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Environmental impacts on health from continuous volcanic activity at Yasur (Tanna) and Ambrym, Vanuatu

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Continuous low-level basaltic volcanic activity, from Yasur Volcano in Tanna, and Marum and Benbow vents on Ambrym, occurred for as long as records have been kept in Vanuatu. The potential chronic health implications for the inhabitants of these two areas were investigated in a preliminary environmental sampling program. The focus was particularly on fluoride and other volcanic gas-derived chemical contamination in areas surrounding the volcanic centres. Little immediate contamination of the environment was evident for areas affected by volcanic ash and gas on Tanna, with water fluoride concentrations being elevated (to 0.42 mg l^{-1}) only within a lake adjacent to the active volcanic cone. Selected re-sampling in April 2001 following the long active phase of Yasur, revealed higher F levels in surface waters (to 1.05 mg l^{-1}). Analysis of cow rib bone and teeth indicated a possible long-term accumulation of F in grazing animals, which probably consume F-bearing volcanic ash and gas hydrates on the surface of plant leaves. No human impacts (including stress and respiratory problems) were noted, probably due to the constant and familiar low-level activity, plus the coarse nature of most ash ejecta. Ambrym appears to be a more F-concentrated system than Tanna, with volcanic ash containing 281 total and 36.7–43.6 soluble mg F kg^{-1} (cf. 178 total and 7.3–9.1 soluble mg F kg^{-1} on Tanna), and water levels reaching up to 2.8 mg F l^{-1} in rainwater tanks. The drinking water F levels on Ambrym are higher than WHO recommended levels, despite the being sampled during a substantial lull in eruptive activity, and signal potential for chronic dental and skeletal fluorosis.

Keywords: Volcanic gas; fluoride; Vanuatu; Ambrym; Tanna; Yasur volcano

Introduction

Volcanic activity of the Yasur cinder cone on Tanna Island and Marum and Benbow craters on Ambrym Island (Fig. 1A–C) has been semi-continuous for as long as records have been kept in Vanuatu (Eissen *et al.* 1991). Acid rains and vegetation damage are reported from periods of elevated volcanic ash and gas emissions from both volcanic areas (e.g., Eissen *et al.* 1989; 1990). However, little attention has been paid to any long-term impacts on human health in the populated areas surrounding the two volcanoes. A report from the provincial community health office responsible for Tanna stated that the activity of the volcano was adversely affecting

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human health, buildings, fruit trees, food crops, the water supply and the environment in general. This led to a request from the Vanuatu Minister of Health to the World Health Organisation Regional Office for the Western Pacific to investigate the impact of volcanic gas and ash on the inhabitants of Tanna and Ambrym. Up to 7,369 inhabitants on Ambrym and 25,840 on Tanna are potentially affected by semi-continuous volcanism. (National Statistics Office 2000).

The three major areas of potential chronic human health impacts from volcanic activity include respiratory problems, particularly silicosis (Buist *et al.* 1986; Baxter *et al.* 1999; Allen *et al.* 2000), psychological stress (e.g., Shore *et al.* 1986), and chemical impacts of gas or ash (e.g., Giammanco *et al.* 1998).

Here the latter type of these three impacts is considered, since the basaltic nature of the Yasur and Ambrym activity implies low potential for silicosis (cf., andesitic-rhyolitic ash falls; e.g., Baxter *et al.* 1999), and the semi-permanent low-level activity is less likely to induce high levels stress compared to isolated large eruptions. A sampling program was carried out from 26 October to 6 November 1999, in order to determine the chemical impact of volcanism on a variety of environmental factors including food crops and water supplies. Waters in the Yasur area of Tanna were also re-sampled on 7 April 2001. Fluoride inputs to the environment were examined in greatest detail; this has proven hazardous to human and animal heath in many past volcanic eruptions (Roholm 1937; Thorarinsson; 1979; Arya *et al.* 1990). Long-term or chronic impacts on health are focused on, as opposed to most published studies that concentrate on impacts of one-off eruptions. This is allowed by the unusual situation where large subsistence-based communities live their entire lives adjacent to constant volcanic activity.

Geological background

Tanna and Ambrym, Vanuatu

Vanuatu is an archipelago of more than 80 islands, which form a portion of an island-arc system extending from New Zealand to New Britain (Fig. 1A). Volcanism on Tanna (near the southern end of the chain), has been confined to the Yenkahe caldera in the southeastern part of the island for 10,000 years (Robin *et al.* 1994). Present basaltic activity occurs from the Yasur cinder cone, which has been in a semi-continual state of activity since 1774 (Eissen *et al.* 1991). Typically small-scale strombolian-style eruptions throw volcanic bombs in and around the crater area along with a semi-continuous emission of a plume of gas and ash (Nairn *et al.* 1988). The gas–ash plume is distributed primarily northwestward, by the prevailing southeasterly trade winds. Gas samples collected in 1988 contained SO_2, and HCl, with an estimated discharge rate of between 400 and 800 tonnes of SO_2 per day (Nairn *et al.* 1988). Sampling in 1990 suggested that the SO_2 emission rate was very high compared to other Vanuatu volcanoes at $1{,}200 \pm 600$ tonnes per day, causing extensive damage to downwind gardens and coffee plantations (Eissen *et al.* 1990).

