor (1991; this volume)</td>
</tr>
</tbody>
</table>
Geological Publications

No detailed geological maps of the Kingdom have been published to date. Preliminary geological maps, however, has been prepared following surveys of some volcanic islands, eg. Tohua (Bauer 1970; Baker et al., 1971). Soil surveys of the three main island groups (Tongatapu, Ha’apai and Vava’u) were conducted by the New Zealand Soil Survey during the 1960s and 1970s. The reports published following these surveys (Cowie et al., 1991; Orbell et al., 1985; Wilson and Beecroft 1983) have highlighted the effect that volcanism has had on the development of soils on all the island groups of the Kingdom.

Several aerial photographic surveys of the Kingdom have been conducted since the 1960s. Early surveys by Huntings Surveys Ltd, United Kingdom during 1968 and New Zealand Aerial Mapping during 1981 provided a good coverage of black and white images. The most recent survey by the Australian Surveying and Land Information Group during 1990-91 produced a series of colour images. Following completion of the aerial surveys in 1968, a series of topographic maps, at a scale of 1:25,000 were prepared from digitised aerial photographic data and published in 1975. Although these maps are still useful, the data is outdated and many are out of print and not available.

Table 5 summarises the status of geological work and volcanic hazard evaluation in the Kingdom.

PROBLEMS IN THE EVALUATION OF VOLCANIC HAZARDS IN TONGA

When evaluating volcanic hazards in sparsely populated and developing regions of the world, problems encountered are due to either geographical considerations (A, B and C) or human influences (D, E and F). In the Kingdom of Tonga, the following problems and their basic effects are noted:

A. The remoteness of many active centres has greatly affected both the initial detection of activity, the frequency of the observations and the progress of the eruptive activity. In fact many periods of activity that have occurred may not have been detected and hence they remain unreported.

B. The predominance of submarine centres along the TVA has also affected the initial detection and the subsequent surveillance of activity.

C. The lack of detailed bathymetric data for much of the TVA has limited the definition of the total extent of the arc and the subsurface morphology of the centres, particularly the submarine centres.

D. The short (max 200 years) period for which records of activity is problematic when assessing whether a centre is active, dormant or extinct. It furthermore, limits the effectiveness of the assessment of the probable character of future activity.

E. The general low level of awareness of the population as to the nature and effects of volcanic activity is of concern. This lack of awareness about the effects of an eruption will ultimately affect the preparedness for future eruptions.

F. A problem of paramount importance that needs urgent attention is the lack of a dedicated volcano surveillance program at even the “high risk” volcanoes. The lack of a mechanism for the detection of activity and the monitoring of the progress of an eruption will markedly hinder the implementation of emergency procedures.

RECOMMENDATIONS

The following recommendations are put forward to enable the evaluation of volcanic hazards to be effectively developed in the Kingdom:

- A detailed database of volcanic activity should be established and maintained within the Kingdom. Details of the character and periodicity of activity and the specific hazards should be included. The development of a preliminary database on volcanic activity has been completed (Taylor and Ewart, 1997), but further detailed fieldwork at the individual centres is needed to establish, where possible, the types of processes that have occurred at the individual centres.
The evaluation of the volcanic hazards at all known active centres should be conducted. Furthermore, the existence of potentially dangerous submarine centres would need to be considered.

Dedicated, volcanologically trained personnel should be assigned the responsibility for maintaining the database on volcanism in the Kingdom and remaining abreast of current developments in the field of volcanology.

Detailed bathymetric surveys of the entire TVA or at least all the known active centres should be conducted to establish the character and extent of the volcanic arc and to establish the existence and location of the potentially dangerous submarine centres noted in C. above.

Perhaps the most pressing need is for the development of a dedicated volcano surveillance program within the Kingdom. It is strongly recommended that all the centres with reported historic activity be monitored in some way. If this is not feasible, at least those centres considered potentially dangerous to their inhabitants or those on surrounding or nearby islands, eg. Niuafou’ou, Fonualei, Tofua, Hunga Tonga and Hunga Ha’apai, should be monitored.

Operational support plans should be developed for each of the high risk centres. Furthermore, education programs should be developed for dissemination to the general population to enhance the awareness of volcanism in general and the perception of the effects (both beneficial and detrimental) of activity.

REFERENCES


MONITORING SYSTEMS FOR A FEW OF VANUATU’S VOLCANOES

M. Lardy, D. Charley and M. Matera

ORSTOM BP 76, REPUBLIC OF VANUATU

INTRODUCTION

The program for the study and monitoring of Vanuatu’s volcanoes was established in 1991 and has two major objectives:

1) The first focuses on the historical study of the country’s major volcanic events. A series of scientific publications have been prepared and the production of a document on “Volcanic Hazards in Vanuatu”, which has been summarised by Esau Wate (this volume). In 1995 and 1996, SOPAC published three maps of volcanic hazards and threats (Monzier and Robin, 1995 and 1996; Robin and Monzier, 1996). A fourth map is due to be published shortly, outlining the volcanic hazards of the island of Gaua.

2) The second focuses on the program for the installation of automatic monitoring systems on some of Vanuatu’s volcanoes.

In this paper, the term “monitoring” refers to the ability to spot, and possibly to account for, any alteration of the activity of a volcano (parameters which sometimes cannot be directly observed). Such operational monitoring, using the tools of remote sensing to keep a continuous scientific watch, must allow for occasional in-depth investigations of short duration: These may take the form of research operations (physical and chemical), or on-the-spot management of a catastrophic event.

The monitoring strategy suitable for a country like Vanuatu, falls somewhere between the installation of full-scale permanent observatory and a temporary observation post, obtaining measurements using portable equipment. This situation is a response to a need for the early warning and protection of the population while, at the same time, providing a long-term collection of scientific data.

THE MONITORING TOOLS

Remote Sensing

The remote monitoring network of Vanuatu’s volcanoes relies on the effectiveness and reliability of satellite remote sensing technology, particularly that of the ARGOS data gathering system (Figure 1).

The accessibility of data in near-real-time (typically with only a few hours delay), and their availability over world-wide information networks, facilitates the exchange of information and co-operation between the scientists concerned.

Processing, Recording and Accessing the Data

Access to the data provided by field observatories requires an interface between the laboratories concerned and the ARGOS system. The “Centre de Teleobservation Informatise des Volcans” (CTIV), or Computerised Volcano Remote Monitoring Centre, founded ten years ago, takes care of processing and formatting the data and, at the same time, of making the results available on the Internet and of compiling them into a database. The Centre is based in France and is able to receive and make available the data collected by ARGOS beacons anywhere in the world (e.g. the Philippines, Indonesia, New Zealand, Vanuatu and other localities around the Pacific). The CTIV can also notify concerned users of any anomaly in the operation of the system and its observations.
The Data Acquisition Station

Many types of measurements can be processed with this kind of station, but the ARGOS beacon is limited to 32-byte transmission for eight passes a day in tropical latitudes. Further details of the (SADAN) monitoring station are in figure 2.

Figure 2: Block diagram of an unattended, multi-sensor SADAN volcanological monitoring station.
EXAMPLES OF PARAMETERS MEASURED AT TANNA ISLAND

Both meteorological and geophysical data are typically processed by this type of monitoring station. Data that is routinely processed includes:

**Meteorology:**
- temperature under shelter
- atmospheric pressure
- relative humidity
- rainfall
- average wind speed
- wind direction (instantaneous)

**Geophysics:**
- seismic counts at: threshold 1
- threshold 2
- threshold 3
- threshold 4
- threshold 5

**Heat flow:**
- 3 ground temperature profiles

A LOOK AT SOME OF THE DATA

Tanna Island

The first permanent instrument installation was established in 1992. Following a few months of testing, the station has been able to obtain a continuous record of seismic activity in the cinder flats, 2 km from the crater, since October 1993. The location of the stations are shown in figure 3.

Analysis of the data, year by year, shows an increase of seismic activity, beginning at the end of 1993 (Figure 4). In 1994, the Yasur volcano was very active with bombs being ejected in a 400 m radius around the crater (Figure 5). In 1994, at a locality 2 km from the crater of Yasur, an ash layer was measured with a depth of 12 cm.

At the beginning of 1995 (Figure 4), there was a noted decrease in activity. In January and early February, however, two violent explosions occurred, causing the death of three people. Activity decreased significantly throughout 1995.

In June 1996 (Figure 6), a moderate-to-low level of activity was again noted. This activity was limited, for a few weeks, to the expelling of lava bombs within a radius of less than 100 m around the crater. Ash output was at “normal” levels.

A summary of the daily seismicity from Yasur volcano during 1994 and 1995 is provided in figure 7.

Ambrym Island

The monitoring station for Ambrym is located at the centre of the caldera (Figure 8) at an elevation of approximately 800 m. Average rainfall at this locality is around 600 mm per annum. Access to the station is limited and, unless the party uses a private plane or a helicopter, the round trip takes a minimum of three days.

Since October 1993, observations recorded at the station have confirmed the continuing activity at Benbow and Marum craters (e.g. evidence of surface lava lakes). The seismic record indicates that constant tremor has occurred.

A strong seismic event (magnitude 7.3 Ms) was recorded in southern Malekula at a distance of 80 km, followed by in excess of a thousand seismic events, during the following month (13 July to 12 August 1994). These events were recorded as part of the seismic count at the Ambrym station (Figure 9). Following this period, an exponential decrease of seismic activity was noted, which was probably unrelated to the volcano. Similarly, two signatures recorded in the seismic count corresponded to the passage of two tropical cyclones (Figure 10; 11). In this case, a minimum of meteorological information available at the time made it possible to validate the data.

At the end of a two-year period of recording wind speed and direction at Tanna and Ambrym, the anemometers and wind-speed indicators mechanically deteriorated within 24 months in this harsh environment.
Figure 3: Location of the monitoring stations for Yasur volcano, Tanna Island.

Figure 4: Frequency of seismic events recorded at Yasur volcano between October 1993 and mid-June 1995.
Figure 5: Yasur volcano, showing the volcanic bomb impact densities for 1994.

Figure 6: Frequency of seismic events recorded at Yasur volcano between January and June 1996.
Figure 7: Daily seismicity at Yasur recorded by the seismometer 2 km from the summit, 1994-95. The upper line shows all events with a seismograph displacement greater than 12 μm. The bars indicate the number of larger events, those with a displacement greater than 60 μm. Note that the scale is logarithmic. Courtesy of ORSTOM.

Figure 8: Geological features of Ambrym Caldera.
Figure 9: Frequency of seismic events recorded at Ambrym volcano between November 1993 and April 1995.

Figure 10: Seismic record from Ambrym volcano, during March 1994. The frequency peaks recorded on 23-24 March and 26 March being the result of the passage of tropical cyclones Thomas and Usha respectively.
Gaua Island
The observatory was mothballed at Garet in early-1995, due to a difficulty of access, breakdown in the electronics and a drastic shortage of funds. It can, however, be easily be reactivated if necessary.

Aoba Island
The installation of the observatory at Aoba is fully documented elsewhere (ORSTOM, 1996), which describes the implementation of the monitoring system. A SADAN-TSA station has been operational since late-November 1996. A bathymetric map of Lake Voui was produced, which confirmed that the area of dissolving gases noted on a SPOT image taken in 1992 was in the same location as the underground water explosion that occurred during 1995 and further identified, during a bathymetric survey conducted during 1996.

A full description of the crisis that developed at Aoba Island is presented elsewhere (Wiart and Lardy, this volume).

FURTHER MEASURES
a. During each site visit, the team attempts to record a digital cassette to evaluate the evolution of the tremors and of the other seismic signals at both Tanna and Ambrym.

b. Activities have also included performing initial measurements for radionuclides (210Po). These have, however, not yet progressed beyond an experimental stage. Magmatic gases are considered to be the motive-force behind the volcanic activity, with gaseous emissions preceding and accompanying volcanic activity. The study of the magmatic gases helps to understand the eruptive process (i.e. the magma dynamics).

c. The emission of volcanic gases has resulted in localised pollution in the form of acid rain. On many occasions, this hazard has caused damage to cultivated crops on Tanna (e.g. during 1994, in the White Sands district of the island) and in northern Ambrym, during 1996 (highlighted during an investigation undertaken by J.B.)
Herrenschmidt, a geographer at Office de la recherche scientifique et technique outre-mer (ORSTOM). At Gaua, acid rainfall from Garet appears not to have affected the cultivated food crops and native gardens.

d. Acoustic studies have been conducted by Institut de Physique du Globe de Paris (IPGP) and should add to the understanding of volcanic activity at Yasur (e.g. the variation over time in the size of the gas bubbles, velocity of ejecta, etc.), and will allow comparisons with other volcanoes (e.g. Stromboli) to be undertaken.

e. A comparative study of low frequency seismic signals recorded at Stromboli and at Yasur is the subject of a paper to be published shortly.

f. A paper on heat flow, which considered the methodology used has recently been submitted for publication.

CONCLUSIONS

Volcanic monitoring needs to combine input from scientific research and long-term data gathering to provide advance warnings to the general public. The information collected must be easily accessible to the relevant sectors of the scientific community through information networks. The seismological observatories of a region must be integrated into the volcano monitoring systems to provide the location and magnitude of events recorded.

The role of ORSTOM in the region is also to provide training to personnel in the techniques of research used in volcanological programs.

The scientific communities of the region’s nations must take responsibility for some of the requirements of the systems that need to be implemented. This may be achieved within the current framework of continuing relationships with ORSTOM and through the development of scientific expertise at regional scale. The development of a regional resource network to be used during a major crisis would bring together the region’s research personnel, engineers, technicians and equipment.

Volcanic hazard management must be integrated within a regional network with the overall aim of monitoring natural hazards and preventing disasters from occurring.

REFERENCES


INTRODUCTION

In this paper the National Disaster Management Structure for Vanuatu will be outlined. This structure was reviewed in 1996 following the formation of the National Disaster Management Working Groups (NDMWG). Volcano emergency evacuation plans and public awareness strategies will then be outlined together with an emphasis on the need to develop institutional strengthening strategies as a major part of the process. Because of Vanuatu’s location in the “Rim of Fire” and recent activity at Lake Vui on the island of Aoba (also known as Ambae) much concern has been caused amongst communities and the government at large that it was necessary to develop strategies during the process of documenting plans and procedures.

THE NATIONAL DISASTER MANAGEMENT STRUCTURE

The Role of the National Disaster Management Structure

The overall role is to coordinate and to make the best possible arrangements to deal with any disaster that may occur in Vanuatu. The need for a two-part structure that includes Disaster Emergency Management and Emergency Response has been highlighted by the Disaster Management Advisor from the United Nations Department of Humanitarian Affairs – South Pacific Disaster Reduction Program (UNDHA-SPDRP). As disaster managers in the Pacific, we are now in the process of adopting this system. This system is generating a lot of interesting work through institutional development and linkages. The establishment of NDMWG is seen as a collective effort to distribute the heavy workload. The role of Director of the National Disaster Management Office (NDMO) is one of coordination, monitoring the day to day activities and conducting follow-up action that needs to be implemented.

Government National Policy Statement

The national policy for disaster management includes the need to:

- recognise disaster problems as part of total government responsibility and to make the best possible arrangements to deal with them;
- recognise disaster management phases of prevention, preparedness, response and recovery as essential ingredients for national development; and
- develop an attitude of self-help within the community through public awareness programs.
Indicators

Well before the UNDHA-SPDRP was established, Vanuatu was already in the process of developing its own disaster infrastructure. Input from consultants was followed by advice from the UNDHA-SPDRP Disaster Management Adviser. So far Vanuatu has managed to develop and implement the:

+ National Disaster and Emergency Plan
+ Disaster Act (1994)
+ Cyclone Support Plan
+ Air Crash Emergency Plan
+ Emergency Animal Exotic Disease Plan
+ Aoba Volcano Support Plan
+ NEOC-SOP

Key Issues

Following the completion of these plans, further development is continuing because operational plans are yet to be completed which link in with the master plans. Therefore, the NDMO is now working on the operational plans. Workshops that are being planned are being targeted at the NDMWG one at the time.

To further develop the process, both internal and external support is needed. This support must be channelled through the NDMO and then to the NDMWG to develop what is necessary for implementation.

The Aoba Emergency Support Plan

No document of this nature has ever been developed in Vanuatu. One point of concern is that local customs and traditional beliefs have dominated almost 70% of the total population of Aoba. Therefore, in order to implement this plan it has been necessary to develop a plan using an institutional approach and the conduct of effective briefings at all levels within the community. This institutional approach to the mobilisation phase of the operation appears to have been effective. If the government policy is to be effective, it must be further developed and implemented with external resources and consultation with experts.

It is now worth noting the key headings from the plan:

+ History of the volcano
+ Operational systems
+ Monitoring, activation and alert systems
+ Evacuation procedures and centres
+ Zoning of communities
+ Pick-up points
+ Communication systems
+ Resource support
+ Public awareness strategies.

Scientific studies conducted to date suggest that Aoba volcano should be considered to be a potentially dangerous volcano. Therefore, should an eruption occur it will be necessary to implement the complex operation to minimise the risk to the population. The NDMO is progressively developing the plan to ensure its needed effectiveness.
INSTITUTIONAL STRENGTHENING STRATEGIES

Over the past decade, disaster management activities that have been conducted in Vanuatu were based mainly on disaster relief response. This situation was due to lack of available training and the development of a disaster management structure rather than the reliance on relief response. Recently, UNDHA-SPDRP has been providing assistance with the introduction of strategies that have begun to develop the perception of disaster management in the South Pacific, and particularly in Vanuatu. Meetings are being held each year for the purpose of strengthening and further developing the disaster management infrastructure. The processes have been further refined during discussions with consultants (J. Tomblin), ORSTOM personnel (M. Lardy) and NDMO personnel.

An important point addressed during these discussions was the importance of institutional strengthening to enable the two sectors to work together and share information as a means of achieving a professional risk management approach. Public awareness strategies for volcanic hazards cannot be developed without technical information, and it has been emphasised that institutional strengthening would play a vital role in this process in Vanuatu. Vanuatu has been very fortunate as the process has involved a collaborative effort between the Minister, the NDMWG, ORSTOM and the UNDHA-SPDRP Disaster Management Adviser to complete the Volcano Support Plan for Aoba.

Through the strong linkages, public awareness strategies are progressively being developed and through continued networking are implemented using a collective approach. It must be noted that the NDMO is a non-technical organisation, but has local technical support from C Douglas, and with this cooperation has made commitments to accept whatever the best possible arrangements that can be adopted to safeguard public lives.

Preventative Alert Strategies

Our aim in volcano emergency planning is to “minimise lose of life”. Preventative alert strategies are implemented in three stages including:

- Installation of monitoring observatories.
- Issuing information bulletins.
- Preparation of hazard maps.

The implementation of these strategies has allowed volcano support plans to be developed.

Installation of Monitoring Stations

In order to collect sufficient data about the state of the volcano, monitoring stations have been established. These stations have been installed and maintained by ORSTOM on several of the volcanoes in Vanuatu for the purpose of data collection. Depending on the level of activity, information is disseminated to authorities and where appropriate community leaders.

Issuing of Bulletins

A series of information bulletins outlining the changes observed in the activity of the volcanoes are issued. Several examples of the sort of information contained in the bulletins have been included in Appendix 1. Some of the materials are published in three languages, English, French and Bislama. These bulletins are distributed through the authorities and the local media as part of the public awareness programs.

Issuing of an Alert – Situation report

This is a continuing process, and it depends largely on the level of activity of a volcano. The situation report is disseminated not only to high-risk communities but also to other authorities as well. After drafting the Aoba support plan which includes the provision of daily situation reports to the nation, negotiations are now underway with the local media services to broadcast these reports in a similar manner to weather reports.
Volcano Hazard Maps

As Vanuatu has progressively improved its disaster management arrangements, technical expertise is required as an integral part of the planning and information. In view of the working relationship, we gratefully acknowledge the support of South Pacific Applied Geoscience Commission (SOPAC) for the production of three Volcano hazard maps so far (Aoba, Ambrym & Tanna). These maps provide clear information on the volcanic hazards at each centre, that are used for the purpose of planning and for the local community awareness of what the hazards are and their effect on human lives. They are very useful public awareness tools when discussing volcano evacuation plans.

SUPPORT PROGRAM STRATEGY

Disaster Management Working Groups

With the assistance of the UNDHA-SPDRP a series of NDMWG have been established which comprise of representatives from government departments, non-government organisations (NGOs), Provincial Affairs, the Police, Vanuatu Military Forces (VMF) and the private sector. The representatives from the constituent agencies provide a wide range of assisting in the research needed to formulate emergency plans and the dissemination of information targeted to the communities they are working with.

So far the NDMWG are very supportive with meetings being conducted each month to review the progress in their allocated tasks and those activities that are still under development. In the case of Aoba volcano support plan, I have allocated several key issues to sub-working groups, ie.: Marine Resources etc. The objective is that once these sub-groups complete their tasks, they will be in a better position to provide effective public awareness materials.

Visiting the Vulnerable Community

Public awareness is not only communicated through the use of pamphlets, etc., but perhaps the most powerful method is through visiting and talking face to face with the vulnerable community. Mr Douglas Charley, our volcanologist, has accomplished this through his knowledge of the geography of Aoba, the characteristics of Vui volcano, his cultural and religious background. He has worked in collaboration with the NDMO and has confirmed that the awareness team visit to Aoba during January 1997 was a success.

It is a real challenge, when you tell ‘Mr. Joe Blong’ that he is living in a hazardous zone, he will turn around and argue in defence of his environment, custom beliefs, religious beliefs, politics, etc. Through listening and responding, through an interpreter, and with body language such as eye contact the message can, in most cases, be effectively communicated. The main aim is to change the attitude of the people and to get them to understand the hazard and get themselves prepared.

An ongoing program of visits to the Aoba communities has been planned. Although expensive, it is considered to be important.

Conducting Meeting with Other Agencies

As part of the continuing institutional capacity building and networking process, a series of meetings are being conducted with other agencies. These meetings address certain key issues including:

- the development of an effective communications network (with the Police, the VMF and Telecom Vanuatu);
- the development and implementation of broadcasts of daily situation reports on the status of a volcano (with the media and ORSTOM);
- the development of a National resource inventory program (with all local ship owners);
- the development of community-based programs (with VNGO and Province groups);
- the development of school curriculums (with schools);
- upgrading of the Public Works capacity on Aoba (with Civil Aviation and PWD);
- development of institutional training programs (with the Government Training Centre);
Further development of National Planning programs (as part of DP4); and specific IDNDR program activities (with ORSTOM, VANGO and Met).

Workshops

As outlined by Rector (this volume), the disaster managers and those in support of the NDMO have had little formal training. A series of workshops and briefings conducted in-country will further develop the capabilities of disaster managers to develop and implement the necessary processes.

The initial workshop targeted the development of the Aoba volcano support plan and was held in 1995. The second was held in 1996. Further workshops have been planned to be held in Aoba in 1997, targeting specific topics highlighted by the management working group. Some of the workshop was conducted by NGO, ie. VANGO, targeting the community-based program issues. The Red Cross also participated. These workshops correspond to recommendations included in the National Disaster Development Program for 1997/1998.

Donor Agencies

Although scientific information is available, the national resources necessary to evacuate the whole of Aoba is insufficient. Unlike the case of a cyclone emergency, our donor agencies need to know what type of support they can provide before, during and after the eruption. Meetings have occurred with several donor agencies (ie. AusAID, FSP, French Embassy, NZ, Japan) and they appear to be most willing evaluate the needs and have pledged support for the NDMO should an emergency develop. During a separate briefing held recently with the diplomatic missions, the importance of continuing linkages throughout the planning and management process was discussed.