Ambrym Island is a large basaltic shield volcano with a 12-km wide central caldera, resulting from highly explosive hydrovolcanic activity *ca.* 1900 years BP (Robin *et al.* 1993). Most historically recorded activity has occurred within the caldera, which contains two continually active vents (often filled with lava lakes) near its centre emitting gas and ash (Marum and Benbow). Several larger-scale eruptions over the last 150 years included major extra-caldera ash falls, lava flows that sometimes overflowed to the volcano flanks and lava flows and ash sourced from extra-caldera flank vents (Eissen *et al.* 1991). In 1979, gas and ash, combined with rain, caused extensive pasture and crop burning in a 90-km^2 area (Mcfarlane 1979). In addition, the

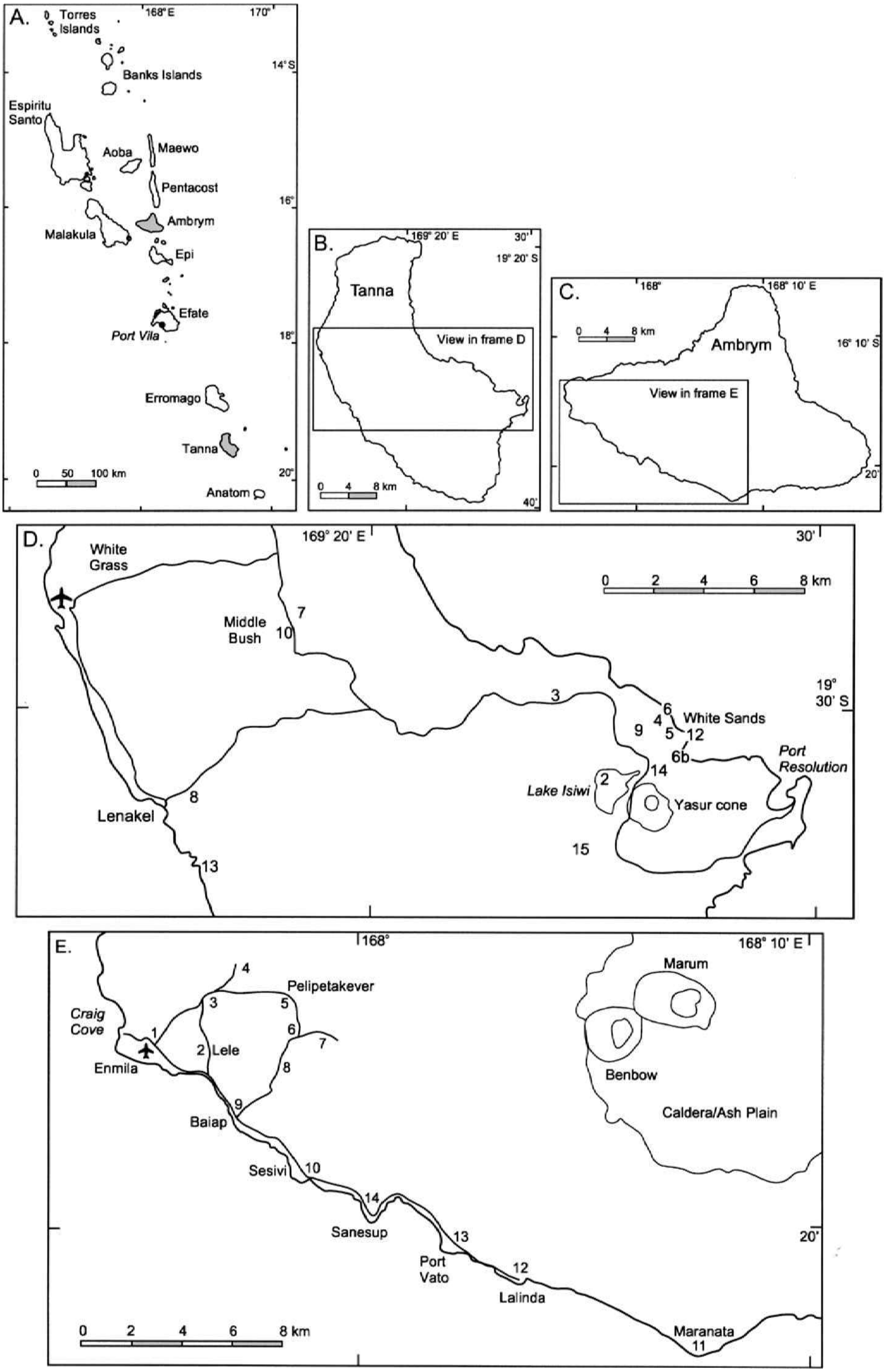

Fig. 1. Location maps of the studied areas: (A) Vanuatu group; (B) Tanna Island; (C) Ambrym Island; (D) sampling areas on part Tanna Island; (E) sampling areas on part Ambrym Island.

local population suffered gastric upsets and burning of the skin due to contact with the acid rainwater. Acid rains also caused vegetation burning during a more energetic phase of activity in 1989 (Eissen *et al.* 1989). In 1997 rainfall was measured with a pH of 2 near the crater, and pH 4 several kilometres away (Vetch and Haefeli 1997).

Volcanic gas/aerosols and ash

Volcanic gases comprise (in generally decreasing order of abundance) H_2O, CO_2, SO_2, HCl, NH_4^+, H_2S, HF and a few other minor constituents (e.g., Symonds *et al.* 1994). Their main hazards include respiration and skin problems in humans along with acidic burning of plants, and corrosion of metal structures. Gases almost always combine with water in the atmosphere to generate acid aerosols and sometimes acid rains (Anderson 1910; Rampino and Self 1984). In addition, volcanic gases and aerosols commonly coat and are transported and deposited with ash particles (e.g., Rose 1977).

In Java in 1979, an eruption in the Dieng mountains released CO_2 and H_2S gases which moved down-slope to kill 145 residents and four rescue workers (Giggenbach *et al.* 1991). In 1986, over 1,700 people were killed by sulphurous and CO_2 gases emitted from Nyos crater in Cameroon (Giggenbach *et al.* 1991). Grazing animals have been affected by volcanic ash and gases in past eruptions in Iceland (50–70% of livestock killed and 10,000 people died in the resulting famine in 1783, Öskarsson 1980), Chile (Arya *et al.* 1990) and New Zealand (Cronin *et al.* 1998). In all cases Fluoride appeared to be the most toxic component, with secondary elements such as excess S and Se possibly having an additional effect.

Sampling and methods

Tanna

Tanna was visited between 28 and 30 October 1999, while Yasur was erupting ash plumes at intervals between 5 and 15 min. These were distributed northwestward to most strongly affect populated areas 2–4 km WNW of the vent.

Drinking water samples were collected from three general locations: a high ash fallout area near the volcano (sites 4, 5, 6, 6b, 9, and 12; Fig. 1D) a low fallout area (sites 7 and 10) and an intermittent fallout area (site 8). Water samples from storage tanks of differing composition were collected to determine if acidity of the water caused leaching of undesirable compounds in any of the cases. In addition surface waters were collected from Lake Iswi (site 2) sited directly northwest and adjacent to Yasur, and from a stream in the area of intermittent fallout (site 13). All samples were tested on site for pH (using a Hach EC10 pH meter), for turbidity (using an Oxfam Delagua portable water testing kit, with a range of 5–2000 Turbidity Units) and for enteric organisms using the H_2S water-quality test (Manja *et al.* 1982). Seven samples were also tested for faecal coliforms using a membrane filtration technique (in the Oxfam DelAgua kit)

Freshly fallen volcanic ash samples were collected by setting out dry glass Petri dishes at site 2 (Fig. 1D). Air quality was measured at sites 1 and 6b, located 3 km W and 2 km NE of Yasur, respectively (Fig. 1D). Air samples were collected using a Dräger multigas tester during a period of heavy volcanic activity (explosions at 5–15-min intervals). Food crop samples including corn, island cabbage and sweet potato leaf were collected at site 3 (5 km NW of Yasur), and island cabbage as well as lichen collected at site 4 (2 km N of Yasur). Samples of rib bone and teeth from a cow (slaughtered 6 weeks earlier) were collected at site 3 (Fig. 1D). Small human hair samples were collected from eight to 10 individuals at sites 3, 4 and 11 (Fig. 1D) the former two in an area of frequent and heavy ashfalls, and the latter in a zone of intermittent falls.

In all areas visited, interviews were conducted with local residents, medical dispensary staff, schoolteachers, and farmers to determine if there were any major psychosocial impacts.

Ambrym

Ambrym was visited from 2 to 4 November 1999, during a time of minor fallout. Drinking water sampling was focussed on the populated WSW sector of the island, 10–18 km downwind of the active vents (Fig. 1E), with groundwater springs sampled at sites 5, 11 and 14. Air quality was measured at site 1, 18 km west of Marum and Benbow craters, and fresh volcanic ash from site 5, 12 km west of the vents.