Public Education Awareness Materials

To date, the following public education and awareness materials have been developed:

- Publishing of volcanological bulletins by ORSTOM.
- Volcanic hazard maps published by SOPAC.
- Geographical maps.
- Video strips produced jointly by ORSTOM/VRTC.
- Press releases.
- Alert levels in development.
- Public exhibitions of volcano awareness material (French Embassy during February - March 1997).

Aoba Public Education and Awareness Programs

Examples of the material that have been developed during the Aoba crisis are given in Appendix 1.

Conclusions

Vanuatu is already in the process of developing and further refining a National Disaster Management Program drawn up by the members of the NDMWG. Specific programs have been developed as part of the annual program, including specific strategies for volcanoes such as Aoba. Vanuatu would like to acknowledge the support already provided, would like to further develop program activities through assistance provided by external organisations as part of the capacity building process.
In summary, in Vanuatu, volcano public awareness materials currently include the following:

1. Scientific information. (ORSTOM)
   - geographical background;
   - history of volcano;
   - volcanic and associated hazards;
   - effects on human life;
   - monitoring of activity; and the
   - development of alert strategies.

2. Volcano emergency management or support plans. (NDMO)

3. Community based programs (NGOs/Provinces)

APPENDIX 1

PRESS RELEASE

AMBAE Volcano

If it seems important to inform the populations of the outbreaks which natural disasters (cyclones, earthquakes or volcanoes) can cause in their region, it is just as important that they do not cede to any form of anguish, or even be overcome by panic.

A programme of survey and monitoring of VANUATU’s volcanoes set up with the agreement of the Archipelago Government enables to have a better knowledge of the background of VANUATU’s volcanoes and to consider the change in activity of some of them. No prediction in the medium term (a few months) can be done with the present state of knowledge.

In November 1996, an alert station was set up above Lombenben; the National Disaster Management Office (NDMO) along with the volcanologist technician of ORSTOM (AOBA) and of the Mining Department have, on two occasions, organised information tours on Ambae Island, with presentation of the volcano risk map. These tours will continue throughout the year so that every village on AOBA is informed.

Nowadays, information is being easily conveyed and it seems difficult to work without informing the people who are most at risk. Public awareness of cyclone, volcanic or seismic risks, in order to reduce their impacts, is one of the principles stated as part of the United Nations programme on the reduction of natural risks for the decade 1990-2000.

The decrease in activity which has been noticed for several months after the ground water eruption of March 1995, together with the ongoing decrease of the global temperature in LAKE VOUI enables us to think that the volcano does not show any danger at the present time.

A third observatory will be set up during the year 1997.

January 1997

NDMO  Department of Mines and Geology          ORSTOM
AMBAE PUBLIC EDUCATION AWARENESS CONCERNEM AMBAE VOLCANO PROGRAMME

BAE I TEKEM PLES LONG OL PLESES AND DATES ‘OLSEM:

WEDNESDAY 15/01/97:
MORNING: 9 Hrs 00 AM
Ples: Loloaru -- ikavremap: Vuialato/Nagire/Loloaru
AFTERNOON: 02 Hrs 00 PM
Ples: Loloaravatu -- ikavremap: Waluriki/Walubue

THURSDAY 16/01/97:
MORNING: 9 Hrs 00 AM
Ples: Wainasasa mo eria kolosap
AFTERNOON: 02 Hrs 00 PM
Ples: Saranavhi mo ol eria kolosap

FRIDAY 17/01/97:
MORNING: 9 Hrs 00 AM
Ples: Lopoluepue mo I ikavremap kasem Tavolavola
AFTERNOON: 02 Hrs 00 PM
Ples: Ambanga mo ikavremap kasem Lolosori mo ol eria kolosap

SATURDAY 18/01/97:
MORNING: 09 Hrs 00 AM
Ples: Tahimamavi mo Lone ko kasem Lolomagada
AFTERNOON: 02 Hrs 00 PM
Ples: Lovuitokohui mo ol eria kasem Lovuimataboe

SUNDAY 19/01/97:
MORNING: 09 Hrs 00 AM
Ples: Lolovatili mo ol eria kolosap
AFTERNOON: 02 Hrs 00 PM
Ples: Lovuvili kasem Nanigama, mo Naqwea, Arorongo

MONDAY 20/01/97:
MORNING: 09 Hrs 00 AM
Ples: Longana Center kasem Wailingi mo ol eria kolosap
AFTERNOON: 02 Hrs 00 PM
Ples: Lolovali mo ol eria kolosap

TUESDAY 21/01/97:
MORNING: 09 Hrs 00 AM
Ples: Redclif mo ol eria kolosap
AFTERNOON: 02 Hrs 00 PM
Ples: Waisine School mo ol eria kolosap

WEDNESDAY 22/01/97:
MORNING: 09 Hrs 00 AM
Ples: Saratamata mo eria kasem Navonda

BRODCAST:
Today 14/01/97 at 10.30 AM/5.30 PM
Tomorrow 15/01/97 at 7.30 AM/10.30 AM/5.30 PM
Some 1800 years ago, a gigantic eruption modified the relief of Ambrym and formed the caldera which crowns the island (a caldera is a big crater). 13 km wide in the case of Ambrym). During the last centuries, Ambrym volcanism has experienced many eruptions. Three activity levels have to be considered:

- Normal (or weak) activity: Lava flows are present in the craters of Marum and Benbow, ash fallout is dangerous only in the immediate surroundings of the active craters.
- Intermediate activity (1893/4, 1901, 1914, 1962, 1965, 1972, 1985 and 1986-88 eruptions): Explosions may produce important ash clouds, several kilometres high, whose ashes, carried by the trade winds, commonly fall over the south west slopes of the island (red ashfall A). Due to the small quantity of ash in the plume, the hazards are not great, but ashfall is probable. Ashes may fall elsewhere on the island if other wind systems are present. During such an eruption, lava flows may cover a limited area of the caldera floor. Due to intense flows of ashes and small boulders (lapilli) near the vents, and the high probability of pyroclastic flows being emitted from the craters and flowing over the caldera floor, the access to the caldera area must be strictly prohibited.
- Strong activity (1620, 1688, 1844, 1913, 1929, 1937 and 1942 eruptions): High ash clouds are responsible for important and/or long lasting ashfall which may affect all of the island if the wind directions are not strong. The thickness of ash deposits may reach 50 cm or more within the area delimited by the B circle and a few centimeters to a few decimeters within the C circle. During this type of eruption, lavas may overflow the caldera wall. Other lavas may erupt along the direct fracture line which cuts the island. Lava flows restricted to the valleys, reach the sea and threaten coastal villages. If strong ashfalls are accompanied or followed by rain, all the valleys of the island as well as the coastal plains near the mouths may be ravaged by mudflows carrying trees and blocks. Such ashflows are extremely destructive (peppers ashfall C). Lastly, rainfall-seawater interactions may induce very dangerous exploitations at the western and eastern extremities of the island, both onshore and offshore (blue circles E). If an eruption occurs at one of these extremites or spreads from the calderas towards it, it might be necessary to evacuate the populations. A plan for the evacuation of the people should at least be prepared beforehand.

The northern part of Ambrym is safe in case of a strong eruption, however, some ashfall may occur if southern winds are blowing.

There is a serious risk that pyroclastic flows will flow down the slopes of Ambrym from Marum and Benbow craters.

There is also a risk of regional tsunamis following volcanic events in the Southern and Central Pacific islands. The first tsunami warning system for the South Pacific region was installed in 1973.
VOLCANIC HAZARD MAP FOR AOBA ISLAND / CARTE DES RISQUES VOLCANIQUES POUR L’ILE D’AOBA (VANUATU)

by par M. MONZIER and C. ROBIN (ORSTOM)

10 km radius area surrounding the Lake Voui (main summit crater), in the case of a resurgence of volcanic activity in the summit area, strong falls of ash, dense lapilli and aciniform lapilli, as well as devastating pumice-lastic flows. Basaltic surge and lahars may occur in this area. Then, it will be wise to evacuate in a first phase the population of coastal villages of this area toward the NE and NW extremities of the island.

5 km radius on- and offshore area surrounding both extremities of the island, where strongly explosive magma-seawater interactions may occur. If the eruption base place near the NE and NW extremities of the island, or spread along fractures from the central vent toward these extremities, then it might be necessary to evacuate the population living in these areas.

N.B. In case of eruption, lava flows may also erupt anywhere from SW-NE flank fissures and flows down to the coast; ash may also fall over the whole island. For example, the Ndu’ iku lava flow emitted about 200 years ago, flowed from about 1200 m altitude and covered a large area of the island before to enter the sea.

Accretionary lapilli: small balls of mud, a few millimeters to 1-2 centimeters in diameter, falling after phreato-magmatic explosions. Ash: volcanic sand which falls during an eruption. Basalt surge: hot and fast pumice-lastic flow rushing down the slopes after phreato-magmatic explosions. Caldeira: Large crater. Lahar devastating incision, of large blocks of vesiculated lava in the detector, important lahars could be produced if an explosion occurred. Lava: heat rays may also appear in case of heavy rains removing recent ash deposits. Lapilli: gravel and small blocks which fall during a volcanic eruption. Magma: very hot molten rock. Pumice-lastic flow: connected to an explosive interaction between magma and water (groundwater or sea water). Pumice-lastic ash, lapilli and block deposits. Pumice-lastic flow: very hot cloud bearing ashes, lapilli and blocks, and rushing down the slopes.

ORSTOM, 1995
VOLCANIC HAZARD MAP FOR TANNA ISLAND

by/por Claudia ROBIN & Michael MONZER (OSRCM)

Present volcanism on Tanna is represented by the Tavu crater cone. Its activity follows a long volcanic cycle that extends back to the southeast of the island. Since 10,000 years ago, two distinct activity periods have been documented: 1) last 2,000 years of growing volcanism; and 2) recent, continuous, and periodic activity since 10,000 years ago. This continuous activity period is characterized by lava flows, small-scale eruptions, and ashfall. The most recent activity was during the 1990s and 2000s, with periods of increased activity in 2005 and 2011.

Type 1: Lava flow activity, which is common near the Tavu crater. This activity is characterized by the presence of hot lava flows, which are often accompanied by ashfall and debris. This type of activity is frequent and can pose a significant threat to local communities.

Type 2: Ashfall activity, which is common near the Tavu crater. This activity is characterized by the presence of ashfall and debris, which can be carried by the wind and deposit a significant amount of material in the affected area. This type of activity is frequent and can pose a significant threat to local communities.

Type 3: Lava dome activity, which is common near the Tavu crater. This activity is characterized by the presence of lava domes, which can be formed by the accumulation of lava and debris. This type of activity is frequent and can pose a significant threat to local communities.

Type 4: Gas and steam emission, which is common near the Tavu crater. This activity is characterized by the presence of gas and steam emissions, which can pose a significant threat to local communities.

In addition to the above activities, there is also the potential for lahars and debris flows, which can be triggered by rainfall and can cause significant damage to infrastructure and property.

Volcanic hazards in the southwest Pacific are a significant concern for local communities and governments. The SPC Technical Bulletin SPC00017 provides guidance on how to manage these hazards and ensure the safety of the population.
VOLCANIC HAZARDS IN SAMOA

P.W. Taylor* and F. Sapolu**

*Australian Volcanological Investigations, AUSTRALIA
**Ministry of Internal Affairs, SAMOA

ABSTRACT

The Samoan Islands are of volcanic origin and both Upolu and Savai‘i show many signs that suggest recent volcanic activity has occurred. Savai‘i, Samoa’s largest island, located to the west of the main island of Upolu covers an area of 1700 km². Savai‘i has been formed by a long period of volcanism that may have commenced during the Pliocene to early-Pleistocene.

Savai‘i is the only Samoan island to have experienced historic volcanic activity. It is home to 50,000 Samoans living in numerous villages around its coast. Regular contact is maintained with the main island of Upolu via regular ferry and air services. A sealed road system circumvents the island. Savai‘i’s history has been dominated by periods of both effusive and explosive activity. Since Savai‘i was first discovered by Europeans, at least three periods of activity are known (Table 1). Two of these eruptions have produced extensive lava flows, resulting in the destruction of numerous villages located along the north and northeast coast. The most recent, during 1905–11 resulted in some spectacular volcanic displays of nature’s might. The crater of Matavanu (Figure 1A) was built up during the activity and was the source for numerous lava flows. During the six-year eruption, a large lava field was formed on the north-eastern side of the island (Figure 1B). Several villages were destroyed during the activity (Figure 1C).

TABLE 1: HISTORIC ERUPTIONS ON SAVAI‘I

(After Taylor and Talia, 1999)

<table>
<thead>
<tr>
<th>Date</th>
<th>Vent/s Name</th>
<th>Characteristics and Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1760</td>
<td>Mauga Afi</td>
<td>Effusive activity with minor explosive phases (?); voluminous lava flows (10⁹ m³) covered an estimated area of 1.9 x 10² km² on the NW flanks of the island with flows reaching the NW coast on a wide front; the village of ‘Aopo was partially destroyed and surrounded by lava flows; a number of other native villages and extensive areas of arable land were destroyed; no fatalities are known.</td>
</tr>
<tr>
<td>1902 (Oct-Nov)</td>
<td>Mauga Mu &amp; Mata o le Afi</td>
<td>Explosive activity with minor effusive phases; activity was preceded by a period of intense seismic activity; several cinder/spatter cones were formed on a series of fissures; lava flows produced flowed 1-2 km to the north of the vents; vegetation was destroyed; no reports of damage to villages or fatalities are known.</td>
</tr>
<tr>
<td>1905 (Aug) - 1911 (Nov)</td>
<td>Matavanu</td>
<td>Effusive with minor explosive phases; three vents formed initially; however, following a collapse episode, the vents coalesced to form an elongate crater 250 x 300 m; lava fountains to a height of 200-300 m were reported; voluminous lava flows (10⁹ m³) flowed toward the NE, reaching the coast on a wide front (est. 15 km); flows were reported to be 8-11 m thick at several localities; many flows, particularly during the later stages of the eruption, flowed from the vent to the coast in lava tubes; several villages, including Satapatu, Malaeaola, Salago, Toapaipai and Saleaula (except for two houses) located along the NE coast were destroyed; large tracts of arable plantation land and extensive areas of lagoon and fringing reef along the NE coast were destroyed; no fatalities have been reported.</td>
</tr>
</tbody>
</table>
Upolu Island, where Apia, Samoa’s capital is located, has not experienced periods of historic activity; however, numerous geological features, particularly the cone Tafua Upolu, in western Upolu (Figure 2), and the young lava flows that outcrop along the southern coast, locally known as O le Pupu, both suggest activity has occurred in the recent past.

Although Savai’i has experienced several historic eruptions, few geological studies have been carried out. The recent geological mapping of Samoa, including Savai’i, was conducted by Kear and Wood (1959). Although their report was comprehensive in terms of the general geological features of Savai’i, little information was provided with respect to the volcanic processes that have occurred. Numerous other features on both islands revealed in Kear and Wood’s study suggest a long period of activity.

There are many signs, suggesting that frequent and long-term activity has occurred on all the Samoan islands, but there is generally a low perception of the likelihood of future activity and the effects of the hazards that would accompany periods of activity. Because of this lack of understanding of volcanic hazards, SOPAC sponsored a project to undertake a volcanic hazards assessment of Savai’i (Taylor and Talia, 1999). The completion of this study provided the Samoan Government with a much better understanding of the type of activity and the associated volcanic hazards that could be expected to occur during future periods of activity.

REFERENCES


CASE STUDIES
INTRODUCTION

Since monitoring began of the Rabaul volcano, after the 1937 eruption, there have been two volcanic crises, in 1983-85 and 1994 to the present. These crises differed in characters; the 1983-85 crisis being a non-eruptive event, while the 1994 event involved simultaneous eruptions from two craters within the caldera. The earlier event was probably the precursor to the 1994 eruption.

The Rabaul caldera is the most intensively monitored volcano in Papua New Guinea for five main reasons:

1. The Rabaul caldera is the most dangerous volcano in PNG based on its hazard rating.
2. The eruption in 1937 left 506 people dead and caused considerable damage to Rabaul Town and its surrounding areas.
3. Areas in and around Rabaul are highly populated.
4. The Rabaul Town is the largest town that serves the New Guinea Island region.
5. The geological history of the Rabaul caldera shows that it has produced catastrophic and disastrous eruptions and that such eruption will be repeated in the future.

RABAUL CALDERA

The Rabaul Caldera is of medium size, measuring 14 km north to south and 9 km east to west (Figure 1). Present indication are that the caldera was formed several tens of thousand years ago and subsequently modified by about a dozen or more major eruptions, the most recent of which was 1400 years BP. Several small volcanoes have developed within the caldera since the last major eruption, mostly around the perimeter of the caldera. The historical record of eruptions of these post-caldera volcanoes dates back to 1767 AD and includes at least six recognisable eruptive episodes, the most recent of which was in 1994-present. Three of these episodes (1878, 1937-43, 1994-present) involved simultaneous eruptions on opposite sides of the caldera.

EVENTS LEADING TO THE 1983 - 1985 CRISIS

The caldera unrest in 1971 occurred after two major tectonic earthquakes of magnitude (ML) 8.0 in the Solomon Sea. The unrest involved progressive increase in uplift and tilting concentrated at a source almost at the center of the caldera (south of Matupit Island) and seismicity along the 1400 years BP. caldera fault boundary. The seismicity was characterised by occasional swarms of hundreds of shallow (0-3 km depth) earthquakes, at intervals of several months to years. Uplift appears to take place steadily but during seismic swarm, episodes of relatively large uplift may have occurred (Figure 2). In response to this activity, a volcanic hazard assessment of Rabaul was completed in 1982.

This slowly evolving situation gave way in 1983 to a dramatic increase in seismic (Figure 3) and ground deformation. This increase may have been linked to major tectonic earthquake of magnitude 7.6, located 200 km east of Rabaul that took place in March 1983.
THE 1983 - 1985 CRISIS

There was more or less a steady increase in seismicity from about 10 seismic events per day in August 1983 to about 50 events per day before the seismic crisis on 19 September, 1983. This intensified caldera activity, was marked by frequent episodes of high seismic energy release and concurrent rapid ground deformation. The monthly count of shallow earthquakes in August was about 330, the month of September was about 2135 and by 1984 exceeded 10,000. The rate of deformation also accelerated in September. Maximum tilt rates increased to between 20 and 30 microradians per month. The biggest individual tilt changes were in the order of 50 microradians at stations 1 km from the deformation source. Levelling towards the deformation source shows a trend of continuous uplift, with an average rate of about 50 mm per month. This compares with previous rates of about 8 mm per month for the preceding decade. The largest measured uplift in a crisis was about 60 mm. However, after activities peaking in April, it declined abruptly and returned to its pre-1983 level in July 1985 (Figure 3 & 4).

The dramatic increase in seismic and ground deformation was believed to indicate a high rate of magma injection at shallow depth which would lead to an eruption in the future.
Figure 2: Changes in elevation within the Rabaul Caldera during the period 1974 to late-1993. The numbers refer to devices located along the eastern part of the caldera (see insert).

Figure 3: Cumulative seismic energy released during events during the period mid-1975 to 1988.

CALDERA ACTIVITY AFTER 1983 - 1985

After the 1983-85 crisis activity in the Rabaul caldera, it returned to its pre-crisis level. Shallow seismicity around the 1400 years BP caldera ring-fault continued to occur with the occasional seismic swarms and the inner caldera block continued to be elevated and tilted. In 1992, an unusual seismic activity consisting of high frequency earthquakes from the northeast, outside the caldera ring-fault started to occur. Sometimes these earthquakes occurred in swarms. The number of earthquakes from 1992 increased but remained almost steady until September 1994 (Figure 5).
Figure 4: Number of seismic events recorded at the device located on the southern side of Matupit Island (see insert) from 1968 to mid-1994.

Figure 5: Amplitude and number of events recorded over the three-day period 17-19 Sep 1994.
THE 1994 - PRESENT CRISIS

At 0251 hours on 18 September 1994, the Rabaul area was shaken violently by a magnitude 5.1 caldera earthquake, from Greet Harbour. A second earthquake of similar magnitude from the Karavia Bay area occurred few seconds later. After the strong earthquakes, caldera seismicity and ground uplift increased exponentially to a high level within the following 27 hours before Tavurvur erupted at 0605 hours, on 19 September. Vulcan erupted one hour later at 0717 hours. This new eruption ended a repose period of about 51 years.

Following the pattern of the last two eruptive episodes (1878 and 1937-43), Vulcan and Tavurvur, on opposite sides of the caldera (about 12 km apart), erupted simultaneously. Pulsating columns of thick grey ash, pyroclastic flows and tsunamis were produced. The eruption at Vulcan was the more powerful, generating an eruption column over 20 km high. Tavurvur's eruption column rose to about 6 km. The surface of the Rabaul Harbour during the eruption was covered by floating pumice and the eastern and southern township of Rabaul was totally destroyed by heavy ash falls with associated mud-flows. Surrounding villages, especially those on the west and north of Vulcan were completely buried and those east and northeast of Tavurvur were severely damaged. Fortunately, there were only 5 deaths; 4 in Rabaul Town and 1 by lighting strikes at the southern caldera wall (compared to about 500 deaths in 1937, at Vulcan). Activity at Vulcan decreased 5 days later until it stopped on 2 October. Tavurvur persisted until 23 December. Eruption at Tavurvur resumed on 13 February and continued until 16 April 1995.

Destruction during 1994 eruption was estimated to be in excess of K300 million (about US$300 m). About 70,000 people were made homeless and taken care of at numerous care-centres, in the Kokopo and inland areas.

A new phase of eruptive activity started on 28 November 1995 and is still continuing. There were two phases of strong strombolian activity, on 4 October 1996 and 9 January 1997 with lava flows of similar volumes (about 4 x 106 m³), flowing to the south, burning and burying agricultural land.

CONTINGENCY PLANNING

A contingency plan was developed rapidly during the early stages of the 1983 crisis and it was evident to the general public that scientists and local authorities were taking all reasonable measures to ensure public safety. The measures taken included identifying safe routes (by road and sea) out of Rabaul and establishing safe refuge outside the caldera. It was recommended that new roads directed to the south or southeast and construction of a new airstrip southeast of Rabaul would be beneficial. A four-stage alert system was devised (Table 1), which has since been adopted in modified form for use at other volcanoes in PNG.

During the 1994 crisis the general public was aware of escape routes to take and the airstrip was commissioned to operate small and military aircraft to evacuate people to other provinces.

<table>
<thead>
<tr>
<th>STAGE</th>
<th>THREAT TO LIFE</th>
<th>GOVERNMENT &amp; PEOPLE ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Preparation (or Review) Stage for PDC, Government bodies, Private sector, and People education on hazards and response. Yearly exercises. No need to evacuate, (or: Population of all habitable areas may return) (or: Rehabilitation, of non-high risk areas)</td>
</tr>
<tr>
<td>2</td>
<td>Medium or Localised</td>
<td>Activation of Intermediate stage disaster plan. Evacuate (or keep clear of high risk areas). (or: Residents of low-risk areas may return). State of Emergency.</td>
</tr>
<tr>
<td>3-4</td>
<td>High or Widespread</td>
<td>Activation of State of Emergency of disaster plan. Full evacuation of population at risk; Relocation/care centres.</td>
</tr>
</tbody>
</table>

Note: These Stages of Alert should:
A. Focus only on the level of threat to life and property (not on the level of activity of the volcano).
B. Consist of three stages.
C. Without definite time frame.
RESPONSES

On 29 October 1983, acting on information from the Rabaul Volcanological Observatory (RVO) on the dramatic increase in activity, government officials declared a Stage 2 alert, and in 1994, Stage 2 was declared on 18 September at 1900 hours (16 hrs after the start of increase activity) and Stages 3 and 4 at about 0600 hours on the following day.