Geochemical techniques

Fluoride analysis of volcanic ash and human hair samples was carried by fusion with NaOH at 600°C in a nickel crucible, followed by dissolution in water (Frankenberger *et al.* 1996). The Al and Fe ions that interfere with F analysis (Bellack 1972) were removed by adjusting solution pH to 8.5 (with HCl) and filtering the suspension. Ash samples were also subjected to a three-stage sequential extraction in water (ash:water, 1:20, and 16 h shaking) to determine the readily soluble F content along with indicating its form in the ash.

In plant samples, F was extracted with 0.2 M perchloric acid (Geeson *et al.* 1968). Since most F is held in an acid-labile form, this method normally compares well with the total fusion method (Cooke *et al.* 1976). Cow bones and teeth were dissolved in 0.5 M perchloric acid (Kierdorf *et al.* 1996). Total solution F in the filtrates, extracts and water samples was measured using an F-ion-specific electrode (Larsen and Widdowson 1971), after adding total ionic strength adjustment buffer (TISAB).

Two of the plant samples were analysed for Se and Cd by inductively coupled plasma mass spectrometry (ICP-MS), following digestion in nitric–perchloric acid. The largest of the hair samples digested for F analysis was also analysed for metals by ICP-MS.

Sulphate and Cl concentrations in filtered water samples were measured by ion chromatography. Metal element concentrations were determined in three water samples (those that showed the highest F and Cl concentrations) using ICP-MS. A full scan was also carried out for semivolatile organic compounds (using GC–MS) on the water sample with highest F content.

Results and discussion

Vegetation and lichen

On Tanna, some food crops are apparently affected by ash fall, including beans and corn plants that are stunted at maturity, with small corncobs and discoloured leaves and husk. Other indigenous leafy crops and natural vegetation showed little (yellowish colours along leaf margins and veins) or no effects. According to interviews with farmers, the most seriously affected crops are fruit, with the blossoms of Mangoes lost during a period of heavier ash fall earlier in the year. On Ambrym, the leaves of a number of coconut trees were damaged but no leafy food crop damage was noted (although most food is from indigenous crops).

All vegetation fluoride contents (Table 1) are within the concentration range of plant material in the absence of pollution, 2–20 mg F kg^{-1} (e.g., Brewer 1966; Robinson 1978). Natural F levels in grazing pastures in the south of New Zealand are representative of typical values, between 5 and 7.6 (Manley *et al.* 1975). The highest of the values (sweet potato leaf) is also within the part of a plant not normally consumed. The leaves of plants are most likely to show

Table 1. Vegetation and lichen analyses from Tanna Island.

Site number (Fig. ID)	*Location*	*Description*	*F* (mg kg^{-1})*	*Se (μg kg^{-1})*	*Cd (mg kg^{-1})*
3	Enima	Juvenile corn cob and husk	3.2	0.56	0.09
3	Enima	Leaf, island cabbage	6.3	0.54	0.48
3	Enima	Leaf, island cabbage	6.9		
3	Enima	Leaf, sweet potato	16.2		
4	Ipkagien	Leaf, island cabbage	<6.2		
4	Ipkagien	Lichen from tree bark	6.7		

* All concentration expressed on the basis of dry weight.

highest concentrations of F from exposure to gas or particulate pollution such as volcanic ash (e.g., Brewer 1966; Gritsan *et al.* 1995). Le Guern *et al.* (1980) reported banana leaves affected by an eruption on Guadeloupe had a concentration range of 8–35 mg F kg^{-1}; fruit skins showed black marks, but pulp contained only 0.7 mg F kg^{-1}.

Lichens tend to accumulate elements over long periods of time and are sensitive bioindicators of environmental pollution (e.g., Nimis *et al.* 1993), which have been used in volcanic areas (e.g., Grasso *et al.* 1999). The single lichen analysis from Ipkagien is similar to those in the shorter-lived vegetation samples, which may indicate no long-term accumulation of F at this site. It should be noted that further analyses from lichen in other areas around Tanna volcano would be required to confirm this preliminary inference.

Selenium concentrations are potentially high within volcanic ash and can strongly affect plant concentrations (e.g., Cronin *et al.* 1998). However in the analysed samples from Vanuatu the concentrations of Se are well below the upper limit for safe human and animal consumption (estimated at <2000 μg kg^{-1}; Gupta and Gupta 1998).

Cadmium is not likely to be an agronomically important constituent of volcanic ash or gas (e.g., Cronin *et al.* 1998); however, its toxicity lies in long-term build-up along the food chain (e.g., Jones *et al.* 1987). Typical normal concentrations within edible vegetation leaf range between 0.093 and 0.880 mg kg^{-1} (Page *et al.* 1987), with the Vanuatu values lying well within this range. However, the concentration within cabbage leaf from Enima is well in excess of the maximum permitted concentration of Cd for Australia and New Zealand (0.1 mg kg^{-1}; ANZFA 2000). This is possibly not directly attributable to the volcanic activity based on the data in this study. Further analysis of plants surrounding the volcano as well as investigation of other Cd sources would be required to determine its origin.

Cow bone and teeth

Farmer interviews revealed no abnormal animal behaviour, impaired growth or bone deformities on either Tanna or Ambrym.

The samples of cow rib and teeth collected from Enima (site 3; Fig. 1D), contained 936 and 842 mg F kg^{-1} (dry weight), respectively. Bones and in particular ribs and vertebrae of grazing animals generally contain the highest F concentrations within the animal, especially in F-contaminated environments (Underwood 1981). Normal whole bone F concentrations range between 300 and 600 mg kg^{-1} (dry weight basis), with teeth containing around half these levels (Underwood 1981). Acute fluorosis, particularly within volcanic environments is indicated by

Table 2. Water sample analyses from Tanna Island: site numbers are indicated on Fig. 1D

Site number (Fig. 1D)	*Date*	*Location*	*Description**	*pH*	*Turbidity (NTU#)*	*F (mg l^{-1})*	*SO_4 (mg l^{-1})*	*CI (mg l^{-1})*	*H_sS test*	*CFUs§*
High ashfall										
2†	29 Oct 99	Lake Isiwi	Lake water	7.08	<5	0.42	54.2	6.9	+	?
4	30 Oct 99	Ipkagien	Rainwater in petri dish	6.80	<5	<0.05	2.6	8.0		
4	30 Oct 99	Ipkagien	Rainwater off taro leaves	5.89	<5	<0.05	0.8	2.9		
5	29 Oct 99	White Sands Health Post	Fiberglass tank	5.88	<5	<0.05	3.8	10.3	–	?
6	29 Oct 99	Yarkei (Petro Village)	Galvanised tank, patched with cement	7.09	<5	0.08	4.1	8.4		?
6	29 Oct 99	Yarkei (Petro Village)	Cement tank	7.96	<5	0.07	16.2	6.3	+	?
6	29 Oct 99	Petro Village	Fiberglass tank	6.48	<5	0.05	5.7	4.6		?
6	29 Oct 99	Petro Village	Fiberglass tank with cement block	6.56	<5	<0.05	2.6	4.2		
6b	29 Oct 99	Ipeukel	Cement tank	7.90	<5					
9	29 Oct 99	Lowiapeng School	Cement tank	8.00	<5					
12	30 Oct 99	Maleiu	Cement tank	8.20						
12	30 Oct 99	Maleiu	Metal basin	7.10						
Low ashfall										
7	29 Oct 99	Lamlu Dispensary	Fiberglass tank	4.91	<5	0.13	12.0	11.4		?
10	29 Oct 99	Lamnatu (Middle Bush)	Cement tank	7.70	<5					
Intemittent ashfall										
8	29 Oct 99	Lenakei Hospital	Rubber-lined galvanised-iron tank	6.54	35‡	0.16	4.4	6.7		?
13	29 Oct 99	Tanna Beach Resort	Surface water, stream	6.80					–	
Resampling in quiet phase										
6b	7 Apr 01	Ipeukel	Warm spring water			2.53				
14	7 Apr 01	Isiwi Stream	Stream waters			0.51				
15	7 Apr 01	Stream near Yapowul	Stream waters			1.05				

* Samples from various types of tanks are all sourced from rainwater.
† Sample taken for full metal scan (Table 4).
‡ Sample contained algae.
# Nephelometric Turbidity Unit.
§ Colony forming units/100 ml of sample; the water was analysed for the presence of thermotolerant (faecal) coliforms in a media of Lauryl Sulphate Broth.

Table 3. Water sample analyses from Ambrym Island: site numbers are indicated on Fig. 1E