During the 1983-85 crisis, monitoring networks in Rabaul were expanded with the introduction of 7 electronic tilts, electronic distant measurement (EDM), 4 telemetered tide gauges and 3 magnetic stations. In this, RVO personnel were assisted by a team from the United States Geological Survey (USGS), OFDA/USAID, and the New Zealand Ministry of Affairs also contributed some equipment. Under the auspices of the East New Britain Provincial Disaster Control Committee (PDCC), a disaster contingency plan was drawn up. Regular status reports were provided to PDCC by the Principal Volcanologist of RVO, who acted as a non-voting member. Appropriate emergency measures were implemented by the PDCC (now East New Britain Provincial Disaster Committee - ENDPDC) in accordance with the Stage 2 alert. This included widening the existing roads and conducting several evacuation exercises (some involving the public) to improve and test the evacuation plan. A simplified evacuation plan in the form of a coloured poster was drawn up in early 1984 and issued to the public (Figure 6). The map outlined high and low risk areas, pick-up points for those in need of transport during evacuation, evacuation centres and routes to follow.

In the 1994 eruption, the monitoring network in Rabaul was extensively destroyed both by the eruption and by vandals. Only 3 seismic stations remained operational until USGS arrived three weeks after the eruption started with replacement and computerised equipment and restored some of the damaged stations. Also during the eruption, AIDAB (now AusAID) was requested to upgrade monitoring in Rabaul and at other active volcanoes in PNG. The project was contracted to the Australian Geological Survey Organisation (AGSO) for implementation, assisted by RVO. In May 1996, Phase 2 of the project was signed between AusAID and AGSO and work began. The monitoring network at Rabaul is being expanded with the establishment of new seismic and ground deformation stations and the introduction of real-time GPS monitoring.

Figure 6: Simplified evacuation plan that was developed during early 1984 and issued to the public during the 1983-85 crisis.
During both crises periods, the RVO conducted an intensive education program to inform government officials and the general public about potential hazards; in 1983 should an eruption occur and in 1994 to remove the confusions and misconceptions. RVO issued an enormous amount of situation reports, information bulletins and other advice to government authorities; other commitments prevented RVO from releasing information direct to the media and public. This created problems as observed in other emergencies-elsewhere around the world until alternative arrangements could be made. During the 1983 crisis, a Public Information Unit (PIU) was established with Public Information Officers and later a Volcanological Liaison Officer (VOL) to disseminate information on the volcanic situation and disaster preparations to the media and the public. The VOL was again established during the 1994 crisis and carried on the task as in 1983 crisis. In 1983, the National Disaster Emergency Services (DES) and Provincial Disaster Committees (DC) were established which eventually led to the formation of a National Disaster Management Plan.

A survey on public awareness and preparation conducted during the crisis showed that by May 1984, there was an encouraging level of understanding of the anticipated hazards and the Evacuation Plan among the indigenous population and that more than half had made adequate preparation for evacuation. About 40% of the population living in Rabaul had voluntarily evacuated to areas outside of the caldera while some others had moved to other provinces. The result of the public awareness and preparation was evidenced during the 1994 crisis. About 100,000 people vacated their homes with only a loss of five lives.

**EFFECTS OF THE CRISSES ON THE SCIENTISTS**

The crises had a number of positive as well as negative effects on RVO scientists. The positive effects included securing an increase in annual funding during the 1983-85 crisis; technical and financial assistance from overseas and gaining a considerable amount of caldera unrest and eruption. The improvement using computerised equipment and expansion of the surveillance network provided valuable information to help the scientists to understand the volcanic processes that take place in the caldera and under the erupting volcanoes (Figure 7).
A survey conducted after the 1983-85 crisis, showed that RVO suffered no loss of credibility from government authorities, the media or the public due to the non-occurrence of an eruption but not so in 1994. RVO suffered loss of credibility because the scientists were not able to predict the eruption and that was the main negative effect on scientists and RVO. The other negative effects was that on both crises, considerable amount of time was spent on monitoring Rabaul Volcano while other volcanoes in PNG were somewhat neglected. Funds and equipment allocated for other volcanoes were diverted to Rabaul. In the 1983 crisis problems were caused with some equipment, especially the electronic tiltmeters, which had been hastily constructed and installed in response to the crisis.

**EFFECTS OF THE CRISES ON THE AUTHORITIES**

The positive effects in the 1983 crisis includes the achievement of a high level of disaster planning and preparation in East New Britain and the passing of emergency legislation to enable creation of a National and Provincial Disaster Committee in PNG. In 1994 crisis the East New Britain Provincial Disaster committee (ENBPDC) implemented the already established Disaster Plan with little ease. The other positive effect is the change of the stage of alert system from four to three (Table 1). The old system was not suitable for an already inflated volcano ready to erupt at any moment.

On the negative side, in 1983 crisis a large amount of unbudgeted expenditure incurred in preparation for a disaster that did not eventuate and in 1994 there was no budget preparation for the unexpected eruption.

**EFFECTS OF THE CRISES ON THE MEDIA**

First the negative aspects: From the onset of the crises, media representatives were not allowed to enter RVO or visit scientists in the field. This was because the scientists were not able to cope with the additional task of disseminating information on the developing and erupting volcanic situations due to the exceptionally heavy workload being imposed on them, and due to experience on volcanic emergencies elsewhere. The local media, Radio Rabaul, early during the 1994 crisis stopped the transmission of information to the public until several weeks later. The bulk of the populations were thus unable to receive regular information during the early part of the crisis period.

On a positive note: The media was happy to obtain information from the Public Information Unit. In 1983, it was found that the highest standard of reporting was from the local radio station which maintained a fairly close relationship with the ENBPDC. The radio station also broadcast verbatim most of the routine situation reports prepared by RVO for release through the ENBPDC.

**EFFECTS OF THE CRISIS ON THE PRIVATE SECTOR**

More negative than positive effects were generated. In 1983, there was a massive increase in insurance premiums and loss of insurance cover against volcanic and seismic risks. There was also a marked loss of profit through reduced business. In 1994, there was enormous financial loss. Some lost 100% of their properties because they were not insured from destruction from eruption and looting. Many small businesses packed-up and moved to other provinces in the country, while others are still waiting to be given new land to establish themselves.

The only positive aspect in 1983 was an unexpected increase in export revenue generated by sales of surplus primary produce from the new cultivated areas that resulted from voluntary movement of people into the safe areas during the Stage 2 alert. After the 1994 crisis, new but large companies moved in (Kokopo Town) and established themselves, which was not possible earlier in Rabaul because of the non-availability of land. Building constructors are much privileged because of the development (expansion) of the Kokopo town and the restoration of houses in Rabaul Town.
EFFECTS OF THE CRISIS ON THE PUBLIC

During the 1983 crisis there was increase in food production and also during the 1994 crisis, evacuees were resettled on new land cultivating it and reaping the benefits of their effort. The most positive expect is a large group of people from affected danger areas were given free land which they would not have if there was no eruption. People are now aware of the dangers from volcanic eruption and what protective measures to take in future eruptions.

The negative aspects included the disruption of social, cultural and family lives because of living away from home either because their home is in the danger zone or their homes was completely destroyed. In 1983 there were closures of some of the educational institutions located in high risk zones because pupils had to be sent to other schools. In 1994 some schools in danger zones were completely destroyed while some had to be closed and students remained with their parents at care centres. In 1983, some parents kept children away from school, afraid that there might be a sudden increase in volcanic activity. There was also the large financial outlay needed to stockpile food and other essential materials which would be required during any eruption. In 1994, there was no stockpile of food and other essential materials for the care centres.

CONCLUSION

Volcanic crises are ongoing events, sometimes they happen more frequently such as the case in Rabaul, but at other times once or never in a life time. Volcanic crises will never go away. Man will live with volcanoes as long as the human race survives as it has been for millions of years and will continue in the future.

To survive during volcanic crises one must learn from the past crises and prepare for future ones. It is only through good preparations and good understanding between the communities at large that the consequences of volcanic disasters are minimised.

REFERENCES


B. J. Scott¹ and V. E. Neall²

¹ Institute of Geological & Nuclear Sciences, NEW ZEALAND
² Massey University, NEW ZEALAND

INTRODUCTION

Mt Ruapehu is one of the larger frequently active cone volcanoes in New Zealand, marking the southern end of the Taupo Volcanic Zone. The active crater normally contains a warm lake (Crater Lake) at 2500 m elevation, being surrounded by permanent snow and ice fields and is 500 m in diameter. Lahars produced by explosion through the lake have posed the major hazard during historic eruptions.

Significant Ruapehu eruptions occurred in 1861, 1895, 1903, 1945, 1969, 1971 and 1975. Nearly all produced lahars in valleys draining from the summit. In December 1953, catastrophic failure of an ice and debris dam on the crater rim sent a $1.6 \times 10^6$ m$^3$ lahar down the Whangaehu River. This lahar destroyed a rail bridge 38 kilometres downstream causing a passenger train to plunge into the flooded river, claiming 151 lives.

The main eruption sequence associated with the 1995 eruption started with 2 lahar-producing phreatomagmatic explosions on 18 and 20 September. This followed 9 months of fluctuating Crater Lake temperatures and numerous small phreatic eruptions (Figure 1). Three spectacular large-scale explosions through Crater Lake on 23 September ejected lake water, blocks and scoria bombs about the summit area. Lahars were generated down three valleys, some through ski-fields. Further significant peaks of activity occurred on 25 September and 7, 11 and 14 October (Nairn and Scott, 1996). These events emptied the $10^7$ m$^3$ Crater Lake, and dispersed about 0.2 km$^3$ of ash and scoria downwind of the volcano (Figure 2). Following cessation of activity in November, a Crater Lake started to reform on the crater floor.

Figure 1: Time series plot showing chemical and seismic parameters associated with Crater Lake (Courtesy of Sherburn and Bryan).
Eruptive activity recommenced on 17 June 1996, following a short (9 hr) but intense period of volcanic tremor on 15 June. The initial eruptions soon removed the small Crater Lake, producing lahars into one valley and a tall eruption column and significant ashfalls across the Bay of Plenty (Figure 2). Enhanced activity occurred between 17 - 19 June, 5 - 11, 15 - 17 and 20 - 28 July. As there was less water involved in the 1996 (smaller lake) eruption, more ash-rich eruptions occurred, producing a different style of eruption from the 1995 activity.

**RUapeHU SURVEILLANCE AND Eruptive Activity**

Surveillance of Ruapehu included tracking variations in lake temperature, water chemistry and lake level/overflow, in addition to ground deformation and seismicity. The Tongariro volcano-seismic network consists of a network of telemetered seismometers to identify volcanic earthquakes and continuously monitors volcanic tremor using a real-time PC-based system (Hurst, 1985; Hurst and Sherburn, 1993).

The Crater Lake acts as a chemical trap and serves as a calorimeter for the heat and mass fluxes from the underlying magmatic-hydrothermal system. Before the 1995 eruptions, the lake was about 150 m deep, over a breccia filled vent in which a pool of molten sulphur controlled heat flow into the lake (Hurst et al., 1991; Christenson, 1994). In-flowing magmatic gases (HCl and SO₂) acidify lake waters to pH<1. Acid fluids leach magnesium from hot vent rocks, so that lake water concentration and Mg/Cl ratios increase when new magma is intruded into the vent system or lake floor (Figure 1). When there is no Crater Lake, it is possible to make COSPEC measurements of the gas levels in the volcanic plume.

A network of survey marks about the Crater Lake has been used to monitor ground surface deformation about the crater. Usually monthly measurements were made of the crater dimensions and, on a less regular basis; tilt levelling measurements have been made. An ARGOS monitoring system, including lake temperature and acoustic noise, was also utilised at Crater Lake.
The 1994-95 sequence

In December 1994 the temperature of Crater Lake started to rise from a low 15°C in November 1994. The temperature of the lake frequently fluctuates between 15 and 40°C over periods of 6 - 9 months. On 21 December the Alert Level was raised to Level 2, having been at Level 1 since July 1994, when they were introduced.

Minor phreatic eruptions commenced about 11 January 1995 and continued into February. On 4 April the Alert Level was lowered as activity declined, along with the lake temperature. When the lake temperature started to rise again, 20 days later, the level was again raised to 2. On 29 June 1995 the largest volcanic earthquake since 1988 occurred, and an accompanying phreatic eruption destroyed the ARGOS monitoring installation. Phreatic eruptive activity continued in July. On 12 September, the declining activity lead to the Alert Level being lowered to 1.

Following unobserved, but seismically recorded activity on 18 and 20 September, the Alert Level was raised to 2. Small lahars were generated into the Whangaehu River by these events. Nine hours after the 20 September event, the temperature of Crater Lake was 48°C with an overflow >1000 l s⁻¹, and abundant fresh scoria clasts had been washed into the outlet area. Geodetic measurements indicated a small (21 mm) inflation about the crater, since 15 August. Increased Mg concentration indicated new magma-water interaction, while the highest SO₄ levels ever recorded, suggested an increased influx (>500 tons/day) of SO₂ gas. Low frequency volcanic tremor which commenced 18 September continued.

1995 Eruption Sequence

The main eruption sequence began on 18 September with the largest lahar-producing eruption since 1975. On 23 September, a series of three spectacular large-scale explosions through the Crater Lake ejected lake water, blocks and scoria bombs onto the summit. Large lahars were also generated down three valleys, some through ski-fields which had closed only 57 minutes earlier. The Alert Level was raised to 3 following this activity. Smaller eruptions continued into 25 September, when volcanic earthquakes and tremor intensified (Alert Level raised to 4). The eruptive activity was predominantly surtseyan in nature. Variable but enhanced activity continued through to 29 September.

Following three days of lesser activity, the Alert Level was lowered to 3 on 2 October 1995. During a resumption on 7 October, which produced ash columns to over 8000 m, it was anticipated the Alert Level could rise to 4, but the activity was not sustained long enough to warrant this. The small volume of water remaining in the lake basin greatly reduced the lahar generation potential. The eruptions were significant but not hazardous.

Crater Lake was finally emptied during an 8 hour explosive eruption on 11 October. Ash fell to 250 km downwind, marking a distinct change in the style of eruptive activity (Figure 2). Another voluminous ash eruption on 14 October was followed by intermittent explosive activity through late October, when eruptions ceased. Crater Lake started to reform in November.

1996 Eruption Sequence

Following the decline in November 1995 and as the new Crater Lake formed, little activity was noted from the volcano until March 1996. In March, a small lava spine was extruded into the lake and formed a small islet. Only minor changes in seismicity accompanied this intrusion (Figure 1).

On 15 June, high-amplitude low-frequency volcanic tremor started and was sustained for over 10 hours. A scientific alert bulletin was issued but the alert level remained at 1. Although the amplitude of the tremor declined to background levels on 16 June, the frequency content remained very low (~1 Hz). Tremor amplitude started to rise again at about 0630h DT on 17 June, and the first eruptions were observed by 0648h DT. These eruptions produced a lahar down the Whangaehu Valley and soon developed into a major sustained explosive eruption that lasted to 18 June. Ashfall occurred for hundreds of kilometres downwind of the volcano and several airports were closed. The alert level was raised to 3 during this activity.

From 19 June to 5 July intermittent explosive ash eruptions occurred, but from 5 to 11 July a period of enhanced activity occurred. This produced significant ashfalls on and beyond the volcano and SO₂ output reached 6000 t/day. Activity declined after 11 July, re-intensifying again on 15 - 17 July, with predominantly strombolian eruptions and ash emissions. This activity ceased abruptly on 18 July. The fourth and final phase of enhanced activity during 1996 occurred from 20 July to 28 July. Continually weakening ash eruptions continued through August into early September as activity waned.
1995-96 RUAPHEHU ERUPTION IMPACTS

The 1995-1996 Ruapehu eruptions caused disruption to several key infrastructure sectors; in particular transportation, water supplies and electricity distribution. The early eruptions through the Crater Lake presented the immediate problem of lahars. Later eruptions were drier and more sustained, depositing ash on land up to 250 km from the volcano, with ash plumes continuing offshore.

Lahars

Most of the lahars and certainly the larger ones were confined to the Whangaehu River valley between 18 September and the end of October 1995. Here they have had a major effect on the riparian environment, in places actively degrading the channel by 5 m and in most places aggrading the channel up to 2 m. The lahars irreparably damaged a monitoring gauge at the foot of the volcano, a lahar warning gauge was silted up, and damage to siphon pipes on an aqueduct beneath the Whangaehu River has led to NZD 250,000 worth of river alignment. Another economic effect was, due to river aggradation, the river channel began eroding a steep cliffside across which a road crosses, causing partial subsidence and NZD 35,000 of repairs by the local district council.

On 28 October, a lahar triggered by heavy rainfall on the mountain’s tephra cover, descended the Mangatoetoenui Stream and contributed substantial volumes of sediment to the Tongariro River just above the Rangipo Hydro-electric Dam. Immediately a sand bar developed and gradually the hydro-lake began to fill with sandy sediment. It was thought that the dam was designed to cope with these types of lahar events, and through one gate in the dam, the water level could be reduced to allow the passage of a lahar, or to rid the hydro-lake of accumulated sediment. This did not work and the major volume of sediment became trapped behind the main part of the dam. This led to decreased power generation and loss of income.

When the dam was allowed to refill, sandy sediment in the river passed through the screens at the Rangipo intake and has led to excessive wear on the turbine blades at the underground power station. This was only noticed on 22 December 1995. The estimated damage to the blades is in the order of NZD 6 million. By 25 April both turbines were shut down because monitoring indicated at these rates, with 5 tonnes of sediment having passed through the turbines, there was only 7 month’s life left for the station, which provides 2% of New Zealand’s electricity. Lost generating capacity may be substantially higher than the damage to the blades.

Now new blades have been installed, which are stainless steel with a “ceramic and plasma nitride” coating, designed to resist the wear, and claimed to be a world first.

Tephra

Air transportation was the most widely affected sector by the larger scale ash eruptions in October - November 1995 and in June-July 1996. The Civil Aviation Authority restricted air-space during eruptive episodes because of drifting ash and the sulphur dioxide haze (vog), resulting in cancellation of many flights and re-routing of others away from the exclusion zones. This has caused major disruption to operations, with up to eight airports affected at times and flow-on effects well beyond these areas.

We are currently still working on obtaining full estimates on the costs of this disruption but currently we have evidence for NZD 0.7 million sustained by the airlines. The physical and financial impact of the ash on airports is demonstrated at Rotorua Airport for example where it costed NZD 10,000 in 1996 for ash removal alone.

On three occasions, 25 September, 11-12 and 14-15 October 1995, ashfalls led to closure of the Desert Road which passes east of the volcano. On two occasions this was initially because of total invisibility for driving, both accompanied or followed by rain that left a slippery sludge on the road. This required removal before safe driving conditions could be restored.

Contamination of water supplies was a common concern but only slight effects were noted on public water supplies. Any major problems are likely to be encountered where roof-fed supplies show minimal dilution with small volumes of water in storage. The public were advised to disconnect roof-fed water tanks as a precaution and those that did not, showed drops in pH. A number of cases of minor corrosion of metal roofs have been reported and some
Earthquake Commission settlements have been paid out for this damage. The major unexpected finding was a huge increase in water usage in Rotorua and Te Puke in the week of 17 June 1996, such that demand almost led to failure of the system. Several people fell off roofs while removing ash with resultant broken bones.

Whenever the ash landed wet or was moistened by later rains, pitting was observed on vehicle paints and water soluble measurements showed extraction of arsenic, chromium and copper from tanned wood surfaces with aluminium and zinc from vehicle paints.

Wet volcanic ash falling on the electricity power lines along the Desert Road early in the 1995 episode lead to shorting. This caused voltage fluctuations and problems to electrical equipment throughout the North Island. This required the thermal power stations to the north to be started up to ensure security of the system. The power lines and pylons were due for maintenance and a team began the task of cleaning the lines and painting the pylons to reduce erosion. Both water blasting and hand brushing techniques were employed.

The impacts of tephra on agriculture and animal health are summarised in Appendix A.

Overall Economic Impacts

True estimates as to the economic impacts of the Ruapehu eruption are extremely difficult to determine since such events are rare and there are no in-place systems for measuring the economic losses. A number of organisations have reported direct losses, additional unbudgeted expenditure, and non-performance because work was delayed to allow additional staff time to respond to the eruption, but few have calculated an actual dollar cost of the eruption to their organisation. There is a clear reluctance among some organisations to make this calculation, as they return to ‘normal’ operations.

Three ski-fields on Ruapehu were closed on 24 September 1995, with two briefly reopening for a few days. Further closures resulted from ash eruptions at the beginning of the 1996 ski season. The closures resulted in the termination of several hundred jobs in the ski industry and related services. From a consultant’s survey conducted for the Ruapehu District Council, the economic losses for the region are estimated at NZD 35 M for 1995 and NZD 85 M for 1996.

Data can also be obtained from the Earthquake Commission. For 1995 there were 22 claims with total payments so far of about NZD 4,700. For 1996 there were 179 claims and so far NZD14,600 has been paid out. These are relatively low numbers for which about half the payouts were to insurance assessors. These figures clearly show how, for tephra eruptions of similar magnitudes, the impact on distant communities is highly dependent on the wind directions. Clearly more damage was sustained in the Rotorua District by the June 1996 eruptions than in the combined Gisborne, Wairoa and Southern Hawkes Bay districts by the October 1995 eruptions.

DISCUSSION

After the eruption had been on-going for 4-5 weeks, many organisations, ranging from Government Ministries, through industry, to regional and local territorial agencies, had volcanic contingency operations in place and were starting to realise some of the financial implications. Although no organisations or agencies had effective plans for their contingency operation, with respect to the scientific alert levels, they had quickly adjusted their respective operation in terms of the alert levels.

During November 1995 the volcanic activity continued to decline but remained “significant” in scientific terms, therefore the alert level remained at 3. As costs to affected organisations or agencies started to mount, so did critical examination of the table of alert levels and the rules for defining level changes. As discussed elsewhere (Scott, 1996), the table was specifically designed for an escalating situation. Any substantial eruption of a volcano could change parameters associated with the volcano. To try and incorporate these into an alert system would only be confusing, as these could not be predicted in advance of the activity. This important but subtle facet was appreciated by the scientific community, and partially elsewhere; however the implications soon became the focus of debate. One by product of this was the political reality of when were the alert levels to be reduced, and on what basis were these decisions to be made. The Ministry of Internal Affairs formed a working party, which ultimately approved a guideline for defining the return to level 2. Parameters included; days since last major ashfall, days since seismic ground velocity exceeded 10 μms⁻¹, SO₂ flux at 1000 t/day or less, and no significant ground deformation. The alert level was officially lowered to level 2 on 29 November 1995 when these parameters were satisfied.
The 1995, Ruapehu eruptions have also raised issues of how the scientific response to a natural disaster of regional to national scale should be funded. It was quickly realised that the funding levels from the Foundation for Research Science and Technology (FRST) to provide an effective minimum level of volcano surveillance, was not adequate to fund an effective response to an eruption of this magnitude. In 1995, the response could not be funded out of the long-term FRST contract for minimum effective surveillance at pre-eruption levels and required special additional appropriations from national Government. The process of obtaining this funding created additional pressures at a time when scientific monitoring and hazard assessment activities were stretched.

Due to the relative timing of the introduction of a “volcanic impacts” annexe into the National Civil Defence Plan (November 1994), incorporating the Table of Alert Levels and the first major eruptions in 1995, no organisations or agencies had sufficient opportunity to incorporate this into their own contingency planning. However, the minor eruptive activities in 1995 served as a good introduction and the ski-field operators, land administrators, local civil defence and media were starting to be aware of the alert levels and consequential actions of them. Organisations distal to the volcano were yet to discover them.

Much was learnt from the 1995-96 eruptions, allowing the present table of alert levels to be developed (Table 1 in Scott and Neill, this volume). The major outcomes identified were the need to set a base level, i.e. 0, and the need to separate the continuously active volcanoes from the dormant volcanic centres or fields. The numbering hierarchy was easily understood, with all concerned being able to identify that 2 is worse than 1, as 3 is worse than 2, etc. This would not have been achieved with colours as used in some alert systems. Also the alert system has no connotations of time, which became a short-fall of the system used during the 1994 Rabaul eruptions (Nairn and Scott, 1995, Finnimore et al 1995, Davies, 1995) it only describes the current status of the volcano. It does not attempt to provide a significant predictive component.

The New Zealand Civil Defence Act creates a civil defence capability at all three levels of government. During the 1995 Ruapehu eruptions, it was necessary to transfer scientific information to each of those levels, and downline to critical industries and the media. Ruapehu 1995 proved an effective test of this complex system. In particular, the need for rapid decision-making meant direct one-on-one contact between the scientific response team and key individuals in regional and local government and industry was essential. This however did stretch resources.

CONCLUSION

In conclusion, the scientific alert levels worked well and provided all responding organisations or agencies, the media and general public with a system they could relate to. As part of the eruption debriefing process, many organisations are reviewing their procedures and operations. It has not been found necessary to adjust the Table of Alert Levels, but it has become common for responses to be set in terms of the alert levels. Many basic aspects of future responses to volcanism in New Zealand will be dictated by the alert level.

Our current accumulated totals for the effects of the eruptions in direct damage and lost income are NZD 46 M for 1995 and NZD 98 M in 1996 with many figures still to be obtained.

The 1995-1996 Ruapehu eruptions were relatively small in comparison to many of the past eruptions from the volcanoes of the central North Island, but their consequences highlight the vulnerability of communities facing the 21st century to even small eruptions. With increasing development and population growth in the area the risk from similar or larger eruptions will continue to increase.

REFERENCES


**APPENDIX A**

**THE IMPACTS ON AGRICULTURE AND ANIMAL HEALTH OF THE OCTOBER 1995 AND JUNE 1996 RUAPEHU TEPHRA FALLS, NEW ZEALAND**

Cronin S.J., Neall V.E., Hedley M.J. and Robinson B.*

Department of Soil Science, Massey University, Private Bag, Palmerston North, New Zealand. [S.J.Cronin@massey.ac.nz]

*Department of Chemistry, Otago University, Dunedin, N.Z.

On October 11 and 14, 1995, two eruptions of Ruapehu deposited up to 0.04 and 0.01 km³ of tephra respectively NE and SE of the volcano. On 17 June 1996 up to 0.01 km³ of tephra was erupted and fell N of the volcano. In total 25,000 km² of land in primary production was covered by between 3 and 55 tonne of ash per hectare. Sulphur (S) made up between 0.7 and 3.6 % by weight of the fallen tephra with 30-70 % of this in a water-soluble form. In October 1995, this caused isolated instances of mis-mothering and loss of lambs. Soluble fluorine ranged between 74 and 27 μg g⁻¹ in the tephra and was attributed to isolated outbreaks of sheep deaths due to acute fluorosis. Other stock died of starvation due to the tephra covering of pastures, coupled with stress of pregnancy and poor condition following winter. Overall stock losses were not high and in the worst affected areas they amounted to 2.5-3 %.

Tephra deposition led to an immediate drop in soil pH. Soil S status rose to 10-25 times pre-tephra fall levels, which was rapidly accompanied by increased pasture S concentrations. Pasture Selenium (Se) concentration also increased to 2-5 times previous levels. Most North Island soils are deficient in S and Se; thus the tephra fall was of benefit, particularly to pastoral farming. Elevated S and Se levels persisted for 3-9 months following tephra deposition, depending on soil properties. The tephras contained low concentrations of other major and trace nutrient elements and were very low in water-soluble, toxic heavy metals.

AN EXAMPLE FROM VANUATU:
THE AOBA (AMBÆE) VOLCANIC
CRISIS 1994-1995

P. A. M. Wiart¹ and M. Lardy²
¹ University of Cambridge, UNITED KINGDOM
² ORSTOM BP 76, VANUATU

INTRODUCTION

Aoba (also known as Ambae) Island is situated on 15°24’S and 167°50’E between Santo Island to the west and Pentecost Island to the east. The island is a large basaltic volcanic structure that reaches 1496 m above sea level. The volcano rises a total 3900 m above its base on the surrounding sea floor, which explains its total volume 2500 km³. It is elongated along the SW-NE axis. The summit region of Aoba consists of two nested calderas, the largest being 5 km in diameter. Three crater lakes are present in the caldera. The active crater lake, Manaro Voui has a diameter of about 2.1 km. Lake Manaro Lakua (with a diameter of 1.3 km), and the periodical dry Lake Manaro Ngoro are located at the eastern and western ends of the caldera respectively. The geological development of Aoba has been described in detail by Warden (1970) and has been further summarised by Robin et.al (1993).

Volcanic activity at Aoba is not well known, despite the volcano being the biggest structure in the archipelago (Robin and Monzier, 1994). We must keep in mind that reports of historic volcanic activity have not been well recorded. It appears that many of the periods of activity may have been forgotten or noted only through references in local legends. However, following geological surveys and investigations of the legends from the island, it is possible to develop a more detailed understanding of the activity that has occurred at Aoba. Table 1 provides a record of known eruptions that have occurred at Aoba volcano.

TABLE 1: Eruption Chronology of Aoba Volcano

<table>
<thead>
<tr>
<th>Year/month</th>
<th>Character of Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1575 +/- 54</td>
<td>Explosions from the central crater; new lakes formed within the caldera.</td>
</tr>
<tr>
<td>1670</td>
<td>Eruption from a radial fault on the western flank; lava flows were produced.</td>
</tr>
<tr>
<td>1870</td>
<td>Eruption; mud flows (lahars) were produced.</td>
</tr>
<tr>
<td>1914</td>
<td>Eruption from the central crater; landslides and lahars occurred; 1 village was destroyed on the eastern flank; 100 (est) inhabitants killed.</td>
</tr>
<tr>
<td>1966 August</td>
<td>Steaming of the crater lake was reported.</td>
</tr>
<tr>
<td>1971 April</td>
<td>Steaming of the crater lake was reported.</td>
</tr>
<tr>
<td>1991 July</td>
<td>Steaming of Lake Voui was reported; aerial observations reported that the water was discoloured and that areas of burnt vegetation were present around the crater rim.</td>
</tr>
</tbody>
</table>

When investigating volcanic centres such as Aoba, evaluations of records outlining the eruptive activity is crucial, which provide information concerning the type of eruptions that have occurred, along with the extent of their effects. More importantly, reports contain information on past volcanic disasters and indicate the potential for similar events to occur in the future.
THE 1994-1995 CRISIS ON AOBA

Volcanological aspects of this crisis have been described by Wiart (1995) and are summarised in Table 2.

TABLE 2: Chronology of the 1994-95 Crisis

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-5 December 1994</td>
<td>Increase in seismicity noted by the population of Ambae.</td>
</tr>
<tr>
<td>7 December 1994</td>
<td>Air reconnaissance of the volcano conducted; crater lake reported to be calm.</td>
</tr>
<tr>
<td>8 December 1994</td>
<td>Initial warning given to the National Disaster Management Office, concerning possible activity.</td>
</tr>
<tr>
<td>1 March 1995</td>
<td>Meeting of NDMO, UNDHA and ORSTOM personnel at the police headquarters.</td>
</tr>
<tr>
<td>3 March 1995</td>
<td>Dark ash/smoke column (~3 km high) observed on the top of Aoba Island by the local residents; also observed from the surrounding islands.</td>
</tr>
<tr>
<td>4-6 March 1995</td>
<td>Continuous white steaming of the crater lake observed; high seismicity recorded.</td>
</tr>
<tr>
<td>8 March 1995</td>
<td>Alert issued for the entire island; a zone of 10 km radius around the crater lake is declared high risk for the population, 3000 habitants are directly affected.</td>
</tr>
<tr>
<td>13 March 1995</td>
<td>Beginning of the decrease of the seismicity; regular decrease in the seismicity continued during the following months; persistent steaming of the crater lake reported for some time.</td>
</tr>
</tbody>
</table>

Although initial seismic activity as early as 1 December 1994 was noted by the local inhabitants of Aoba, it was not until 3 March 1994 that a steam plume from the crater was observed. It is, however, important to note that the Vanair pilots did report activity at the surface of Lake Voui from 1-2 March 1994. These reports, which were subsequently communicated to Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM), described the situation on the 1 March 1994 as:

“...lake calm; discolouration; bubbles (gas escaping) around the edge of lake in numerous places...”

and on 2 March 1994 as:

“...steaming all over; surface rough; bubbling up in centre; black sediment blowing up...”

A phreatic explosion on the morning of 3 March 1995 generated a vapour-and-ash column ~3 km high. On the morning of 5 March, a vapour plume rose ~500 m. It is possible that vapour plumes were emitted over a period of several days, but were not observed at other times because of the thick clouds that usually hide the summit area. The activity of 3 March was centred on an area between the two small islands in the Lake Voui (Figure 1). A drop in the level of Lake Voui that began on 6 March was visible in photographs taken on 20 March, during the mission ORION by the Royal New Zealand Air Force (Figure 1). The distinction between Lake Voui in the fore-ground and Lake Manaro Lakua in the background is obvious. Convection cells, ~300-400 m in diameter, are clearly visible within Lake Voui (Figure 1). The vegetation around Lake Voui has been burnt by the sulfurous gases. During another flight on 6 April, the level of the crater lake had dropped ~2 m.

On 26-27 June, a group of ORSTOM scientists reached the crater lake by helicopter, and landed on one of the islands in Lake Voui. The lake level had dropped ~5 m below the maximum, which was determined by recent vegetation. Water temperatures measured around the most accessible parts of the island averaged 38-40°C, with highs of 63-67°C. The waters of Lake Voui were sampled and analysed in the ORSTOM-Noumea laboratory centre. These first in situ scientific analyses (Table 3) confirmed the strong acidity (pH = 2.2) of the lake. Sulfur deposits were noted at a number of localities, and gas bubbles were coming from numerous fissures at the edge of the island (Figure 2). Several blocks of dried mud (40-50 cm in diameter), ejected during the phreatic explosion at the beginning of March were still visible, but no juvenile material was identified.

This reconnaissance mission, sponsored by the National Disaster Management Office (NDMO) of Vanuatu, confirmed the strong links developed between the two organisations.
Figure 1: Lake Voui in the foreground and Lake Manaro Lakua in the background as observed 20 March 1995 (Photo Mission ORION - Royal New Zealand Air Force).

Figure 2: View of the landing site 27 June 1995. The waters of Lake Voui surrounding the island are steaming. Sulfur deposits can be observed on the edge of the island. Note the dead vegetation (Photo Mission ORSTOM).
TABLE 3: Analysis of Water Samples from Lake Voui, 27 June 1995

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cl meq/l</th>
<th>SO$_4$ meq/l</th>
<th>Ca meq/l</th>
<th>Mg meq/l</th>
<th>Na meq/l</th>
<th>K meq/l</th>
<th>Sum anions</th>
<th>Sum cations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A # 1</td>
<td>89.00</td>
<td>186</td>
<td>14.10</td>
<td>160.85</td>
<td>46.65</td>
<td>11.13</td>
<td>275.0</td>
<td>267.4</td>
</tr>
<tr>
<td>B # 1</td>
<td>95.00</td>
<td>178</td>
<td>14.35</td>
<td>160.62</td>
<td>46.05</td>
<td>10.96</td>
<td>273.0</td>
<td>266.5</td>
</tr>
<tr>
<td>B # 5</td>
<td>91.00</td>
<td>178</td>
<td>14.47</td>
<td>153.83</td>
<td>43.42</td>
<td>11.21</td>
<td>269.0</td>
<td>256.4</td>
</tr>
<tr>
<td>C # 8</td>
<td>90.00</td>
<td>171</td>
<td>14.44</td>
<td>152.58</td>
<td>42.58</td>
<td>11.72</td>
<td>261.0</td>
<td>254.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH</th>
<th>PO$_4$ mg/l</th>
<th>SiO$_2$ mg/l</th>
<th>Fe mg/l</th>
<th>Mn mg/l</th>
<th>Ni mg/l</th>
<th>Al mg/l</th>
<th>NO$_3$ mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>A # 1</td>
<td>2.20</td>
<td>9.50</td>
<td>560</td>
<td>433</td>
<td>80.6</td>
<td>0.39</td>
<td>76.6</td>
</tr>
<tr>
<td>B # 1</td>
<td>2.23</td>
<td>8.80</td>
<td>560</td>
<td>433</td>
<td>73.5</td>
<td>0.39</td>
<td>77.2</td>
</tr>
<tr>
<td>B # 5</td>
<td>2.26</td>
<td>8.40</td>
<td>554</td>
<td>420</td>
<td>72.2</td>
<td>0.37</td>
<td>74.8</td>
</tr>
<tr>
<td>C # 8</td>
<td>2.27</td>
<td>7.30</td>
<td>548</td>
<td>414</td>
<td>71.2</td>
<td>0.35</td>
<td>73.3</td>
</tr>
</tbody>
</table>

MONITORING TECHNIQUES

During the crisis, a variety of monitoring techniques were used and included:

- in situ observation;
- seismological monitoring conducted by a team during the three-week campaign;
- on-line monitoring system linked to ORSTOM in Port Vila via a telephone connection; and
- fixed monitoring system (telemetry connection).

Following initial aerial observations of activity by ORSTOM, after activity was first reported on 3 March. A seismic monitoring device was located on the island from 4 March, which immediately began to record strong continuous tremors. Although seismic tremor remained at constant levels during 9-13 March, it was, however, of less intensity than during the period of 4-6 March. The monitoring equipment remained on the island, housed in Nabangahake village until June 1995.

COMMUNICATION MANAGEMENT

This crisis highlighted how a number of organisations, the NDMO, ORSTOM and the United Nations Department of Humanitarian Affairs (UNDHA) worked together. Figure 3 provides a diagrammatic representation of these linkages. The following outlines the management of communication during the crisis:

- Regular press releases:  
  - 1 in 1994  
  - 6 in 1995  
  - 1 in December  
  - 3 in March  
  - 1 in May  
  - 1 in July  
  - 1 in December

- Short video produced by ORSTOM and NDMO in Bishlamar
- Volcanic hazard map: Completed but unpublished and not communicated to the population prior to the crisis. This map has been subsequently published (SOPAC, 1995).
- Regular meetings with the local population:
  - Meetings in villages on Aoba
  - Meetings with the Aoba community leaders in Port-Vila (>600 people). These meetings included personnel from the NDMO and ORSTOM
  - Discussions
  - Explanations
Figure 3: Relationship of the major national and regional organisations that played an important role in the Aoba crisis.
CURRENT MONITORING NETWORK

Following the 1994-95 crisis, the entire monitoring network on Aoba has been upgraded. In 1996, a satellite-based (ARGOS) communication system was implemented, which is based in Manaro-Ngoro. During 1997, plans were to install a hydroacoustic monitoring device in Lake Voui to enable signal frequency and lake temperature to be continuously monitored.

CONCLUSION

A number of lessons have been learnt from the 1994-95 Aoba (Ambae) crisis. This ‘real-time’ event provided an opportunity to trial and further develop the different mechanisms employed in the management of natural disasters in Vanuatu, and to generally improve the level of knowledge. The following points have to be noted:

- The interpretation of the seismic activity near Ambae in December 1994, has been, and is still difficult to identify as volcanic tremor. The United States Geological Survey (USGS) located the epicentres at distances of more than 60 km from South Aoba. An alert, however, was given by volcanological authorities, following the seismic events. The population of Aoba was not conscious of the possible danger until after the phreatic activity of 3 March was observed.

- The response to the crisis worked efficiently. Due to the isolated nature of the island, if was difficult to obtain reliable information on the situation.

- It has been shown that help of all other external elements can improve the monitoring of the developing threat. In particular, a mechanism for communication should be established between Vanair and NDMO or ORSTOM. During this crisis, the information reported by the Vanair pilots proved to be crucial. Other mechanisms, including remote sensing techniques should further developed in the future.

- The lack of a monitoring system was remedied by the installation of a basic instrument. Use of basic monitoring devices allows on-site installation within short time frames if they are available. It is crucial that these devices should installed, or if not, be available and ready to be installed, following the first indication of a developing situation.

- The strong and effective interaction between scientists, politicians and natural disaster managers was reinforced. Following the meeting with UNDHA, the interaction between ORSTOM and NDMO was further improved. These strong links and effective coordination helped to manage the crisis. The development of the initiatives from UNDHA should be encouraged elsewhere.

- We should be reminded that this crisis did not cause the destruction of any property or any loss of life, only because the activity returned to background levels. If an eruption had occurred, the consequences could have been dramatic, and any parties involved during the crisis could have done nothing to stop it, hence the population of Aoba are very lucky!

REFERENCES


NIUAFO’OU, TONGA: VOLCANIC HAZARDS AND THE RISK FROM FUTURE ACTIVITY

P. W. Taylor
Australian Volcanological Investigations, AUSTRALIA

ABSTRACT

Niuafo’ou Island, located within the northern Lau Basin, is Tonga's most active volcano. Due to its degree of habitation and remoteness, it must be considered to be a ‘hazardous’ volcano. Effusive and explosive activity has occurred throughout the development of the island. At least 10 periods of activity have occurred since 1800, producing extensive lava flows and tephra deposits. Among the hazards, lava flows have been the most frequent and have had the most direct effect on the island’s population. The effusion of lava resulted in at least 25 deaths in 1853 and the complete evacuation of the island, following the 1946 eruption. Tephra falls, although less frequent, have also caused considerable damage to both buildings and vegetation and may have indirectly resulted in a number of deaths during the 1886 eruption. Other hazards, including pyroclastic surges, volcanic gases/acid rain, ground fracturing and earthquakes have had only a minor effect on the island’s population. The frequency of recorded eruptions and the distribution of the resultant products have been used to construct preliminary hazard maps for lava flows and tephra falls. The zone of highest risk from lava flow is confined to the lower seaward flanks of the volcano. Although the entire island is at risk from a tephra fall produced during explosive activity, the western quadrants of the island are at highest risk. Perception of the risk is sometimes complex and, in Niuafo’ou’s case, this is true. The degree of perception varies considerably within the population. The older generation have a definite perception of the risk. In contrast, the younger generation, although being aware of the hazards, have a lesser perception of the risk to life and property. Because of the strong cultural traits of the Niuafo’ouans, they have accepted the high risk from future activity and the ties to family and traditional lands have overridden the high risk. There is, however, still a fear evident in the population that can be attributed to the risk of future activity. Because of Niuafo’ou’s remoteness and the high risk accepted by the population, the only effective and realistic form of mitigation against the hazard, particularly lava flows, is the strict control of village location. This has been accomplished in part by the fact that all villages are now located within zone 3 and within the eastern quadrants of the volcano. Further steps must be taken by the authorities to enhance the population's perception of the hazards. This could be achieved by an education program for the island’s population and the implementation of a permanent volcano monitoring program, involving both seismic monitoring and periodic observations of the volcano by trained personnel. Interpretation of the data collected during such a program would allow forecasts of future activity to be made.

INTRODUCTION

The Kingdom of Tonga, like many other Pacific nations is prone to many geological, geophysical, oceanographic and meteorological hazards, being that it is located in an oceanic island arc setting. Hurricanes have caused extensive damage to buildings, crops and have accentuated the effects of coastal erosion on many islands of the group. Earthquakes have also frequently caused considerable damage, but have had more localised effects. On several occasions during the last 100 years, tsunamis have also caused concern because of the effects on coastal regions. The direct effects of volcanic eruptions, however, have generally been confined to the chain of active centres – the Tofua Volcanic Arc, located to the West of the main island chain (Figure 1). Despite the frequent occurrence of hazardous natural phenomenon, few studies of the effects of natural hazards have been conducted. The need for improved training and preparedness strategies has been outlined by Hamnett (1983). One study specific to Tonga, was completed during the late-1970’s (Lewis 1978, 1981, 1982). It addressed disaster vulnerability and mitigation in general terms, but gave little emphasis to the individual hazards, e.g. volcanic hazards.
Volcanic activity that has occurred on several of the Tongan volcanoes, specifically Tofua in 1854 and Niuafo’ou in 1946, has resulted in the evacuation and relocation of the inhabitants. Although Tofua remains uninhabited, Niuafo’ou was resettled in 1958 and today supports a population of approximately 850. Due to the frequency of eruptions and the remoteness of Niuafo’ou, the population is at high risk from the effects of future eruptions.

Niuafo’ou

Niuafo’ou, the emergent summit of a basaltic volcanic pedestal, is located in the central part of the northern Lau Basin (Figure 1). The island has been built by volcanic eruptions over a period of at least several hundred thousand years.

With at least 10 periods of activity (Table 1) having occurred since the early 1800’s, Niuafo’ou is Tonga’s most active volcanic centre. Both effusive and explosive activity has occurred throughout the volcanic history of the island, producing extensive lava fields and deposits of tephra. An initial shield phase was dominated by voluminous lava flows, probably originating from a central vent area. A subsequent cone-forming phase involved alternating explosive and effusive activity, resulting in a sequence of interbedded lava flows and tephra layers. These products may have also originated from a central vent area. Post-caldera activity has also been characterised by both explosive and effusive eruptions. Typically, Hawaiian-type effusive activity has been restricted to tangential fissure systems on the lower seaward slopes of the island. The historic eruptions have produced extensive lava fields on the northern, western and southern flanks, while prehistoric but recent lava flows have been observed on the
eastern flank. Less frequent phreatomagmatic, Surtseyan-type explosive eruptions have been confined to within the caldera, sometimes blanketing the island with tephra and building cinder/tuff cone complexes. Because of the structural complexities of the outer flanks, minor phases of phreatic activity during recent effusive eruptions have built small pyroclastic cones along several of the fissures. A detailed study of the volcanic processes that occur on Niuafo’ou has been reported elsewhere (Taylor 1991). The major geological features of Niuafo’ou are given in figure 2. This study also highlighted the need for a detailed assessment of the hazards associated with the frequent volcanic activity to be conducted.

Figure 2: Geological map of Niuafo’ou (after Taylor 1991), showing the gross relationships of the major geological units.
TABLE 1: HISTORIC ERUPTIONS OF NIUAFO’OU - THEIR CHARACTER, LOCATION AND EFFECTS

(After Taylor 1991; Simkin and Seibert 1994)

<table>
<thead>
<tr>
<th>Eruption</th>
<th>Character</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1814</td>
<td>Explosive</td>
<td>Within the caldera, location unknown.</td>
</tr>
<tr>
<td>1840</td>
<td>?</td>
<td>Location and character unknown.</td>
</tr>
<tr>
<td>1853</td>
<td>Effusive</td>
<td>SW flank; ‘Ahau village destroyed.</td>
</tr>
<tr>
<td>1867</td>
<td>Effusive</td>
<td>SSW flank.</td>
</tr>
<tr>
<td>1886</td>
<td>Explosive</td>
<td>Within the caldera, NE side behind the village of Mata’aaho.</td>
</tr>
<tr>
<td>1912</td>
<td>Effusive</td>
<td>W flank, south of Futu village.</td>
</tr>
<tr>
<td>1929</td>
<td>Effusive</td>
<td>W flank; Futu village and arable land destroyed.</td>
</tr>
<tr>
<td>1935-36</td>
<td>Effusive</td>
<td>S flank; Petani village threatened, relocated as a result of eruption.</td>
</tr>
<tr>
<td>1943</td>
<td>Effusive</td>
<td>SW flank; most crops destroyed.</td>
</tr>
<tr>
<td>1946</td>
<td>Effusive</td>
<td>N flank; Angaha village destroyed, island completely evacuated December 1946; not resettled until 1958.</td>
</tr>
</tbody>
</table>

This paper will: outline the volcanic hazards affecting Niuafo’ou and assess the relative risk of the population from the hazards; outline hazard maps that have been constructed for lava flows and tephra falls; outline the population's perception of the hazards and the risk from future eruptions, and the need for the development of an education program to ensure that the awareness of the population is increased; outline an effective mitigation program against the hazards; and outline the need for a practical volcano monitoring program to aid in the forecast of future activity.