Site number (Fig. 1E)	*Date (1999)*	*Location*	*Description**	*pH*	*Turbidity (NTU#)*	*F* ($mg\ l^{-1}$)	*SO_4* ($mg\ l^{-1}$)	*Cl* ($mg\ l^{-1}$)	*H_sS test*	*CFUs§*
West of vents										
2	2 Nov	Lélé	Cement tank	7.80	<5					0
3	2 Nov	Lolibulo School	Fiberglass tank	7.96	<5					0
4	2 Nov	Tou Village	Cement tank	6.48	<5				–	0
5‡	2 Nov	Pélipétakéver village	Galvanised and cement tank	9.59	<5					0
5†‡	2 Nov	Pélipétakéver village	Metal drum tank	5.79	<5	2.80	6.0	13.9		
5	2 Nov	Pélipétakéver village	Creek, spring fed	7.11	<5				+	TNTC
6	2 Nov	Émiotungan Village	Cement tank	8.85	<5					21
7	2 Nov	Yaotilié Village	Cement tank	7.77	<5					8
8	2 Nov	Yelovuvu Village	Fiberglass tank	4.22	<5					2
9	2 Nov	Baïap Health Post	Cement tank		<				–	0
9†	2 Nov	Baïap Health Post	Fiberglass tank	4.03	<5	2.45	9.7	26.2		0
9	2 Nov	Baïap Presbyterian	Cement tank	6.97	<5					0
9	3 Nov	Baïap (SDA mission)	Cement tank	6.59	<5					
9	4 Nov	Baïap Health Post	Fiberglass tank	4.71	<5					
10	3 Nov	Sesivi (Catholic school)	Cement tank	7.28	<5					38
South and WSW of vents										
11	3 Nov	Maranata School	Surface water, creek	7.46	<5	1.08	16.2	34.2	+	7
11	3 Nov	Maranata School	Spring at source	6.94	<5					6
11	3 Nov	Maranata School	Cement tank	9.10	<5					48
12	3 Nov	Lalinda	Cement tank	8.98	<5					1
13	3 Nov	Port Vato	Cement tank	8.66	<5					TNTC
14	3 Nov	Sanesup	Spring, piped supply	7.95	<5					9
14	3 Nov	Sanesup	Metal drum	6.64	<5					269
14	3 Nov	Sanesup Bungalows	Spring, piped supply	7.66	<5					TNTC

* Samples from various types of tanks are all sourced from rainwater.
† Samples taken for full metal scan (Table 4).
‡ Sample taken for Semi-volatile organics analysis.
# Nephelometric Turbidity Unit.
§ Colony forming units/100 ml of sample; the water was analysed for the presence of thermotolerant (faecal) coliforms in a media of Lauryl Sulphate Broth. TNTC denotes 'too numerous to count'.

bone F concentrations up to 13,000–20,000 mg kg^{-1} (e.g., Underwood 1981; Araya *et al.* 1990). Following a volcanic eruption in New Zealand, incisors of fluorotic and other affected lambs contained zones of between 1000 and 4000 mg F kg^{-1} (Coote *et al.* 1997). Chronic fluorosis symptoms were noted in around 50% of a population of central European wild deer that had similar F concentrations in bone and teeth to the Tanna samples (Mean 883, SD 444 mg F kg^{-1}; Kierdorf *et al.* 1996).

Water supplies

On Tanna (Table 2) rainwater samples from the three different ash-impact areas showed no systematic variation in any of the measured parameters. Most pH differences apparently related to storage conditions including cleanliness of tank and possibly tank materials (with the lowest pH recorded in fibreglass tanks). The highest F and SO_4 contents were found within waters of Lake Isiwi, directly adjacent to Yasur.

The Ambrym rainwater samples (Table 3) showed a greater range in pH, again with lowest values recorded within fibreglass tanks. Fluoride and chloride concentrations were considerably higher than the Tanna values in the two rainwater and one stream sample analysed. High faecal coliform counts are due primarily to unprotected sources, open storage tanks, human or animal contact, and/or no cleaning or disinfection of tanks practiced. The fibreglass tanks showed low counts primarily because they were newer. It seems that pH is not related to the coliform counts observed.

The higher pH of waters within concrete compared to fibreglass tanks is probably related to reaction between acid rainwater with carbonate cement in the concrete tanks, compared to inert fibreglass. All Tanna and Ambrym, SO_4 and chloride values are well below aesthetic quality levels of 400 and 250 mg l^{-1}, respectively (WHO 1984).

Most surface waters and rainwaters generally contain between 0.08 and 0.22 mg F l^{-1} (e.g., Köpf *et al.* 1968; Manley *et al.* 1975). High F levels are normally associated with deep aquifers in areas of phosphatic geology (e.g., Walker and Milne 1955), or mineral springs and thermal pools and lakes, which can reach values of up to 5200 mg l^{-1} (Mahon 1964). Tolerance levels for F in drinking water for cattle are 4–8 mg l^{-1} (Shupe and Olsen 1987), but water concentrations as low as 5 mg l^{-1} have caused fluorosis in sheep in hot and dry climates (Harvey 1952). For human water supplies, international drinking water levels are recommended not to exceed 1.5 mg l^{-1} (WHO 1984). Above 1.5 mg l^{-1} mottling of teeth can occur, skeletal fluorosis may be observed at values of 3–6 mg l^{-1}, and total intake of 20–40 mg of F day^{-1} over long periods can result in crippling skeletal fluorosis (WHO 1970; NRC 1977).