VOLCANIC HAZARDS

Among the volcanic hazards, lava flows have been the most frequent and have had the most direct affect on the island's population. Tephra falls, although being less frequent, have also resulted in considerable damage to both buildings and vegetation and may have possibly resulted in an unknown number of deaths. Other less frequent phenomena, including pyroclastic surges, volcanic gases ground fracturing and earthquakes have had only a minor effect on the population.

Lava flows

Lava flows have been erupted from either a single or a series of fissures and have caused the destruction of large areas of arable land of the lower seaward flanks of the volcano.

Two main types of lava have been produced during effusive eruptions on Niuafo’ou. Pahoehoe lava (Figure 3), the most common and voluminous type, has been erupted during all the historic effusive eruptions. Due to the lava's low viscosity, the flows have been thin; averaging from several tens of centimetres to no more than a metre or two in thickness, but have covered extensive areas of the lower flanks. During the initial phases of activity, pahoehoe lava has been erupted along the entire length of the active fissures. Toward the end of the eruptions, however, flows have become channelised, with lava being erupted at point sources along the fissures. The descriptions of the 1929 activity given by Taylor (1991), suggest that lava effusion rates were high with most of the area shown in figure 4 being covered by lava within the first hours, following the commencement of activity. On the other hand, aa lava flows (Figure 5) have been produced during either late-stage activity at individual vents (e.g. 1946) or when pahoehoe flows have slowed and fragmented some distance (commonly >1.5 km) from the vents (e.g. 1929). The more viscous, aa flows produced during the 1946 eruption moved only short distances (typically 20 to 30 metres), originating from breaches in the cinder cones that formed over the fissures during the late-stage explosive phases.

Lava flows have resulted in the destruction of large areas of arable land and tens of hectares of coconut plantations and, on occasions during the 1853, 1929 and 1946 eruptions, entire villages have been destroyed (Figure 6). On only one occasion (i.e. during the 1853 eruption) have lives been lost as a direct result of the lava flows. Although loss of life has been minimal, lava flows present the main threat to the island's population.
Figure 3: Features of pahoehoe lava flows cropping out on Niuafo’ou. Upper Photo: The typically ropy surface of the 1946 flows. White bar is 20 cm. Middle Photo: Lava channels formed, following the build-up of spatter around a vent area. White bar is 50 cm. Lower Photo: Tree moulds formed in the 1946 pahoehoe flows. White bar is 50 cm.
Figure 4: Distribution of the lava flows produced, during the 1929 effusive eruption.

Figure 5: Features of aa lava flows present on Niuafo’ou. Shows the limited extent of the aa flows produced at vents on one of the fissures formed, during the 1946 eruption. The broken line represents the extent of the tephra apron produced during a late-stage explosive phase.
Tephra falls

The evolution of the island outlined by Taylor (1991) has indicated that numerous tephra-producing eruptions have occurred during the development of Niuafo’ou. The most recent eruption occurred in August-September 1886. This eruption covered the entire island with a tephra layer (Figure 7) that varied in thickness from 10 centimetres to more than 6 metres on the western side of the island. The tephra caused considerable damage to both the vegetation and buildings. Although no deaths have been directly attributed to the eruption, eyewitness accounts suggest that acute respiratory problems were experienced by many of the population (Taylor 1991). Todd (1886) and Bonney (1886) have suggested that several deaths may have occurred as a consequence of this eruption.
Taylor (1991) has noted that during latter stages of the 1886 eruption, ballistic fragments were ejected. The ejecta were only found within a 1-1.5 km radius of the vents. Assuming that future explosive eruptions will be of a similar magnitude, the risk from the impact of ballistic ejecta is likely to be confined to within the caldera. The degree of risk to villages, however, would be dependent on the location of the vents within the caldera.
Phases of phreatic activity that have occurred during the effusive eruptions in 1867, 1912 and 1929, have produced variable amounts of tephra. Most of these ejecta have been deposited as tephra aprons within 1 km of the vents. Littoral explosions that occurred during the 1943 eruption were more destructive with a glassy tephra and acid rain being deposited over most of the island. This deposit caused extensive damage to the island’s vegetation. On this occasion the entire harvest of coconuts and root crops was destroyed, resulting in a drastic shortage of food for a number of months.

Several accounts of the 1886 eruption (e.g. Bonney 1886, Phillips 1898) noted that violent thunderstorms were generated and bolts of lightning being produced within the tephra column. Where bolts of lightning struck the ground severe damage was caused, particularly to the vegetation. No human fatalities from lightning strikes were reported.

It is considered the tephra falls and the associated phenomena will occur during future periods of explosive activity would pose a considerable threat to the island’s population.

Pyroclastic surges

Pyroclastic surges that have occurred at basaltic volcanoes have typically travelled only short distances from the vent, eg. < 10 kms. The 1790 eruption of Kilauea, in Hawaii, affected areas as far as 9 kms from the vent area (Swanson and Christiansen 1973, McPhie et al. 1990). Large areas of land were also devastated by the surges that occurred during the 1965 eruption of Taal volcano in the Philippines (Moore et al. 1966, Waters and Fisher 1971). The surges produced during eruptions at Surtsey (1963-66) and Capelinhos (1957-58) were less violent and only moved short distances from the vent areas (Kokelaar 1986).

The pyroclastic surges that occurred during the 1886 eruption of Niuafo’ou were not witnessed but may have been similar in character to those that occurred during the eruptions of Surtsey and Capelinhos, with the effects being restricted to near-vent localities, ie. within 1-2 kms (Taylor 1991). Surge deposits (Figure 8) from these phases of activity have been confined to within the caldera itself. Explosive surge-producing eruptions are much less frequent but the presence of a number of tuff/cinder cones within the caldera, suggests that at least several periods of this type of activity may have occurred in the recent past.

Although no deaths or significant damage have been attributed to pyroclastic surges, they still represent a significant hazard to the island’s population.

![Figure 8: Probable pyroclastic surge deposit located on the northeast edge of the caldera lake. Left Photo: Shows the poorly sorted and generally unstructured nature of the deposit. White bar is 50 cm. Right Photo: Shows the dominantly angular lithic clasts supported in an altered matrix.](image-url)
Volcanic gases and acid rain

Variable amounts of volcanic gas are emitted during most types of volcanic eruptions. The most common gases produced are water vapour, sulphur dioxide and carbon dioxide. Recently, several major disasters have occurred, e.g., Dieng, Indonesia in 1979 (Le Guern et al. 1982) and Lake Nyos in 1987 (Tazieff 1989, Baxter and Kaplia 1989), following the release of toxic carbon dioxide from the volcanic structures. These events caused the deaths of almost 2000 people (Simkin and Seibert 1994) and a large number of livestock. Other hazardous emissions include chlorine, fluorine and carbon monoxide. Mullineaux et al. (1987) also noted that mercury vapour has also been detected at vents on Kilauea.

Although no deaths have been attributed to emissions of volcanic gas on Niuafo’ou, descriptions of the eruptions given in Taylor (1991) indicate that breathing problems were experienced by many Niuafo’ouans during the eruption. The descriptions highlighted that breathing was extremely difficult and that eye irritations were also experienced. Furthermore, the descriptions noted that there was a strong sulphurous odour present throughout much of the eruption. Numerous gas vents were active on the floor of Vai Kona (Figure 9) during 1958 (Richard 1962), 1982 and 1984 (Taylor 1991).

Figure 9: Evidence of recent activity within the caldera. Upper Photo: Active vents on the floor of Vai Kona. Lower Photo: Shows the poorly sorted and generally unstructured nature of the deposit. White bar is 50 cm.
The current (1983 - to date) eruption of Kilauea has highlighted another volcanic hazard that must also be considered in the case of Niuafo’ou. Gerlach et al. (1989) and Wright and Pierson (1992) have emphasised the hazardous nature of lava haze or ‘laze’ (a form of hydrochloric acid bearing acid rain) formed as a result of the interaction of the basaltic lava and sea water and volcanic fog or ‘vog’, which is formed when sulfur dioxide is converted to sulfuric acid near the vent. Both these phenomena have an adverse affect on the local vegetation, as well as causing respiratory or heart conditions. Scott (1995) noted the concern from laze that was produced during the 1995 eruption of Metis Shoal. The descriptions of the 1943 eruption of Niuafo’ou also highlighted the devastating effect of acid rains that fell over much of the island during the eruption. Except for some coconut palms, all of the island’s vegetation was destroyed as a result of this rain (Taylor in prep).

Volcanic gases and acid rain (lava haze and volcanic fog) are thus considered to pose a potential hazard to the population of Niuafo’ou.

**Earthquakes, ground fractures and subsidence**

Ground fractures, subsidence and earthquakes commonly occur simultaneously as a result of the movement of magma beneath the volcano. Mullineaux et al. (1987) have noted that fracturing and subsidence occurs on the summit and in the rift zones of both Kilauea and Mauna Loa volcanoes in Hawaii. Earthquakes, however, are more frequent and widespread and have caused significant damage to buildings and other structures at many locations. It should be noted that seismic events of both volcanic and tectonic origin may occur simultaneously during periods of activity at a volcano.

Periods of seismic activity on Niuafo’ou have preceded all of the eruptions that have occurred since the early 1800’s but no significant damage or deaths have been attributed to this phenomenon. Although none of the reports of the 1985 seismic activity suggested that significant damage occurred, it could be inferred from the estimated intensities of the shocks that occurred during the crisis (intensities of V-VII on the modified Mercalli scale) that minor damage to masonry structures would have occurred.

Until the 1985 crisis, ground fracturing was considered to be of little hazard but, as noted by McClelland et al. (1989) and Taylor (1991), several cracks opened during this activity, one of which opened through the centre of Fata’alua village (Figure 10). No injuries or damage were reported.

![Figure 10: Map of the northeast part of Niuafo’ou, showing the location of the cracks (A and B) formed during March 1985, the villages affected by the earthquake activity and the approximate distribution of the pumice raft on the caldera lake at the end of May 1995 (after McClelland et al. 1989).](image)
Ground subsidence may occur on either a regional or a local scale. Subsidence of entire islands is a much slower continuous process, e.g. the Hawaiian Islands. Subsidence of the flanks and summit areas of a volcano may be directly related to volcanic activity. Niuafo’ou, like Kilauea and Fernandina in the Galapagos, exhibits a series of border benches around the periphery of the caldera. Simkin and Howard (1970) have noted that the presence of such structures is evidence to suggest that caldera collapse or enlargement has occurred. Jaggar (1945) suggested that displacement of the benches occurred during the 1886 eruption, suggesting that further enlargement had occurred. These, however, may have only been minor changes since none of the descriptions given in Taylor (1991) describe any such movements. If, however, subsidence was to occur on a larger scale on Niuafo’ou, it would have a direct impact on the island’s population.

Other hazards

Tsunamis are generally related to large magnitude submarine tectonic events, but as noted by Blong (1984), a significant number may be generated by volcanic phenomena which are associated with large magnitude caldera-forming eruptions, e.g. Krakatoa in 1883 and Santorini in 1500 B.C. Because of the nature of the future activity that could be expected to occur at Niuafo’ou, tsunamis would probably not be generated. Should, however, major edifice collapse occur on the submarine flanks of the island, tsunamis may be generated, having an effect on the surrounding islands, as well as Niuafo’ou. As Niuafo’ou is located in a tectonically active region of the southwest Pacific, it may be affected by tsunamis that are generated elsewhere. In these cases, low-lying areas of the coast would be affected, particularly the area around the village of Futu on the west coast, which is the only part of the island not bounded by 10-20 metre sea cliffs.

HAZARD ZONES

Preliminary hazard maps have been constructed on a base map of Niuafo’ou. The zones have been derived by considering vent location, frequency of the recorded eruptions and the distribution of the resultant products. The products of the recent prehistoric activity have also been considered.

Lava flows

Three zones have been constructed for the hazard from lava flows (Figure 11) and are based on the assumption that the present character of the activity will continue in the future. As noted earlier, all historic effusive activity has been confined to the lower flanks of the island, generally below the 50 metre topographic contour. It has also been shown in figure 2 that where recent prehistoric (i.e. prior to 1800) effusive activity has occurred, vents/fissures have also been located seaward of the 50-metre contour. Zone 1 is confined to the area where one or more historic eruptions have occurred. This zone covers most of the western and southern flanks and part of the north coast. It has been classed as the zone of highest risk. Zone 2 is the area where there have been no recorded eruptions but evidence of prehistoric activity has been observed. This zone covers all other areas of the seaward flanks not assigned to Zone 1. It has been classed as the zone of moderate risk. Zone 3, however, is the area where there has been no evidence of post-caldera effusive activity and it includes all other areas of the island and that within the caldera. It has been classed as the zone of lowest risk.

Tephra falls

From the distribution of the tuff/cinder cone complexes that have been formed during post-caldera explosive activity, the majority of the eruptions have occurred within the caldera. As noted earlier, the entire island was covered by tephra produced during the 1886 eruption, a moderate-to-large magnitude eruption with a VEI of 3 (Figure 12). It can thus, be inferred that most of the island is at high risk from tephra fall that would be produced during an explosive eruption in the future. Based on the proximity to the vents and the predominance of the prevailing east to southeast trade winds, the northern, western and southern quadrants of the island have been classed as being at high risk (Zone 1), while the eastern quadrant of the island has been classed as moderate risk (Zone 2) (Figure 13). For convenience, the boundary between zones 1 and 2 approximates the 50 cm isopach given in figure 12 and assumes that future tephra-producing eruptions will occur near the eastern edge of the caldera and will be of a similar magnitude to that of the 1886 eruption.
The zones on the tephra hazard map do not take into account the surges and the ballistic ejecta produced during the 1886 eruption. It appears, however, that the effects of the surges were confined to within the caldera. It was also noted by Taylor (1991) that during late-stage activity, ballistic fragments were ejected but were only found within a 1-1.5 km radius of the vents. Assuming that future explosive eruptions were to be of a similar magnitude and character to the 1886 eruption, the risk from both surges and ballistic impacts would probably be low in the area outside the caldera. The degree of risk, however, would be dependent on the location of the vent within the caldera.

It is a similar case for the deposits that were produced during periods of phreatic activity that occurred during several of the recent effusive eruptions (e.g. 1867, 1912, 1929 and 1946) as well. This phase of activity resulted in the formation of small tephra aprons close to the vents (e.g. within 1 km), which caused little or no damage. During the 1943 eruption, the steam and tephra plume produced during littoral explosions deposited a salt-encrusted deposit over much of the island, destroying most of the vegetation, causing a drastic food shortage. Thus, extracaldera explosive phases that occur during effusive activity must also be considered hazardous.
PERCEPTION OF THE HAZARD AND RISK

Hazard perception can be defined as the acceptance by a person or an entire population that a hazard or risk exists and that there is a general understanding of it and the possible consequences. As noted by Blong (1984), perception is very complex and is affected by many factors, including family tradition, religion and other cultural and economic aspects. Although formal interviews with residents of Niuafo’ou were conducted to determine the population’s perception of the risk, all members of both the older and younger generations with whom the author spoke during the 1982-83 and 1984 field seasons were aware of the hazard of future eruptions and the associated risk. The degree of perception did, however, vary considerable. The younger generation, i.e. those who have not experienced an eruption, were generally aware of the effects of an eruption but were not fully aware of the risk to their lives. The older generation, particularly those of the age of forty-five years and older who had experienced the 1946 eruption; the evacuation and the subsequent resettlement were fully aware of both the hazards and the risk. One informant, Tu’a Āholelei, a former resident of Angaha, now a resident of Kolofo’ou village, experienced the 1946 eruption as a young boy. He related several stories of what the eruption was like and the damage that it caused in Angaha. As he experienced the fear of the eruption, he possessed a high perception of the hazard and the risk from future activity. Tupou Kata, also a resident of Kolofo’ou village, was fully aware of what an eruption could do but, because he had not experienced an eruption, he was not fully aware of the risks involved.

Many of the older Niuafo’ouans were aware that eruptions could not be predicted and, on numerous occasions, made the following comment to the author:

“If only you could tell us when the volcano was going to erupt again.”

Statements like these highlight the level of knowledge of volcanic activity and the fear that many of the residents hold concerning future eruptions.

The perceptions of the population can be divided into two categories:

i). those who are native Niuafo’ouans; and

ii). those who are temporary residents from other parts of Tonga.

The temporary residents, normally government employees, express the desire to leave the island as soon as they have served their time and are generally fearful of what might happen during a future eruption. This is in direct contrast to the views held by the native Niuafo’ouans who are willing to accept the risk of a future eruption in order...
to live in the land of their forefathers. This is echoed in the statement made by Siaosi Telefoni Ongoloka, a resident of Sapa’ata (Rogers 1986):

“My four main ancestors are resting here in Niuafo’ou and are not transferable. My family lands are here and they are not transferable. This is my island and here I intend to stay.” (p.127)

This attitude of the native Niuafo’ouans is not surprising as many of the local traditions involve strong ties between family and village units (G. Rogers, pers. comm. 1982). This was also reflected in the Niuafo’ouan's willingness to resettle the island in 1958 with little or no government support. Initially, 237 Niuafo’ouans chose to return, with many more following later. Today, Niuafo’ou supports a population of approximately 850 in eight villages.

MITIGATION OF VOLCANIC HAZARDS

The mitigation of volcanic hazards involves the avoidance or control of the hazard and by the minimisation of their effects (Mullineaux et al. 1987). As emphasised by Tilling and Bailey (1985), an effective mitigation program can only be based on long term basic research on a volcano.

Although the recorded history of volcanic activity on Niuafo’ou is relatively short, less than 200 years, an assessment of both historic and prehistoric patterns of activity, as inferred from the stratigraphic relationships described by Taylor (1991), has revealed definite patterns in the character and location of the eruptions. These patterns have allowed attempts at the mitigation of the hazards to be made, but these attempts have been complicated by Niuafo’ou’s remoteness.

Lava flows

Mullineaux et al. (1987) have stated that the only way to avoid human and economic losses from lava flows in Hawaii is through land-use zoning and by the use of strict evacuation procedures. This appears to be the case for Niuafo’ou as well where the location of the villages needs to be carefully considered. Because of the geography of Niuafo’ou, most of the villages are located around the flanks of the volcano, generally above the 50-metre topographic contour. This, however, was not always the case. Prior to the 1929, 1935/36 and 1946 eruptions, the villages of Futu, Petani and Angaha were located either on the coast or a short distance from the coast (Figure 14). Futu was completely destroyed by lava flows produced during the 1929 eruption and Angaha was partially destroyed by the 1946 lavas. Angaha was totally abandoned and was not resettled after the resettlement of the island in 1958. Futu, on the other hand, was resettled to a limited extent, following the eruption and has been used as the alternative ship-loading point, following the eruption and, following the island’s resettlement, it has become the major port facility for the island. Although Petani was not damaged during the 1935/36 activity, the threat was considered to be great enough to warrant its relocation. The village of ‘Ahau, on the other hand, was located in a similar position on the southwest flank but was completely destroyed, with many casualties, during the 1853 eruption, which occurred during the night with little or no warning. This region of the island has not been resettled as it has been the site of subsequent eruptions.

Because of the type and nature of activity, the local geography, the remoteness of the island and the general lack of resources available to the Niuafo’ouans, controlling or diverting the lava flows by the use of barriers or diversions or the cooling of the lava flows using water are not practical. Thus, strict control of village location, i.e. ideally within Zone 3 on figure 11, and the immediate evacuation to high ground, following the onset of activity, appear to be the most effective and realistic form of mitigation against lava flows available to the Niuafo’ouans. Notably, no lives have been lost as a result of recent activity.

Tephra falls

As already noted, the entire island was covered by a tephra layer during the 1886 eruption, which varied in thickness from 10 cm to more than 6 metres (Figure 12). If it is assumed that future explosive eruptions will be of a similar character and magnitude and that the same wind patterns will prevail, all areas of the island can be expected to experience tephra fall. As it is not possible to prevent the distribution of the tephra, it is then necessary to reduce the effects by considering village location and the design of the structures.
Blong (1981) has considered building design in terms of the likely effects of tephra loads. He noted that high pitch roofs were able to withstand high tephra loads better than other roof types. This, however, is highly dependent on the prevailing wind direction and other meteorological factors, such as the occurrence of rain during the eruption. Structures positioned with their long axes, longitudinal to the expected wind direction, would be affected to a lesser extent than those with other orientations. On Niuafo’ou, many of the dwellings are of a simple traditional construction, and may fare somewhat better than the more complex western designs.

It has been suggested that there is a moderate-to-high risk of tephra fall at any locality on Niuafo’ou thus village location is the critical factor to be considered to minimise the effect of tephra. Strict control of the location of the villages to a location on the leeward side of the island, i.e. to within Zone 2 of figure 13, would minimise the effect of tephra. This has been indirectly accomplished since all villages are now located on the northern and eastern flanks of the island.

Effective mitigation must also include education of the Niuafo’ouans on the medical consequences of tephra. Where adequate shelter cannot be found during an eruption, the population must be educated in the protective measures necessary to shield themselves from the effects of the tephra, e.g. the use of facial protection to avoid the inhalation of tephra.

Table 2 summarises the hazards that could be expected to occur during future activity.

---

Figure 14: The current location of the villages on Niuafo’ou and a comparison of the sites of the villages affected by the historic eruptions and their present location. The pattern area indicates the areas covered by the historical (post-1 800) lava flows. (- -) represents the 50 metre topographic contour (after Government of Tonga 1975).
TABLE 2: PRINCIPAL VOLCANIC HAZARDS AFFECTING NIUAFO’OU: PROBABLE WARNING PERIOD, CAPACITY FOR DAMAGE INJURY, LIKELIHOOD OF INJURY/DEATH AND PROBABLE LOCATION

(After Blong, 1984)

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Probable Warning Period</th>
<th>Capacity for Damage/Injury</th>
<th>Likelihood for Injury/Death</th>
<th>Probable Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava flows</td>
<td>Minutes to hours</td>
<td>High</td>
<td>Moderate to High</td>
<td>Outer flanks below 50 metre topographic contour</td>
</tr>
<tr>
<td>Tephra falls</td>
<td>Minutes to hours</td>
<td>High</td>
<td>Low to moderate</td>
<td>Entire island; north, west and south quadrants at greater risk due to dominant SE trade winds</td>
</tr>
<tr>
<td>Ballistic ejecta</td>
<td>Seconds</td>
<td>Extreme</td>
<td>High</td>
<td>Within 1-2 km of the vent; dependent on vent location</td>
</tr>
<tr>
<td>Lightning</td>
<td>None to seconds</td>
<td>Moderate to high</td>
<td>Very high</td>
<td>Entire island</td>
</tr>
<tr>
<td>Pyroclastic surges</td>
<td>Seconds</td>
<td>Extreme</td>
<td>Moderate to high</td>
<td>Generally with the caldera</td>
</tr>
<tr>
<td>Volcanic gases</td>
<td>Minutes to hours</td>
<td>Low</td>
<td>Low</td>
<td>Within several hundred metres of the vent; dependent on vent location</td>
</tr>
<tr>
<td>Seismicity</td>
<td>None</td>
<td>High</td>
<td>Moderate to high</td>
<td>Entire island; effects are dependent on magnitude of the event/s</td>
</tr>
<tr>
<td>Ground deformation</td>
<td>Minutes to hours</td>
<td>Moderate</td>
<td>Low</td>
<td>Flanks of the island</td>
</tr>
<tr>
<td>Tsunami</td>
<td>Minutes to days</td>
<td>High</td>
<td>Moderate to high</td>
<td>Coastal areas of the island</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Based on the historical record of eruptions and the fact that the stratigraphy suggests that numerous periods of activity have occurred prior to 1800, it is concluded that eruptions can be expected to occur in the future and will be both effusive and explosive in character.