The F concentrations of all Tanna water supply samples, including Lake Isiwi and stream waters are well below the internationally recommended level. The warm water springs are not normally used for drinking supplies, and are also low for mineralised waters. However, the two Ambrym drinking water samples are substantially higher, almost within the range which may cause chronic skeletal fluorosis, particularly in the warm (high-water intake) climate of Vanuatu. Even the creek value from Amrbrym contains significant F, despite the fact that fluoride has great affinity for adsorption onto the volcanic soils of the area (e.g., Bower and Hatcher 1967). Differences in water storage tank materials appear to cause no systematic change in F concentrations.

Drinking water in streams around Soufrière of Guadeloupe during its 1976–77 eruption reached F concentrations of 0.22–1.14 mg l^{-1}, with condensates from the volcanic fissure registering 0.2–2.5 mg F l^{-1} (Le Guern *et al.* 1980). Hence, the Ambrym values appear to be significant, even for active volcanic areas.

Table 4. Metal element concentrations in water samples (mg/l) as measure by ICP-MS; for site and location details see Fig. ID and 1E, plus Tables 2 and 3

Metal (mg l^{-1})	*Tanna site 2 Lake Isiwi*	*Ambrym Site 5 Pélipétakéver village*	*Ambrym Site 9 Baïap Health Post*
Lithium	0.0009	0.0002	0.0008
Boron	0.021	0.006	0.021
Aluminium	0.305	0.973	2.43
Vanadium	0.005	<0.001	<0.001
Chromium	<0.0005	0.0026	0.0044
Iron	0.27	0.04	0.02
Manganese	0.0134	0.0181	0.0119
Cobalt	<0.0002	<0.0002	0.0044
Nickel	<0.0005	0.0007	0.0061
Copper	0.0251	0.0037	0.014
Zinc*	0.007	8.77	4.03
Arsenic	<0.001	<0.001	<0.001
Molybdenum	0.0003	<0.0002	<0.0002
Cadmium	0.00531	0.00047	0.00058
Tin	<0.0005	<0.0005	<0.0005
Antimony	<0.0002	<0.0002	<0.0002
Lead	0.0002	0.0021	0.001

* Zinc contents are likely affected by galvanised iron roofing materials and/or tank materials.

The Ambrym water supplies appear to be more strongly affected by volcanic ashfall and gas release. However, the compositions of water supplies on both islands are likely to be strongly variable over time depending on the frequency and distribution of ash falls or gas plumes. Elemental concentrations in water supplies will likely rise considerably immediately, during and following eruptions or increases in activity. To understand fully the variability and magnitude of F concentration change in the waters, more samples should be collected at different times both during and between eruptions and at different locations around the volcanoes.

The full metals scans of three samples of high F concentration (Table 4) show most potentially toxic elements to be below internationally recommended levels, with the exception of Cd, which in two samples slightly exceeds recommended values of 0.005 mg l^{-1} (WHO 1984). A semivolatile organic compounds scan of A4 rainwater from Pelipetakever village in Ambrym showed no compounds above detection limits.

Human health and psychosocial effects

On Tanna, public health nurses from two health posts (sites 5 and 7; Fig. 1D), described no unusual increases in ARI, chronic respiratory problems or eye infections or irritations, compared to other areas of the island that received little or no ash. Two teachers new to the area suffered throat and nose irritations since they had arrived. Residents were apparently used to the frequent explosions, often as loud as thunder, although the new teachers had difficulty sleeping. Similarly, on Ambrym, interviews indicated that there appeared to be no major health affects attributable to the volcano and its activity was an accepted part of life of the island's residents.

All hair sample analyses from Tanna for fluoride and metal scans were inconclusive because the sample sizes were too small. Maximum possible F concentrations range between <17 and $<78\,mg\,kg^{-1}$, but are confounded by the high detection limits possible using the small sample sizes provided. To further clarify these results larger samples will be required to be collected under a more controlled sampling plan. It may be that urine samples collected during eruptions or gas emissions could provide a short-term estimate of F intake in location population. Kidneys have the highest F content of all soft-tissue, since F is lost mainly in urine (NRC 1974).

Volcanic ash

On Tanna the grey-black silty sand ash covers the ground downwind of Yasur, increasingly markedly near the volcano. It accumulates mostly on thatch-roofed houses where it is trapped and deteriorates the roofing materials. The ash is preferentially washed from other (galvanised iron roofs). Tests for fallout rates in different locations overnight were confounded by rainfall. On Ambrym, fine silty sand ash was distributed over the south and southwest sector, despite no large ash plumes occurring during the visit.

The samples collected in this study (Table 5) indicate that Ambrym is a more fluoride-rich system than Yasur, which is consistent with the significantly higher F concentrations in drinking and surface water on Ambrym. Not only is the total fluoride higher in the Ambrym sample, but the difference is 5-fold for water-soluble levels. Most water-extractable F appears highly soluble, being released in the first extraction, and is probably contained within $CaSiF_6$ and NaF salts (e.g., Öskarsson 1980). A component of more slowly but still short-term available F is also indicated in the second and third extractions, and this may be contained within CaF_2 and/or Al-F compounds.