Consideration of the preliminary hazard maps that have been developed for lava flows and tephra falls will allow contingency measures to be developed to ensure that minimal loss of life and property occurs during future periods of activity.

RECOMMENDATIONS

As it is almost certain that eruptions on Niuafo’ou will continue to occur, the following recommendations are made:

1. A volcano monitoring program should be implemented for Niuafo’ou. The program should include continuous seismic monitoring and periodic observations of the general character of the volcano, e.g. temperature measurements of the lakes and hot springs, etc. The analysis and interpretation of the data obtained from such a program may make it possible to give more precise forecasts of the onset of future activity with the overall view of reducing the risk to Niuafo’ou’s inhabitants.

2. An education program should be established to increase the perception of the hazards and the risk from future eruptions. The education program should be directed at both the national level to ensure the establishment of emergency procedures to be followed in the event of future activity, and at a local level to ensure that the Niuafo’ouans are fully aware of the risk to their lives and property and that they understand what they should do when an eruption does occur.

ACKNOWLEDGEMENTS

The fieldwork for this project was undertaken as part of a Master of Science project conducted at Macquarie University and, as such, I would like to thank Associate Professor T. H. Green for his assistance throughout the project. The majority of the funding for this project was provided by the author. The School of Earth Sciences at Macquarie University provided minor funding, which is gratefully acknowledged. Thoughtful reviews by Tony
Ewart, Russell Blong and Wally Johnson, have enabled the manuscript to be improved. The Government of Tonga is thanked for allowing me to enter the Kingdom to conduct the fieldwork. On Niuafo’ou: Tupou Kata provided many hours of support in the field. My foremost thanks must go to “my Niuafo’ou family”, Tu’a and Kaufo’ou ‘Aholelei and their children, Lisiate, Naisa, ‘Ilisa and Matamoana who made my stay on Niuafo’ou both enjoyable and profitable. On Tongatapu: Tevita and Lusia Koloamatangi are thanked for their hospitality and for introducing me to my Niuafo’ou family. Paea Heva provided meteorological data for Niuafo’ou.

REFERENCES


Taylor, P.W. in prep. The 1943 Eruption of Niuafo’ou volcano, Tonga, An Example of the effects of Lava Haze (Laze) and Volcanic Smog (Vog).


Todd, Captain. 1886. The 1886 eruption of Niuafo’ou. In Tin Canner, vol.3 (No. 6) p6-8.


Volcanic Hazard Assessment of Savo Volcano, Solomon Islands, SW Pacific

M. G. Petterson*, D. Tolia#, A. Papabatu#, T. Toba#, and C. Qopoto#

* British Geological Survey, UNITED KINGDOM
# Ministry of Energy Water and Mineral Resources, SOLOMON ISLANDS

ABSTRACT

The volcanic island of Savo, Solomon Islands, is part of the Greater Melanesian arc (developed above the destructive Australian-Pacific Plate margin) of the SW Pacific. Savo is one of only four subaerial or near subaerial volcanoes known to be active in the Solomon Islands. The island of Savo is almost circular in plan with a maximum height of 465 m above sea level. The island is the subaerial expression of a much larger volcanic edifice, which extends to submarine depths of 900-1000 m, and has a basal diameter of 9-10 km. Savo, has an asymmetric central crater 1 km in diameter which contains two recent dacite domes: one located within the central crater and one peripheral to the crater. The crater is surrounded by a 1 km annular ring of pyroclastic fall dominated deposits. The bulk of the interior of the island comprises steep coastward-dipping flanks which are underlain by homogeneous, extremely poorly sorted, unwelded and unvesiculated block and ash deposits, with minor basalt and andesite lava flows. The SW quadrant of Savo contains a number of older, steep sided, volcanic domes or plugs composed of basic to ultrabasic hornblendeite, pyroxenite, gabbro, and welded breccia. The flatter coastal plains of Savo are dominated by block and lapilli rich ash flows with laharic/fluvial, fall and surge components. These fans have sub-aqueous morphological expressions and are the products of an important island-building process. Around 3,000 Melanesian people live on Savo: they have their own distinct language, customs and culture. Their villages are concentrated on the coastal lowlands where the economic life revolves around subsistence agriculture which includes cultivating tropical crops, raising livestock, fishing and collecting eggs of the indigenous megapode bird. Savo is only 16 km from NW Guadalcanal, 35 km from Honiara (population c. 80,000), and a similar distance from the Russell and Florida Island groups. At the present time, Savo is in a dormant state with hydrothermal and solfatoric activity concentrated around the dome within the central crater and in SE Savo. Temperature records of the fumaroles collected over a 40-year period indicate that Savo is presently in thermal equilibrium with approximate time-constant boiling (92°-105°C) temperatures. Volcano-tectonic seismicity has, however, recently been detected on Savo. Analysis of written historical records and oral traditions, together with sparse C14 and K-Ar radiogenic data indicate that: 1) Savo is probably <100,000 years old; 2) four volcanic eruptions dated at 1568; between 1600 and 1700; 1830 to late-1840s; and undated (?pre-1568) respectively, have occurred; 3) Savo has a probable volcanic repose period of between 100 and >300 years; 4) the dominant eruptive style is best described as Peleéan-Montserratian block and lapilli rich ash flow eruptions with accompanying Plinian-sub-Plinian ± phreatic fall-dominated activity; and 5) previous eruptions have resulted in large numbers of fatalities and casualties, mass evacuations and ashfall affecting areas at least 20 km distant. Tephra lithofacies studies have subdivided the deposits into: 1) pyroclastic flow dominated subaerial-subaqueous fans ± surge, fall and laharic/fluvial deposits. These deposits display the widest vertical and lateral lithofacies variations on the island; 2) homogeneous, coarse, very poorly sorted block and lapilli rich ash flow deposits occupy the bulk of the interior of the island. These deposits are termed ‘medial flank block and ash flow deposits’; 3) proximal crater wall fall dominated deposits which include proximal surge and flow deposits. Tephra studies support accounts of historical and pre-historical eruptions: i.e. the tephra deposits are largely the result of highly explosive pyroclastic flow and fall eruptions. The hazard implications of volcanological investigations are summarised by including the first ever volcano-geological and volcanic hazard maps of Savo. The implications of these maps, together with other related hazard work, and recommendations for further study are discussed.
SCOPE OF PAPER

This paper focuses on aspects of our work which are of direct relevance to volcanic hazard assessment. It is beyond the scope of this paper to describe details of litho-stratigraphy or geochemistry (these subjects will be described in other papers to be published elsewhere), but aspects of this work will be mentioned where relevant. We aim to present data relating to the general setting, the geology and geomorphology of Savo, and documented accounts of eruptions with the objective of building a picture of the most likely eruptive style of future eruptions and their likely consequences. By establishing the predominant hazards, we can then proceed to develop aspects of this work which deal with hazard mitigation and risk assessment which are invaluable to local people, government, planners, etc. It is our hope that this paper will stimulate further work.

The work presented in this paper is largely the result of a three and a half year attachment to Solomon Islands by the first author who, together with the co-authors and others, made regular visits to Savo with the objective of studying the volcanic deposits of the island. Most of this work, with the exception of short papers in Petterson, 1995, and Petterson et al (1997a, b) remains unpublished, although it is the authors’ intentions to publish this work.

GEOLOGICAL-TECTONIC SETTING OF THE SOLOMON ISLANDS

The key elements of the geology and tectonic setting of Solomon Islands and Savo are summarised in Figures 1 and 2. The Solomon Islands, together with New Britain, Santa Cruz, and Vanuatu form the Greater Melanesian arc which has formed as a result of the collision between the Australian and Pacific Plates. At the present time the Australian Plate is subducting northwards beneath the Pacific Plate. Most workers believe that the polarity of subduction was opposite to the present day, with the Pacific Plate subducting southwards beneath the Australian plate until about 12 Ma (e.g. Yan and Kroenke 1993).

Figure 1: The Solomon Islands form part of a relatively upraised block, the Solomon block bounded by two trenches: the northern Vitiaz and the southern New Hebrides-San Cristobal trenches respectively. Since 12 Ma the Australian plate has been subducting northwards beneath the Pacific plate; from the Eocene to the Lower Miocene subduction polarity was in the opposite sense with the Pacific plate subducting beneath the Australian plate. The largest ocean plateau in the world; the Ontong Java plateau is currently colliding with the Solomon arc. A number of young ocean basins such as the Woodlark basin and upraised plateaux, such as the Louisade plateau are situated to the south and west of the Solomon block. Note the highly oblique convergence of the Pacific and Australian plates. Figure reproduced by courtesy of Elsevier Publications Ltd.
Figure 2: Solomon Islands are sub-divisible into five ‘terrains’ on the basis of basement age, lithology and geochemistry, and the relative development of (or lack of) two major arc building stages (stage 1; Eocene-Lower Miocene; stage 2: Upper Miocene-present day). Choiseul and Guadalcanal display the widest spectrum of geology with N-MORB like Cretaceous basaltic basement on which are developed both stages of arc crustal growth. Malaita and Santa Isabel, together with other smaller islands are upraised parts of the Cretaceous Ontong Java plateau. Makira is a hybrid island with both OJP and N-MORB basement affinities and preserved relics of a probable stage 2 arc. The Shortlands, Floridas, and south Isabel formed mainly during stage 1 arc times and have a variable development of stage 2 arc. The New Georgia Group, Russells, submarine volcanoes south of the New Hebrides trench, as well as Savo form part of the Upper Miocene to present day active arc. Figure reproduced by courtesy of Elsevier publications Ltd.

The Solomon Islands are part of an upstanding block (the Solomon Block) that is flanked to the northeast and southwest by deep ocean. Two trenches bound the Solomon Block; that is, the Vitiaz Trench system (known locally as the North Solomon Trench) to the north and the New Britain-San Cristobal Trench to the south. The currently active trench is the southern New Britain-San Cristobal Trench although there is evidence that the northern Vitiaz trench is intermittently active, at least on a local scale (e.g. Petterson et al, in press a, b). To the north of the Vitiaz Trench lies the largest ocean plateau in the world, the Ontong Java Plateau (OJP). This plateau is currently colliding with the Solomon arc and upraised parts of the OJP form some of the larger Solomon islands, e.g. Malaita island, the Malaita anticlinorium region, northern Santa Isabel and possibly parts of Makira (Figure 1 and 2, Petterson et al, in press a, b). To the south of the Solomon Block are located a number of deeper ocean basins such as the Woodlark and Solomon Sea Basins and upraised ‘plateaus’ of largely unknown origin such as the Louisade and West Torres Plateaus.

Figure 2 presents a new ‘terrains’ map of Solomon Islands (Petterson et al, in press, b,) which is a development of the older Coleman province map (Coleman, 1966). This map subdivides the Solomon Islands on the basis of: a) basement age, lithology, and geochemistry; and b) subsequent development (or lack of) of two major arc building events which are named stage 1 arc (Eocene-Lower Miocene) and stage 2 arc (Upper Miocene to present day) respectively. There are five main sub-divisions: 1) northern Santa Isabel, Malaita and other smaller islands are uplifted and obducted parts of the OJP with no subsequent arc development; 2) Makira appears to be partly of OJP origin and partly of ‘normal’ ocean floor (non-plateau) origin, and contains relics of probable stage 2 arc in the form of dacite dykes; 3) south Santa Isabel and the Shortland and Florida island groups have a stage 1 arc basement and variable development of the younger stage 2 arc; 4) Guadalcanal and Choiseul have Cretaceous ‘normal’ ocean floor basement with subsequent crust development during both stage 1 and stage 2 arc times; and 5) the New Georgia Group, the Russell Islands and Savo together with submarine volcanoes (many of which are south of the New Britain-San Cristobal Trench) form the present day arc and are largely, if not entirely composed of stage 2 arc material.
PRESENT DAY ACTIVE VOLCANISM IN SOLOMON ISLANDS

There are surprisingly few active subaerial volcanoes in Solomon Islands. In the western Solomons only Savo and Simbo are permanently subaerial (Figure 2). Both Savo and Simbo are presently solfatorically and geothermally active. The main difference in the perception of their relative ‘activity state’ is that whilst it has been clearly documented that Savo has erupted during recent times, this is not the case for Simbo. There has, however, never been an appraisal of the volcanic hazards of Simbo conducted. Kavachi, in the southeast New Georgia Group, is a volcano with its summit presently at a depth of only 20 m below sea level. Whilst Kavachi is in eruption, every 5-10 years or so, it forms a temporary subaerial island displaying typical Surtseyan-type activity. It is only a matter of time before Kavachi forms a permanent subaerial island. In the eastern Solomons near Santa Cruz (Figure 1) the island of Tinakula is by far the most active subaerial volcano in Solomon Islands. It is in a constant state of eruption mainly displaying Strombolian-type explosive activity. This once populated island was evacuated during the 1960s to 1970s; however, local people still periodically occupy the island, farming the less dangerous parts.

In contrast to the paucity of subaerial volcanoes, it is now known that there is a plethora of submarine volcanoes within the Solomon Island territory. The submarine seamounts of Kana Keoki, Coleman, and on the Ghizo and Simbo Ridges south of the New Britain Trench and the New Georgia Group (Figure 2) are comprised of highly evolved andesite to dacite, calc alkaline, stage 2 arc material (e.g. Crock and Taylor, 1994). The recent SOPACMAPS swath mapping surveys east of Makira have discovered tens of volcanoes which form three sub-parallel lines, two of which are spatially and genetically associated with the San Cristobal and Vitiaz Trenches respectively, and a third one which has formed as a result of intra-oceanic rifting (Kroenke, 1995).

GEOGRAPHICAL SETTING OF SAVO

The position of Savo within the Solomon archipelago is shown in Figure 3, and Figure 4 highlights the main features of the island. Savo is located 35 km NW of the Solomon Islands capital of Honiara, 16 kms north of NW Guadalacanal, and close to the Russell and Florida island groups. Savo is an almost circular island 6 km in diameter (Figure 4), with a central crater, and the highest point of elevation being on the crater rim, 465 m above sea level. The bulk of the island comprises steeply seaward dipping flanks to the volcanic edifice, with a series of older domes in the SW and on the coastal plains to the north, east, and south, respectively. The drainage is radial, being centred on the crater region. Most of the rivers are dry except in times of heavy rainfall. Rivers with virtual year-long water flow include the Poghorovurughala, Rembokola, and Tuluka (Tutuka).

The population of Savo is currently estimated at between 2500 and 3000 Melanesians. The language of the Savo people is unique and distinct from the languages of neighbouring islands, which suggests that the anthropological background of the Savo population is somewhat different to neighbouring island populations. All villages are located along the coastal fringe of the island: there are no permanent villages within the island interior.

Most of the inhabitants of Savo are subsistence agriculturalists cultivating crops such as sweet potato, yam, and taro, cash crops such as coconut, raising livestock such as pigs and poultry, and engaging in fishing as food supplementation. In addition, Savo people encourage the indigenous megapode bird to lay eggs in the sands of the coastal areas; megapode eggs are also gathered from the interior. Megapodes form an important element of the economic life of Savo.

From a volcanic hazard perspective it is important to emphasise that the population of Savo inhabitants live on, and make their living from, the flat coastal plains. As will be explained, these plains are largely the products of pyroclastic flows and the majority of the population live within the highest risk zones of the volcano. This is not an uncommon situation as many millions of people throughout the world live on or near to dangerous or potentially dangerous volcanoes (e.g. in Indonesia). Volcanoes can produce very fertile and rich agricultural land on which human populations thrive and grow. The very same volcanoes can, of course, pose a very serious threat to those same human populations: what volcanoes can give them, but can also take away.
Figure 3: Savo is situated some 16 km north of NW Guadalcanal and 35 km NW of the capital of Solomon Islands, Honiara. Close neighbouring islands include the Florida and Russell island groups, and southern Santa Isabel. Solomon Islands is a modern island archipelago state situated between Papua New Guinea to the NW and Vanuatu to the SE (see Figures 1 and 2 for regional geographical situation).

Figure 4: Savo is a circular island some 6 km in diameter and containing a central, asymmetrical crater measuring 1 km in diameter. The highest point of the central crater wall (and Savo) is 465 m above sea level. Steep, seaward-dipping volcanic flanks, deeply incised by a radial drainage system, comprise the bulk of the island interior. The 3,000 Melanesian inhabitants of Savo have all settled on the flatter coastal plains and are mainly involved in subsistence agriculture as a way of life. See Figures 5 and 6 for further details.
PHYSICAL MORPHOLOGY OF SAVO

The island of Savo is merely the surface expression of a much larger stratovolcano, two thirds of which is below sea level. The subaerial expression of the volcano forms an approximately circular island some 6 km in diameter. The highest point of the island is 465 m above sea level, with the base of the volcano rising from the sea floor at depths of 900-1000 m below sea level (SOPACMAPS, 1994). The submarine basal diameter of the volcano measures 9-10 km. Volume calculations based on a basal diameter of 9 km and a total height of 1385 m give a value of 1010 m$^3$ or 10 km$^3$. The crustal thickness beneath Savo is estimated to be only around 14 km (Furomoto et al, 1970). The modern day central crater of Savo is asymmetric measuring 1.5 km along a NW-SE long axis and 1 km along a NE-SW short axis (Figure 4 and 5). A dome occupies much of the crater area. The crater wall contains one significant low point on its eastern side where its height is < 400 m. This low point is an easy access point from the crater floor to the Upper Rembokola river valley. Six older domes have been identified, five of which are situated within south-western Savo (Figure 5). The larger domes are significant structures in their own right, being steep sided mounds rising steeply from their surroundings and measuring up to 240 m high. The remainder of the island comprises predominantly of two geomorphological types: 1) coastal fans formed by the accretion and coalescence of pyroclastic flow and laharic deposits. These are particularly common in the northern part of the island (eg. the Megapode field coastal fan). The pyroclastic fans have a typical triangular plan-view deltaic morphology. The apex of the fans are points at which the steeper upper river valley profile joins the flatter coastal plain. The river valleys which connect the crater to the pyroclastic fan have acted as flowpaths/escape channels for crater centred pyroclastic flows. The upper surfaces of the pyroclastic fans have a gentle seaward-dipping gradient to them. The pyroclastic fans have large submarine topographic expressions in the form of near surface frontal lobes and deeper level turbidite fans. Pyroclastic fan aggradation has been a most important island growth process; and 2) the flanks form steep, seaward-dipping slopes away from the central crater, and are deeply dissected forming a series of radial steep sided ridges with deep intervening valleys. Aerial photographic evidence suggests that a number of ill defined old crater wall lineaments exist which are concentric about the present day crater (Grover, 1958, Petterson unpublished data).

PRESENT DAY GEOTHERMAL-SOLFATORIC AND SEISMIC ACTIVITY

The most obvious manifestation of volcanic activity on Savo is the presence of a number of hydrothermal and solfatoric areas. Figure 6 shows the distribution of present day hydrothermal activity. These areas are located within the central crater, peripheral to the central dome, and within the south-eastern quadrant of Savo. The most active and extensive areas of hydrothermal activity include Mbitivoghala and Fisher Voghala within the central crater, Voghala valley (Upper Poghorovurughala; the largest hydrothermal field on Savo), Toakamata (Upper Rembokola), and Vutusuala (Figure 6). The distribution of present day hydrothermally active areas suggests that a magma chamber may be located under SE Savo.

The hydrothermal activity is either vent centred or manifests itself as less dramatic, but continuous gaseous and vapour emissions over a wide area. Individual vents are up to 1-2 m high, measuring 1 to >1 m in diameter with vent flanks composed of sulphurous and siliceous sinter precipitates and encrustations deposited radially about the actual gas-vapour conduit.

Activity varies between vigorous jets of steam and vapour being ejected up to 1-1.5 m high to gentle bubbling of subterranean water. The more regional activity produces a large number of ‘mini-vents’ <1 cm in diameter through which gas and vapour emanates. These mini-vents are transformed, with time, into pipe structures several cms to ms long, resembling the fines-depleted gas pipe structures typical of many ignimbrite deposits (eg. Cas & Wright, 1987). These regional hydrothermal fields are generally unvegetated, and comprise highly altered tephra deposits shrouded in sulphurous gas and vapour. The regional hydrothermal areas and the larger discrete vents display a striking array of colours from yellow, brown, and green, through to black, reflecting the presence of a wide variety of mineral precipitates.

Temperatures of individual hydrothermal vents on Savo have been recorded on an ad hoc basis since 1956 (eg. Grover, 1956). One of the present authors (TT) has documented the recorded temperature data (Toba, 1995). The bulk of recorded temperatures for any one vent fall within the temperature range 92°C to 103°C, exceptionally falling as low as c. 60°C, and as high as c.110°C. Time -temperature profiles for individual vents are complex and beyond the scope of this paper, suffice to say that they suggest that at the present time Savo is in thermal equilibrium with essentially constant boiling temperatures being recorded over a forty year period.
Figure 5: Savo is a basaltic-dacitic arc volcano. The oldest rocks on Savo are preserved within the older steep sided volcanic domes, located mainly in the SW. These volcanic domes are composed of basalt, gabbro, welded breccia and ultramafic rocks. The crater area and an annular area around the crater some 1 km in radius comprises fall-dominated unwelded acid andesitic tephra with contributions from proximal surge and flow. The bulk of the interior of Savo is underlain by coarse, poorly sorted medial flank tephra deposits interpreted to be of flow origin, and minor proportions of basalt and andesite lavas. Pyroclastic fans dominate the coastal fringes of Savo, particularly in the north. These form deltaic-like subaerial to submarine fans with gently seaward-dipping fan tops. The fans are subdivisible on the basis of drainage development and incision into a younger and older sequence. The fans formed primarily from the coalescence of block and lapilli rich ash flows. Smaller fluvial and laharian dominated fans occur in the west and east.

Figure 6: Hydrothermal map of Savo. Hydrothermal vents are most active in central and south-eastern Savo. The fumarolic fluids are mainly at boiling temperatures some 90-105°C. Fumarolic activity manifests itself in the form of individual vents and more widespread disseminated ground vapour release.
It is important to note that the hydrothermal activity has important implications for volcanic hazard assessment. Hydrothermal activity by its very nature tends to weaken and degrade primary rock and tephra material. This rheological weakening, the weakening of natural stratigraphic cohesive bonds and general ‘loosening up’ of primary materials, together with possible destabilisation of domal structures increases the probability of more destructive eruptions. This is achieved by weakening potential physical barriers to flow and increasing the availability of loose ‘accidental’ lithic material to pyroclastic flows, thus increasing their total volume and mass.

A seismometer has been permanently located on Savo for >15 years, but the instrument has proven to be ineffective in detecting volcano-related seismicity. In 1995, Drs Michel Lardy and Michel Larue of ORSTOM in Vanuatu, together with two of the present authors (MGP and TT) installed a sensitive, portable seismometer in the crater of Savo. During two hours of operational time two significant volcano-tectonic events were recorded, suggesting that Savo is indeed seismically active. Furthermore, this data suggests that a seismometer with similar specifications should permanently replace the existing ineffective instrument on Savo.

HISTORICAL AND PREHISTORICAL ERUPTIONS

Prehistorical Accounts

Melanesia has no tradition of written history but has a rich tradition of recording important historical events in the form of oral traditions. Important events are passed down through the generations through oral traditions or ‘custom story telling’ as it is locally known. Although a study of local custom stories may be an unorthodox way of instigating volcanological research relating to previous eruptions on Savo, we felt that in spite of its limitations this data source was too important to ignore. One of the authors (TT), a native of Savo, investigated the validity of Savo custom stories by interviewing a number of village elders from a number of different areas on Savo (Toba, 1993). Toba discovered a high degree of consistency in the content of the stories that were related by the old men. The Savo village elders record three distinct events in their custom stories:

1) The most violent and catastrophic eruption is termed the ‘Toghavitu eruption’. The word ‘toghavitu’ means ‘7000’ in the local Savo language and may refer to the number of people who were supposedly killed by the eruption. The eruption was preceded by precursory activity which included earthquakes and infilling of the central crater by water (presumably as a result of heavy rainfall and/or phreatic activity). The eruption manifested itself in terms of violent (Peleean to sub-Plinian/Plinian to small scale Phreatoplinian) pyroclastic fall and flow activity, and associated lahatic activity. Thunderstorms with lightning accompanied the eruption. There are reports of landslides and tsunamis, and other islands being affected by the volcanic activity. People sheltered under wooden ‘bowls’ (probably refer to boats), and tried to escape by launching canoes from the island. The Figure of ‘7000’ mentioned implies a high number of casualties. This record of a particularly violent ‘Toghavitu’ eruption has no parallel in any written historical record suggesting that it refers to a time when the European presence was either non-existent or limited, that is, pre-1568 or during the seventeenth or eighteenth centuries. Whilst the details of this particular custom story may be open to a degree of scepticism, the important point is the consistency of the stories, that is, that Savo did experience, during relatively recent times, a particularly violent eruption which caused a great loss of life, almost wiping out the entire population of the island. Interestingly, there is support for the ‘Toghavitu’ event from accounts of custom stories recorded in the scientific literature by Grover (1958) who recounts that islanders remember a time when the population was destroyed by a ‘glowing’ cloud which had properties resembling a very fast mass of ‘hot water’.

2) The second custom story is less precise and vaguer than the ‘Toghavitu’ eruptive event. This eruption was of a smaller scale compared to the ‘Toghavitu’ eruption. It affected mainly the northern (Ndavalaka), eastern (Rembokola), and southern (Poghorovuroghala) extremities of the island and led to some loss of life (tens of people), crop damage, and the evacuation of inhabitants to the Florida Islands and western Guadalcanal. Recorded events include landslides, water partially filling and then spilling out from the central crater, volcanic explosions and gas clouds producing a plume of sufficient magnitude to ‘darken the sun’ and ‘people sinking into hot water and ash’ (probably referring to block, ash and related lahatic flows). There appears to have been several phases in this eruptive sequence. This event is interpreted as being perhaps a more typical Savo eruption of sub-Plinian-type and resulting in the eruption of small-medium scale block and ash flows with related lahatic and pyroclastic fall activity, that is, Peleean-type activity. Grover (1958) also records a custom story which correlates with this second event of our study. Grover’s account records how
one woman escaped from the eruption by sheltering in a cave located in the lee of one of the south-western volcanic domes. This second ‘custom story’ could correspond to eruptions recorded by written history (see below) or to another unrecorded event.

3) The final custom story describes a mudflow which devastated the main river drainage channels of the island. The mudflow resulted from a prolonged period of heavy rain and may refer to a series of mudflows that affected the island during the early 1950s.

Historical Accounts

The most reliable written accounts of eruptions on Savo are recorded by Guppy (1887) in his book entitled ‘The Solomon Islands: Their Geology, General Features, and Suitability for Colonization’ which includes a chapter on Savo. Guppy records details of two distinct eruptive events, one in 1568, and another prolonged eruption during the 1830s and 1840s.

The first European to ‘discover’ the Solomon Islands was Alvaro del Mendana in 1568 (some accounts record the year as 1567). At this time Savo was reported to be in a state of eruption. Mendana’s ship logs record pyroclastic activity manifested by a volcanic plume and falling ash, and by the presence of ‘roads cutting through the jungle from the centre of the island to the shore’, which we interpret as referring to the production of valley constrained block and ash flows and their related coastal fan deposits.

Guppy records a protracted period of activity commencing during the 1830s with the main eruptions continuing into the mid-1840s, with possible phreatic activity in the central crater continuing to the 1870s and 1880s. Guppy notes that descriptions of the 1830-1840 eruptions by local people include key phrases such as ‘erupted materials rushed down deep channels’, ‘large quantities of water, dust, and ash were ejected’, ‘day and night were the same’, ‘dust affected adjacent islands’, and ‘several islanders were killed’. Guppy also noted that the ash flows were unvegetated until about 1877, resembling roads which afforded an easy access to the summit. Grover (1958) records an account of this stage of eruption as relayed to him by a cleric, Bishop J M Aubin, who first arrived in the Solomons in 1906, and was given an account of the eruption by local people. Bishop Aubin’s account records a mass evacuation of the island by people taking to their canoes. This eruption knocked over trees in the southwest of the island, with the felled trees pointing seawards. The trees were felled by a ‘glowing cloud’, which we interpret as referring to a block and ash flow being erupted from the crater and moving down the Poghorovurughala valley to the sea. Grover also recorded a particularly lucid account of an eye witness account of an eruption from the 1830s-1840s eruptive period in 1961 (Grover, 1961, unpublished record; Appendix 1). The account given by Grover was recounted by Mr Marino Tandabara (born 1915) of Harango village in western Guadalcanal (some 16 km south of Savo), he had heard the account from his father, Mr Suggati, who had witnessed the eruption as a youth. The account records that the eruption took place ‘at the gnali nut time of the year (June-July), before the white man came to Guadalcanal’. The eruption was preceded by earthquakes and heavy rain, starting in a relatively quiet fashion during the late afternoon. By midnight there were continuous noises ‘like the hooting of a steamer, or like a river in flood rolling large boulders against each other’. The noise became louder and louder. The climax of the activity lit up the sky ‘as though by daylight’ with ‘great fiery rocks, red like the moon, being thrown into the sky above the fire on Savo, falling into the surrounding illuminated sea’. A thin layer of ash fell on Guadalcanal itself ‘from Kesau in the west to Ndorma in the east’, indicating that ash fell to distances of c. 20 km from the central crater. This violent eruption lasted for two days. People arrived in western Guadalcanal, (some had gone to the Floridas), many of them remaining for ten years or more as Savo ‘had been made completely desolate from Koela on the west coast to Kaongelle on the east’, (indicating a predominant southerly or Poghoovurughala channelled route for the block and ash flows).

Radiometric Data

One wood sample taken from the base of a continuous c.6 m thick sequence of pyroclastic flow dominated tephra deposits from the Ndavalaka fan yielded a C14 age of 270 years ±45 years. The age was determined in 1995 by Dr G S Burr of the University of Arizona, USA. Applying the calibration calculations of Stuiver and Reimer (1993), the Savo C14 data gives a most likely calendar age of 1630-1680AD (± 45 years), with a most likely probable range of between 1600AD and 1700AD. This age is important as it indicates that there may have been a major eruption between the ‘definite’ historical eruptions of 1568 and 1830-1840. This dated 17th century eruption produced at least one multiple block and ash flow dominated sequence which was channelled along the Tuluka river channel and deposited within the Ndavalaka pyroclastic coastal fan.
Four samples of the postulated oldest material exposed on Savo (from vents located in the southwest of the island) were sent to Dr David Rex of Leeds University, UK to be dated by K-Ar techniques. All four samples proved to be too young to yield an age, suggesting a maximum age for the samples of 100,000 years BP (Rex, pers. comm.).

Summary of Age Data for Recent Eruptions

The least ambiguous age data derived from an analysis of the historical records and C14 and K-Ar data imply that; 1) the presently exposed part of the Savo stratovolcano is younger than 100,000 years BP; and 2) there are three distinct eruptions or eruptive periods recorded, i.e. 1568, between 1600 and 1700 (most likely between 1630 and 1680), and during the 1830s and 1840s (possibly continuing at a much lower level until the 1870s or 1880s). Additional local ‘custom stories’ record two eruptions, one of which may coincide with one of the historical eruptions and, the most explosive and violent eruption, named the ‘Toghavitu’ eruption which is distinct from the historical eruptions (Table 1). From the limited data available we infer that the repose period of Savo is of the order of <100 to 200 or 300 years which is not a long repose period in geological terms. As a comparative example the Caribbean island of Montserrat has been experiencing violent Pelean-type activity for over two years now, forcing many of the inhabitants to evacuate and those who remain behind to move to the less developed north of the island. Montserrat last erupted (and only briefly) some 340 years ago (Wadge & Isaacs, 1988), but the most recent large-scale eruption determined from C14 studies was around 4,000 years ago (Loughlin, pers. comm.): Wadge and Isaacs (1988) also record several eruptive events aged > 16,000 years BP.

**TABLE 1: SUMMARY OF ERUPTION HISTORY OF SAVO**

<table>
<thead>
<tr>
<th>Postulated Age of Eruption</th>
<th>Evidence</th>
<th>Nature of Eruption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1568 (1567)</td>
<td>Recorded by Alvaro del Mendana in his ship’s log book during his pioneering discovery voyage in the SW Pacific</td>
<td>Pelean block and ash flow eruptions from the central crater. Pyroclastic flows formed a series of ‘white roads extending from the crater to the sea.’</td>
</tr>
<tr>
<td>1630-1680 AD</td>
<td>Wood sample in pyroclastic flow with a C14 age of 1725AD (+/- 45 years)</td>
<td>Large-scale pyroclastic eruption. Block + lapilli rich ash flows were channelled down the Tuluka river.</td>
</tr>
<tr>
<td>1830’s to 1840’s with lesser scale activity may have continued until the 1870’s or 1880’s</td>
<td>Eruption recorded by Guppy (1887)</td>
<td>Protracted period of moderate to large-scale activity. Dominated by Pelean block + lapilli rich ash flows, laharic activity, and sub-Plinian fall activity. Dense ash plume developed intermittently. Several fatalities and casualties. Evacuation of population. Neighbouring islands affected during height of activity.</td>
</tr>
</tbody>
</table>

GEOLOGICAL MAP OF SAVO

The most up-to-date geological map of Savo is presented in Figure 5 and is a major revision of the map prepared by Proctor and Turner (1975), and the published map of 1989. The map is based on numerous field traverses, including coastal sections and detailed aerial photograph interpretation. The central region of Savo exposes deposits associated with the most recent activity within the central crater. A c.1 km wide concentric zone around the crater is underlain by proximal fall deposits and associated surge and flow deposits. The crater floor itself is largely composed of hydrothermally degraded tephra of probable fall origin. Two recent dacite domes are present, one within the central crater and at the head of the Mbazo River.

Much of the interior of the island comprises ‘medial flank tephra deposits’ which are dominated by relatively homogeneous, coarse and very poorly sorted block and ash flow deposits with minor proportions of fall, surge and laharic deposits. A number of older lava domes are present in SW Savo and another in NW Savo. The domes are major topographic features which could form significant physical barriers to future pyroclastic flows. They are composed of basaltic and ultrabasic material in the form of welded basaltic and gabbroic breccias, gabbrons, hornblendites, and pyroxenites. Laves (of andesite and basalt composition) are modally unimportant on Savo and tend to form massive to well-jointed sheets which crop out in the upper parts of the major river valleys.
Coastal exposures are dominated by pyroclastic flow deposits with associated fall, surge, and laharic deposits. They form typical fan-like triangular plan outcrop patterns which emanate from their ‘parental’ river channel. These sequences form the bulk of the coastal lowlands with gentle, seaward dipping, and upper surfaces. The pyroclastic fans can be sub-divided on the basis of drainage density and depth of river channel incision into an older and a younger series: the Megapode Field, Mbazo, and Kuila fans are ‘older’ whereas the Ndaivalaka, Rembokola, and Poghorovurghala fans are younger. This fan subdivision has obvious applications to hazard assessment.

A number of small epiclastic/fluvial dominated sand rich fan deposits are present at Mbirasu, Siata, and Semburu.

**Pyroclastic and Epiclastic Lithofacies**

The main features of the pyroclastic and epiclastic deposits on Savo are summarised in Table 2 and Figure 7. We have simplified the tephra classification of Savo into three main deposit types: 1) pyroclastic flow dominated fan deposits; 2) medial flank block and ash deposits; and 3) crater wall deposits. Only the general characteristics of the respective lithofacies are discussed here.

<table>
<thead>
<tr>
<th>Lithofacies Type</th>
<th>Dominant Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyroclastic Flow dominated Fan Deposits</td>
<td>Heterogeneous. Rapid vertical and lateral facies variations. Exposures dominated by massivemassivelybedded, poorly sorted, unwelded &amp; unvesiculated ash with lapilli + block pyroclastic fan deposits. Max. clast size: 7-20 cm, exceptionally 50 cm. Clast lithology dominated by dacite/acid andesite. Deposits are matrix supported with lapilli + blocks forming 20-40% of the deposits (higher proportions in lapilli conc. zones) within a pale ash matrix. Coarse-tail normal &amp; reverse grading; hydrothermally altered accidental lithics &amp; wood/charcoal fragments present. Associated surge &amp; fall deposits locally present.</td>
</tr>
<tr>
<td>Peléean-type block and lapilli rich ash flows</td>
<td>Channel lag; cross-bedded silt/sand &amp; heterolithic breccias. Interpreted as laharic &amp; fluvial deposits.</td>
</tr>
<tr>
<td>Interbedded fall, surge, and fluvial/laharic deposits</td>
<td>50% of Savo is underlain by this facies. Homogeneous, thickly bedded (&lt;2= 20-40 m beds); unwelded; very poorly sorted block &amp; ash flow deposits. Massive-very crudely bedded. Max. clast size: 250-8 cm. Block concentration: 10-60%. Unvesiculated, angular to sub-angular dacite / acid andesite blocks supported by a pale ash matrix. Erosive bases to some individual deposits. Occasional interbeds of fall material.</td>
</tr>
<tr>
<td>Medial Flank Block and Ash Flow Deposits</td>
<td>Two main lithofacies (both are monolithic (dacite/acid andesite) and unwelded. These facies are:</td>
</tr>
<tr>
<td>Occasional interbedded fall deposits</td>
<td>1) Well sorted ash + lapilli displaying: parallel and mantled bedding; locally repose-dip bedding; alternating ash + lapilli layers; occasional low angle cross-beding (surge units); moderate sorting; maximum clast size: 2-6 cm. Interpreted as fall and surge deposits.</td>
</tr>
</tbody>
</table>

The coastal fan deposits of Savo are dominated by block and lapilli rich pyroclastic flow deposits which exhibit a wide range in facies variation both laterally and vertically. In general the pyroclastic flow fan deposits have three main sections to them: 1) an upper proximal and valley confined section through which the pyroclastic flows travelled and were mainly in transport and erosive mode; only thin sediment veneers are locally preserved; 2) a medial subaerial fan section with a nodal focus point at the position where the steep valley meets the coastal plain. The resulting change in topographic gradient leads to a sudden decrease in flow momentum and the commencement of clast deposition; and 3) a distal submarine frontal flow lobe which forms a pyroclastic flow delta front with associated deeper water volcaniclastic charged turbidite sequences. Figure 7a is a photograph of coastal exposures present in southern Savo. It illustrates a number of features of pyroclastic flow fan deposits including: the undulating contact between an upper white ash dominated flow and a lower lapilli + ash flow; layering in the lower flow is defined by alignment of lapilli clasts; general poor sorting in the lower flow; monolithic nature (dacite/acid andesite) of the deposits; the matrix supported nature of the deposits; and general coarse-tail inverse grading of the upper deposit. Coastal fan deposits also contain contributions from lahars, fluvial reworking of loose unconsolidated pyroclastic material, and surge-related deposits.
Figure 7: Field photographs of typical tephra lithofacies: Upper Photo this page: (Reko, Poghorovurughala pyroclastic fan) illustrates an upper, pale coloured; ash dominated pyroclastic flow with coarse-tail inverse grading, resting on top of a poorly sorted block and lapilli rich ash flow with bedding defined by alignment of lapilli clasts. Lower Photo this page: (Middle Poghorovurughala) illustrates a typical very poorly sorted block & lapilli rich medial flank ash flow deposit. Upper and Lower Photos next page: (Voghala) illustrate poorly sorted medial flank block and ash flow deposits with both overlying and underlying, parallel bedded fall tephra deposits typical of the proximal crater wall lithofacies.
Medial flank block and ash deposits are much more massive and homogeneous relative to the pyroclastic coastal fans. They are typified by thick to very thick sequences of very poorly to extremely poorly sorted, unwelded, block and ash deposits. Individual blocks and lapilli are angular to subangular, unvesiculated dacite/acid andesite in composition and can comprise up to 60% of an individual deposit. The largest clast long axes can exceed 1-2 m. Figures 7b and 7c (upper deposit) illustrate some of the general characteristics of this facies including: poor sorting; the general monolithic dacitic composition; densely packed but matrix supported blocks and lapilli, and the pale dacitic ash matrix.

Crater wall and related proximal deposits are dominated by fall, associated surge and proximal flow deposits. Two main subfacies are present (Table 2) – a poorly sorted coarse deposit not unlike some of the medial flank block and ash deposits, and a well sorted deposit which exhibits typical ‘fall’ characteristics, such as parallel and mantle bedding, moderate to good sorting, alternating layers of varying grain size (e.g. lapilli layers interbedded with ash layers) and local repose angle (c. 33º dips) bedding. Local low angle cross bedding indicates the influence of surge activity. Figures 7c (lower deposit) and 7d (upper deposit) illustrate some of these features, including good sorting, parallel layering and alternating layers of lapilli and ash.

The most important hazard-related conclusion to be drawn from Savo tephra studies is that tephra deposits are dominated by the products of highly hazardous explosive volcanism. In order of decreasing modal contributions to Savo tephra deposits these ‘explosive’ processes are identified as: 1) Peleéan (or Montserratian for a current eruption example) -style block and ash flow eruptions; 2) Plinian to sub-Plinian to phreatic-style fall dominated eruptions; and 3) pyroclastic surge eruptions. Fluvial-laharic reworking of explosively derived tephra is an additional hazardous process which is also significant on Savo.

VOLCANIC HAZARD MAP OF SAVO

The preliminary volcanic hazards map of Savo presented in Figure 8 is a summary and interpretation of all the data presented in this paper. There are a number of assumptions involved in developing the map including: 1) the principal of uniformitarianism holds, i.e. the geological record on Savo suggests that future eruptions will be dominated by highly explosive Peleéan-type block and ash flows with accompanying Plinian to sub-Plinian and possible phreatic fall activity; 2) the eruptions will occur in the region of the central crater (a lateral blast style of eruption would require a different hazard map to be constructed); and 3) the magnitude of future eruptions will be similar to previous events. A very large scale cataclysmic, Krakatoan style eruption would not really require a hazard map.

The map highlights six zones which vary between the highest risk (Zone 1) and the lowest risk (Zone 6). The zones of highest risk correspond to the areas of recent pyroclastic flows that have originated from, and the central crater region itself. For example the Rembokola zone corresponds to the area which has experienced the most recent pyroclastic flows and whose upper reaches contains a large breach in the crater wall. Zones 2 and 3 are also relatively high risk zones and correspond to the sites of older pyroclastic flows and laharic fans but without defined exit routes from the central crater. For example the Mbazo zone has experienced older pyroclastic flows and includes a recent dacite dome that blocks the exit route from the crater to this part of Savo. Zone 4 is a lahar-dominated risk zone, but may, in extreme cases be subject to pyroclastic flow activity. For example, the Mbirasu area has a well developed fluvial fan with a ‘tail’ which extends towards the crater. Zone 6 is the lowest risk or ‘safest’ zone which comprises areas which are on the lee-side of the numerous older lava domes. For example the Kalaka zone is in the lee of the large Kalaka dome which is perhaps the most effective physical barrier on the island. Zone 5 is an intermediate-low risk zone between Zones 6 and 4. Figure 8 includes large areas of ‘undetermined’ risk which comprise largely of the steeply sloping flanks to the volcano. As such, it is an area which contains no permanent habitation and does not afford either a long-term sanctuary or easy evacuation access. It may, however, be more appropriate to assign a low-moderate risk (Zone 5) to these areas.

It must be noted that although the hazard map presented here is provisional, it is a contribution to hazard assessment of Savo and will act as a starting point for future work and discussions.
Figure 8: Volcanic hazard map of Savo showing the most hazardous areas (Zones 1-3) located within the pyroclastic flow fan deposits, and the crater respectively; lesser hazards (Zone 4) located within lahar dominated fans; and the safest areas (Zones 5 and 6) located on or close to the lee side of upraised volcanic domes and plugs. The area labelled ‘undetermined’ comprises the steep sided slopes of the volcano which neither offer long-term sanctuary nor easy evacuation access: this area could be reclassified as a Zone 4/5 risk area.

SYNOPSIS OF THE MAIN HAZARD/RISK AND HAZARD MITIGATION FACTORS ASSOCIATED WITH A MAJOR ERUPTION FROM SAVO

The list below provides a number of points which are felt to be particularly important conclusions of this volcanic hazard assessment of Savo. The list is by no means exhaustive or all-inclusive. The final point itemises recommendations for further work:

- Pyroclastic flow-related hazards (Zones 1 to 3 of Figure 8) pose the greatest threat to the population of Savo. At least 50 per cent of the population are at risk.
- The inhabitants at highest risk are those living in areas which are within a relatively easy access, direct flowpath from the crater. Specifically these are the Rembokola-Paimbeta and Poghorovurughala-Reko areas respectively.
- Pyroclastic fall-related hazards are a major hazard not only to inhabitants of Savo but also to those on neighbouring islands. Documented accounts of residents from NW Guadalcanal (e.g. Appendix 1) indicate that ash fall has affected areas within at least a 20 km radius of Savo. Furthermore, Latter (1991) has estimated tephra thicknesses for eruptions of differing magnitudes and seasonal wind patterns. Latter’s worst-case scenario involves a 1 km$^3$ volume eruption (Figure 9) which would produce a 1 cm compacted thickness tephra fall deposit, at a distance as great as 400 km from Savo, in the direction of the most favourable winds. The minimum distance for this scale of eruption and tephra thickness is estimated to be some 70 km. Heavier (>1 cm; <10 cm) ash falls pose a risk to Savo, northern parts of Guadalcanal (including Honiara) and the Russell and Florida Island groups. Ash fall hazard and mitigation maps and plans should be prepared on the basis of the worst-case scenario presented by Latter (1991).
Larger scale eruptions could induce edifice collapse, resulting tsunami generation. Tsunami-related damage is of particularly concern in coastal areas, including those which are \( \leq 10 \) m above sea level, in regions which are within a direct trajectory of Savo-generated tsunamis. These regions include: the eastern-facing coastal areas of the Russell Islands; west-facing coastal areas of the Florida Islands; south and SE facing coasts of southern Santa Isabel; west-facing coasts of Malaita; possibly east-facing coastal areas of the nearer New Georgia Islands such as Vangunu; and, most importantly in terms of population north-facing coastal areas of Guadalcanal, including the capital of Honiara. Much of the township of Honiara is at a height of \( \leq 5 \) m above sea level, including the Central Hospital, Government offices; fuel containers/storage areas; many residential areas; hotels etc.

- It is strongly recommended that further detailed risk assessment and hazard mitigation studies be undertaken. These studies should include: 1) a detailed C14 study of Savo to determine a more comprehensive eruptive history than is presently known; 2) the development of a modern evacuation plan for Savo including plans for the relocation of the Savo people; 3) a scientific assessment of tsunami and ash fall related risks in relation to areas such as Honiara, Tulagi, northern Guadalcanal, the Guadalcanal plains etc; and 4) an assessment of the most appropriate monitoring program for Savo should be undertaken, which includes identifying the most effective instrumentation that should be deployed on the island.

### ACKNOWLEDGEMENTS

This paper results from an invitation to submit a paper by Mr Paul Taylor, editor of this SOPAC volcanic hazards bulletin, who suggested that it was timely to publish on this subject.

The authors would like first and foremost to thank the people of Savo and fellow officers at the Mines and Minerals Division in Honiara without whom this paper would not have been possible. MGP thanks the UK Department for International Development (UKDFID, formerly UKODA) and the British Geological Survey for their assistance and support. The authors also thank the Solomon Islands National Disaster Council, UNDHA in Suva, and SOPAC for their encouragement and support. Drs G. Burr and D. Rex are thanked for their C14 and K-Ar determinations respectively. Michel Lardy of ORSTOM and Michel Larue formerly of SOPAC are thanked for their assistance.
REFERENCES


APPENDIX 1

The following story was recorded by JC Grover in 1961 and is included in this report for completeness. The story records an eye witness account of an eruption in circa 1830 on Savo as seen from Guadalcanal.

Department of Geological Surveys

Savo Volcano – An Eye Witness Description of the 1830 Eruption:

“Suggati, the father of Marino Tandabara of Takamboru village on the Kotina - Sasa River, was a very old bald headed man of 80 to 100 years old in 1927 when he told his 12 year old son about the eruption of Savo volcano. Which, he had seen from his hill village, on Guadalcanal, (Figure A1) nearly a life time before.

It was before the white man came to Guadalcanal and at the Gnali nut time of the year - June or July. Very heavy rain had fallen on Savo that day, and the old man thought that this might have had something to do with the volcano as there was no earthquakes felt on Guadalcanal at the time. It started in the evening in a small way first, but at midnight there were sounds like the continued “hoot of a steamer”, and also like a river in flood rolling large boulders against each other. The sounds of many muffled concussions; these became louder and felt as earthquake shocks like repeated thumping about 120 to a minute.

Then came the cataclysmic outburst: The Guadalcanal mountains and all the people standing outside their houses watching the spectacle were lit up as though by daylight, and millions of great fiery rocks “red like the moon”, were thrown into the sky above the fire on Savo, falling into the surrounding illuminated sea. Some fell on Guadalcanal near Visale. At Chapuru ashes in a thin layer covered the jungle leaves, the ground and gardens between Ndoma on the east and Kesau on the west coast of Guadalcanal.

All that night the explosion continued, and all the next day – with hot rocks being ejected. The eruption died away the following night.

At dawn the Guadalcanal people flocked down from their hill top villages to the beaches and found there many Savo people who had managed to escape by canoe. Everyone was kind to them as many were relatives. Those with relatives and friends in the Florida Group escaped that way; others to their friends along the west coast of Guadalcanal. Many of them remained for ten years or more, for Savo had been made completely desolate from Koela on the west coast to Kaogele on the east.”

Suggati of Harango a bush village in the Sasa River valley west Guadalcanal. His son Marino was born in 1915. Suggati died in 1929. Story told to Mr JC Grover by Marino Tandabara 12. 04. 61.

JC Grover’s Comments

Undoubtedly the roaring is associated with escaping gases. It is essential that people of Savo should know this story because it agrees with what geologists expect to happen. The story may not be exactly true in that there might have been earthquakes in the week before the eruption, which people did not take note of. The story says that activity apparently began in the evening and the climatic eruption at midnight; giving only several hours warning.

In my opinion there should be more canoes on Savo. Every family should have one and every family should maintain friendly relationship with kinsfolk on the adjoining islands. Every tremor on Savo should be reported as soon as possible by radio to the Chief Geologist. There should be more than one man able to use the radio.

REPORT BY JC GROVER 1961
B.S.I. GEOLOGICAL SURVEY.
Retyped 20. 04. 93.
Figure 1: Location map of Takamboru village west Guadalcanal and the area affected by an eruption in c. 1830.
IS THERE VOLCANIC HAZARD IN FIJI? VOLCANIC GEOLOGY INVESTIGATIONS ON TAVEUNI

S. J. Cronin

Massey University, NEW ZEALAND

ABSTRACT

Recent geological investigations on Taveuni reveal that basaltic volcanism has occurred on average every 105 years since the earliest known time of human occupation on the island, c. 2180 years B.P. The last known eruption is dated at c. 340 ± 70 years B.P. This information indicates that Taveuni should be considered an “active” volcano. Volcanism on the island has been dominated by Hawaiian and Strombolian processes with lava flows and tephra falls of individual eruptions, typically covering areas of up to 24 km² with substantial deposits. Population and rapidly developing infrastructure on Taveuni are at risk from future eruptions due to their close proximity downslope and downwind of possible new vent areas. Advances in mitigating this volcanic risk include construction of a GIS-based hazard and risk assessment system that is flexible enough to predict likely effects of eruptions in differing possible vent areas and can be updated with the developing infrastructure of the island. Workshops will be used to promote the development of an emergency response plan, early warning system and public education programs, run in partnership with disaster management authorities.

INTRODUCTION

Taveuni, located in the Northern Division of the Republic of Fiji (Figure 1), is the largest of four potentially active volcanic islands in the Fiji group – and geomorphologically the most promising of recent activity.

Taveuni is a large shield volcano complex located in the Koro Sea area, where it is inferred that the youngest volcanism in Fiji occurred in response to back-arc spreading over the last 3 Ma (Colley and Hindle, 1984). The elongate 437 km² island rises steeply to a central ridge that runs along its long-axis. Peppered along this ridge are >150 scoria cones, craters and fissure zones, expressing the basaltic-hawaiite monogenetic volcanism throughout at least the late Pleistocene and Holocene (Woodhall, 1998; Cronin and Neall, 1998).

Taveuni is also the home of 14,500 people (Ishri, 1997) who live in relative prosperity from farming the young and fertile volcanic soils. Development (including sealed road construction, water reticulation, electrification, and communications) is proceeding rapidly on the island due to its current wealth and the approaching new millennium – Taveuni being located astride the 180° meridian.

Taveuni has largely been ignored by those with a volcanic hazards interest but has hosted archaeological, soil and pollen studies, which, along with the geologic mapping in the area form the starting point of this study. From the past work, it was recognised that young volcanic activity had occurred in three different locations on the island at times of <2050 years B.P., <1645 years B.P., and >1500 years B.P. (Frost, 1974; Southern, 1986, Shepherd and Neall, 1991).

OBJECTIVES

In undertaking this research project, the following questions were put forward:

- Will Taveuni erupt again?; if so,
- What will happen when it erupts?
- Where will future eruptive vents be?
- Who and what is at risk; and
- What can we do about it?

**Figure 1:** Taveuni, with some of the younger mapped units, those in grey are undated, but are probably all <2000 years B.P.
NEW RESULTS

Will Taveuni erupt again?

The youthful geomorphology of Taveuni coupled with its young Andisol soils (Shepherd and Neall, 1991) point to recent volcanic activity on the island. Place names, such as Tavuyaga - meaning “burning place” (Geraghty, 1998) for a prominent scoria cone also indicate volcanic activity during the time of human occupation. In addition, vague stories describe volcanism on Taveuni (Kotobalavu, 1995), which so far, appear to be based in geologically reasonable places.

An extensive geologic mapping campaign has been undertaken on the island, concentrating on delimiting, dating and characterising the Holocene and late Pleistocene activity. So far, using tephrostratigraphy, 12 new radiocarbon dates, and past dates that can be related to volcanic activity, and a comprehensive stratigraphy over the latest Holocene have been developed (Table 1). Several important summary points can be taken from this stratigraphy:

- A new date provides the oldest direct evidence for human occupation yet found on Taveuni at 2180 ±70 years B.P. (Wk6208).
- A new date provides the youngest direct evidence for eruptive activity yet found on Taveuni at 340 ±70 years B.P. (Wk6209).
- Since the earliest known human occupation, there is evidence for at least 21 eruptions, indicating an average eruption recurrence interval of 1 per 105 years.
- There is some evidence of clustering of eruptions in time or “eruptive intervals” which may be separated by longer periods of time, perhaps 1 in 300-400 years.
- Given the large number of eruptions evident from the recent geologic record, it is difficult to quantify eruptive frequencies before 2000-2500 years B.P., due to burial and poor preservation of the older deposits in areas of younger volcanism.
- Given the eruptive frequency of Taveuni over the last 2000 years and the age of the latest known volcanism, the probability is very high that Taveuni will erupt again in the future and should be considered an “active” volcano.

What will happen when Taveuni erupts?

Investigation of the deposits from past eruptions has revealed three main types of eruptions occur on Taveuni: 1) non-explosive, Hawaiian style effusive eruptions, producing voluminous lavas; 2) mildly explosive, Strombolian style eruptions, producing moderate-sized tephra falls and small-volume lavas; and 3) explosive, phreatomagmatic style eruptions, producing tuff rings. The first two types of eruptions are by far the most common. Most past eruptions on Taveuni have only directly affected areas between 5-10 per cent of the total island.

Lava Flows

Lava flows appear to accompany almost all eruptions and often flow to the sea down the steep flanks of the island, covering distances up to 8 km. Lava 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 the south of Taveuni). Highly mobile, low-viscosity pahoehoe type lava flows occur, forming and flowing within tubes and channels. In addition, clinkery/blocky aa-type lavas also occur. Normally, several lava flows were extruded with each eruption. The earlier extruded lavas from an eruption flowed down and infilled the main drainage channels. Later, extruded lava flows diverged from these flow paths to flood out over new areas.

Late Pleistocene and Holocene lava flows from typical eruptions on the steep central portions of the island covered areas between 3 and 7 km², being mostly valley-confined. Lavas on flatter areas at the north and south of Taveuni usually covered much larger areas, between 11 and 24 km². Lava flow volumes ranged from 0.01–0.25 km³ or 10–250 million m³, the largest flows resulting from Hawaiian-style eruptions.

Lava flows are likely to cause the greatest damage from future eruptions on Taveuni, not only burning and destroying everything in their paths but also generating potentially widespread fires from their margins. The potential for fires is great due to the heavily forested nature of Taveuni. 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. However, many of the Taveuni flows were apparently gas-poor and only weakly explosive on entering the sea. Clinkery aa-type lava flows emplaced
TABLE 1: PRELIMINARY COMPOSITE STRATIGRAPHY OF MAPPED VOLCANIC UNITS ON TAVEUNI, WITH RELATION TO RADIOCARBON AGE DETERMINATIONS. STRATIGRAPHY OF UNITS <2180 YRS B.P. IS THOUGHT TO BE NEAR COMPLETE, ALTHOUGH FOR >2180 YRS B.P. STRATIGRAPHY MANY CORRELATIONS HAVE YET TO BE MADE AND THE STRATIGRAPHY REPRESENTS ONLY A FEW LOCATIONS ON THE ISLAND.

<table>
<thead>
<tr>
<th>Dates (Yrs B.P.)</th>
<th>Mapping Units</th>
<th>Correlated Mapping Units</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>340 ± 70</td>
<td>South Cape lavas</td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Tutu lavas</td>
<td>Naqara lavas</td>
<td></td>
</tr>
<tr>
<td>499 ± 162†</td>
<td></td>
<td></td>
<td>Shepherd and Neall, 1991</td>
</tr>
<tr>
<td>510 ± 60</td>
<td></td>
<td>Naqara lavas</td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Des Voeux 2 tephra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>640 ± 60</td>
<td></td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td>1020 ± 130</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1090 ± 60†</td>
<td></td>
<td>Soqulu 2 tephra ?</td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td>1460 ± 160</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tavuyaga cone and tephra</td>
<td>Ngatavo cone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coloci cone and tephra</td>
<td>Ngatutu cone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Holmhurst cone tephra and lava</td>
<td>Vatuwiri lava</td>
<td></td>
</tr>
<tr>
<td>1500 ± 120</td>
<td></td>
<td></td>
<td>Southern, 1986</td>
</tr>
<tr>
<td>1560 ± 60</td>
<td></td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Tagmaucaea 2 tephra</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Des Voeux 1 tephra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1645 ± 55†</td>
<td></td>
<td></td>
<td>Shepherd and Neall, 1991</td>
</tr>
<tr>
<td></td>
<td>Likuvauosomo tephra</td>
<td>Ura tephra</td>
<td></td>
</tr>
<tr>
<td>1750 ± 65†</td>
<td></td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Delai Vuna tephra</td>
<td>Narata cone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Palo crater/cone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manuka tephra</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mbenubenu tephra</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hillsborough cone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Qila cone</td>
<td></td>
</tr>
<tr>
<td>2180 ± 70</td>
<td>Soqulu 1 tephra</td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Soqulu lava</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4830 ± 170</td>
<td>Nayavuloa cone and tephra</td>
<td>Naqilai tephra?</td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Ndana tephra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7812 ± 61†</td>
<td>Tagmaucaea 1 tephra</td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td>14 120 ± 370</td>
<td>Tagmaucaea crater</td>
<td></td>
<td>Southern, 1986</td>
</tr>
<tr>
<td></td>
<td>&gt;45 000</td>
<td></td>
<td>Cronin, unpublished</td>
</tr>
<tr>
<td></td>
<td>Koronitivora tuff</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>South Cape tuff</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All Cronin dates were analysed by the Waikato Radiocarbon Dating Laboratory, and will be published with their respective Wk numbers in a future journal article.

† These are AMS age determinations, the remainder are conventional dates.
onto steep slopes on Taveuni have generated block-and-ash flows, presumably via collapsing of the rubbly lava flow fronts. The block-and-ash flows were probably 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 increased the hazards in the downslope areas of the aa lava flows, and these block-and-ash flows may have affected larger areas than the lava flows that generated them.

**Tephra Falls**

Only the Strombolian-style eruptions produced widespread tephra falls that were preserved in the geologic record. Field data of 10 tephras on the island was used to construct isopleth maps (maps of the distribution of the largest clasts within tephras) for assessing eruption parameters, and isopach maps to calculate volumes of eruptions. Tephra volumes were found to range between 6 and 16 million m³, and typical eruptions covered areas between 6 and 17 km² with >10 cm of scoriaceous tephra (e.g. Figure 2). Wind dispersal of tephra is normally towards the populated western half of the island, driven by the prevailing trade winds from the south-east (e.g. Mbenubenu tephra, Figure 2). Isopleth data confirm that tephra eruptions were of a Strombolian style. Using the Taveuni isopleth data and plotting it on the diagrams of Carey and Sparks (1986), it appears that eruption columns depositing these tephras were probably between 6 and 11 km high. Many tephras were erupted from more than one vent, e.g. the Tavuyaga tephra (Figure 2) comprises the products from three separate vent locations, erupting within a short space of time (<1-2 years est.).

![Figure 2: Isopach maps (isopachs in cm) and isopleth maps (isopleths in mm) of two typical Taveuni tephras. Eruption column heights estimated from the isopleth data plotted onto the diagrams of Carey and Sparks (1986).](image-url)
This scale of eruptions on Taveuni, although small from a world 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 and, 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 fires, which occurred during past eruptions of >30 cm tephra (containing hot clasts of >4 cm diameter) onto the dominantly forest vegetation. Lightening associated with tephra plumes may also start fires. The isopach maps of Taveuni tephras indicate that tephra falls of >20 cm thick can occur up to 4-5 km from the source vent. Isopleth data indicates 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). 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, areas may need to be cleared of tephra to enable replanting.

**Phreatomagmatic Eruptions**

Phreatomagmatic eruptions (involving the interaction of hot magma and water) 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 phreatomagmatic eruptions, where magma encountered standing water, swamps or saturated sediments.

During these eruptions, rapidly lateral moving pyroclastic surges were generated (>100 km/hr in historical examples; e.g. Moore et al. 1966). On Taveuni, these surges deposited ejecta, containing clasts up to 5 cm in diameter, up to at least 1 km from the vent; beyond this point, deposits are poorly preserved. Pyroclastic surges in similar types of eruptions elsewhere in the world have travelled between 2 km and up to 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. Phreatomagmatic eruptions also generate fine-grained tephra columns, which distribute tephra long distances from source (e.g. Self et al., 1980). Offshore phreatomagmatic eruptions around Taveuni have the potential to generate small tsunamis that could possibly affect coastal communities on Taveuni and neighbouring islands.

**Lahars**

Some eruptions on Taveuni were accompanied by lahars, particularly when freshly erupted tephra was remobilised from the steep upper slopes of the island by heavy rainfalls. Rainfall exceeds 6 m per annum in the central portions of the island, and often falls in high intensity downpours (Krishna, 1980). Lahars are likely to be generated if eruptions occur during a heavy rainfall event or if heavy rainfall were to directly follow an eruption (before vegetative cover could re-establish).

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 have the potential to affect downstream communities on the flat-lying coastal portions of the island for 1-2 years after an eruption.

**Where will future eruptive vents be?**

On Taveuni, like in all monogenetic volcanic fields, the location of the next eruption is difficult or impossible to predict until pre-event seismicity is detected. In excess of 150 volcanic vents are identified along the central axis of Taveuni (Woodhall, 1998). As a first-order measure, a map can be constructed showing areas of relative probability of the location of future eruptions on Taveuni (Figure 3). This map is based on the spatial density of past eruptive vents; higher density indicates a higher probability of future eruptions. The highest probability for the location of future eruptions is along the southern central axis of the island. With the eruption ages presently known, there appear to be no obvious trends or progressions in age of volcanism along the island’s central axis. Hence the probability is equally high anywhere along this zone (zone A on Figure 3). The next zone, flanking the southern central axis and extending along the remainder of it contains a lower spatial density of past vents, indicating a lower probability of new activity from this area relative to zone A. The lowest relative probability occurs over the remainder of the island, although the presence of more widely spaced past vents indicate that activity is certainly possible in this area.
Figure 3: 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.
Who and what is at risk?

Around 14,500 people (Ishri, 1997) live on Taveuni, with around 75 per cent of these people concentrated on the leeward side of the island at greatest risk from the wind-driven tephra falls. Most village locations are also beside streams or in flat coastal areas and are at greatest risk from lava flows and lahars. Only one road services the entire length of the island, on its western side, hence eruptions may well cause isolation of communities from hospital services, shipping and air transport. Taveuni is an important centre for communications and hospital services for the surrounding islands, and its importance in these areas is planned to grow. The new development initiatives taking place over the next few years on Taveuni (e.g. hospital redevelopment, electrification, water supply systems, sealed roads, and communication systems) will increase the infrastructure at risk to volcanic action and will probably also increase the population.

What can we do about it?

There are several mitigation activities that are planned over the next year of this project. These activities will be carried out in partnership with the Disaster Management Unit (formerly the South Pacific Disaster Reduction Programme of UNDP), and the Hazard Assessment Unit of the South Pacific Applied Geoscience Commission (SOPAC), and the National Disaster Management Office of the Fijian Ministry of Regional Development.

a) A volcanic hazard assessment will be developed from the geologic mapping, radiocarbon dating, and volcanic process interpretation work on Taveuni. Due to the constantly shifting location of volcanism on the island, construction of a hazard map will be somewhat different to that for a volcano with a relatively fixed vent location. Instead, the presentation of hazard assessments on Taveuni will show example scenarios of the most probable type and magnitude of eruptions (as well as extreme events), with hypothetical vent locations. Details of the most probable and maximum eruption scenarios will be derived from geological evidence on the island and its volcanologic interpretation. It is planned that this volcanic hazard assessment will be in a GIS format, using a digital terrain model (DTM) of the island, with population and infrastructure overlays that can be easily updated. The system will be designed so that the differing eruption scenarios can be run at any point on the island and the areas affected (controlled by the topography of the DTM, and wind information) can be quickly assessed. Emergency management authorities in Fiji can then use such a system once they receive seismic or other evidence of the location of a possible new eruption.

b) A volcanic risk assessment will be made for the island, taking into account the volcanic hazards information, the population and infrastructure at risk, and the vulnerability of the elements subject to volcanic hazard. Risk analyses will be able to be performed ad-hoc on the GIS system once population and infrastructure information is entered onto it.

c) Communication of the volcanic hazard and risk information will be made to the permanent planning authorities in Fiji (planned for Feb-Mar 1999) in a specifically designed workshop. A document outlining volcanic hazard aspects relevant to future development of the island will be prepared during this meeting.

d) Preparation of an Emergency Response Plan for volcanic activity on Taveuni. This plan will be communicated and revised during a workshop on Taveuni (planned for April-May 1999), involving all relevant disaster management, regional and local authorities.

e) Preparation and distribution of public awareness booklets and leaflets, outlining volcanic hazards present on Taveuni and key features of the Emergency Response Plan. These leaflets, along with a public awareness tour and campaign (planned for April-May 1999) will aim to increase the knowledge of the Taveuni people about volcanic hazards, as well as inform them of what to do in the case of the onset of an eruption.

f) Development of recommendations for a monitoring or surveillance system on Taveuni. Already, a new seismometer has been installed on the island as a result of the first findings of this study (the old machine was out of commission for several years). However, long-term strategies need to be developed for timely and accurate warning systems on the island.

g) Development of plans for on-going education and awareness activities with public, permanent planning and disaster management groups, as well as regular updates of Emergency Response Plans.

CONCLUSIONS

Geological evidence suggests that Taveuni is an active volcano. New radiocarbon dating reveals that during the time of human occupation (c. 2200 years B.P.), there has been on average one eruption every 105 years.
Basaltic eruptions on Taveuni are most frequently of Hawaiian or Strombolian style, with each eruption producing lavas and/or tephras that cover areas of up to 24 km² with substantial deposits. Strombolian eruption columns on Taveuni may reach high enough altitudes to affect passing international air traffic. Lahars may be generated during or in the 1-2 years following tephra eruptions in response to heavy rainfall events. Less frequent eruptions occur through water and engender the additional volcanic hazards of pyroclastic surges (up to 3 km from the vent) and small tsunamis.

Due to the number of people at risk from eruptions on Taveuni and the rapidly developing infrastructure on the island, several steps need to be taken toward mitigating the potential volcanic risk. These include the preparation of an interactive GIS volcanic hazard and risk assessment system, preparation of an emergency management plan, incorporation of hazard information into long-term development planning, development of a timely warning system, and on-going civil administrator and general public education.

To allow the best use of geologic information in the disaster management arena, there should ideally be a seamless transition between collection of geologic data and the dissemination and incorporation of that data into a country’s disaster management plan and its long-term development planning strategies. This project on Taveuni is to be used as demonstration of this integrated approach for other Pacific Island countries, beginning the process of assessing and mitigating their potential geologic hazards.

ACKNOWLEDGEMENTS

The core of this project is funded by a New Zealand Science and Technology Post-Doctoral Fellowship, contract MAU702. I thank Russell Howorth, Alf Simpson, and Graham Shorten, of SOPAC, Isabel Calvert of the New Zealand High Commission in Fiji, Atu Kaloumaira and Joe Chung of the SPDRP, Akapusi (Tui) Tuifagatele and Jone Bolatamana of the Disaster Management Office of the MRD for their generous assistance in supporting my work in Fiji, and for their continued support for the next phase of the project. I also thank Vince Neall for his introduction to the area and ongoing support, Fr M. McVerry, R. Ali, R. and M. Pao, and L. and M. Leuma, for their help on Taveuni, and P. Kabakai and S. Rabici for doing the lions-share of the tracking.

REFERENCES