Fresh volcanic ash has volcanic gases adhering to its particle surfaces, either with moisture or in sublimate form. Many of these compounds, particularly F compounds, are highly soluble (e.g., Öskarsson 1980; Cronin *et al.* 1998). Hence, the delay between ash fall and collection can significantly alter F concentration measurement, especially if rainfall occurs following ash fall. The F contents of the two sampled Vanuatu ashes is relatively low compared to that from Mt St. Helens ($300\,mg\,kg^{-1}$; Smith *et al.* 1983), Ruapehu ($350–850\,mg\,kg^{-1}$; Cronin *et al.* 2000), Soufrière of Guadeloupe ($540–800\,mg\,kg^{-1}$; Le Guern *et al.* 1980) and Hekla (often $>2000\,mg\,kg^{-1}$; Georgsson and Petursson 1972). However, it is higher than ash from

Table 5. Fluoride concentrations within freshly collected Tanna and Ambrym volcanic ash

Site	*Date collected*	*Total F** *($mg\,kg^{-1}$)*	*Water extraction 1†* *(mg F/kg ash)*	*Water extraction 2* *(mg F/kg ash)*	*Water extraction 3* *(mg F/kg ash)*
Tanna, site 16‡	1994	not determined	7.7	1.1	0.3
Tanna, site 2	29 Oct 99	178	7.3	1.0	0.4
Ambrym, site 5	2 Nov 99	281	36.7	4.7	2.2

* Total F determined by NaOH fusion and measured using an F-specific electrode.
† Water extractions carried out at a 1:20 ash:water ratio with 16 h shaking and measured by Ion Chromatograph at Landcare Research, Palmerston North, New Zealand.
‡ Sample collected by Mr Douglas Charley, Department of Geology and Mines, Vanuatu.

Lonquimay volcano in Chile (75–100 mg kg^{-1}) where grazing animals died of fluorosis during and following an eruption in 1988–89 (Araya *et al.* 1990), as well as other South American volcanoes (Smith *et al.* 1982). Some of the fluoride in the Vanuatu tephras will be soluble only in the long-term (being in mineral form), and may be released into the environment only after months to years of weathering.

Air quality

The air quality analyses included tests for H_2S, SO_2, CO, and nitrous gases. The only Tanna air quality analysis that showed a positive reaction (for < 15 ppm SO_2), was at the uninhabited site 1 (Fig. 1D) nearest Yasur. At this location an intermittent sulphur odour was detected, and nearby villagers occasionally detected a rotten-egg smell of sulphur (H_2S). Analyses on Ambrym were negative for all gases tested, but there was no strong ash emission at the time of testing.

Conclusions

Given the limitations of this study, with low sample numbers and no repeat surveys made on Ambrym, the following preliminary conclusions can be made:

1. The overall environmental heath risk for humans from present levels of activity on Yasur volcano (Tanna) appears low. This volcano appears to produce moderately low fluoride emissions leading to little environmental contamination of food crops and drinking waters. However, the moderately high bone and teeth fluoride concentrations of the cattle sample may signal long-term chronic effects of the environment on grazing animals. Grazing animals probably also ingest fluoride from ash-coated feed and soil intake (Cronin *et al.* 2000). For humans, intake of F may be lower if vegetables are washed before consumption and since root crops comprise a large portion of their diet (F is generally not transferred from plant leaves to roots; Brewer 1966). Conversely, humans have a longer period of exposure to the environment and if the volcanic inputs increase periodically, local inhabitants may also potentially suffer chronic F effects.
2. The Ambrym volcanic complex appears to be a more F-rich system than Yasur on Tanna. Fluoride concentrations in drinking waters on Ambrym are high enough to engender chronic dental fluorosis and possibly skeletal fluorosis, particularly if these values are representative of the long-term status within the zone of gas and ash deposition. Given that the samples were collected during a lull in eruptive activity, the concentration values may represent the lower end of the potential range present. These data suggest that further investigation of environmental F (e.g., in waters, food crops, animal bone; different times of year and in various areas of the island) should be undertaken on Ambrym. This could include a survey to identify dental fluorosis symptoms in areas both downwind and upwind of the volcanoes.
3. Acid rain impacts on drinking water supplies on the two islands appear also to be modified by the construction material used for storage tanks, with concrete tanks having some buffering effect on pH compared to fibreglass tanks.
4. Other chemical and physical impacts of the long-term activity on the two volcanoes appear low. The absence of excessive respiratory problems in areas of heavy ash fall is probably caused by the coarse grainsize and low silica content of the ash produced by the low-energy basaltic eruptions. Continuous low-level activity also appears become part of daily life on the islands with no evidence for undue stress within local inhabitants.

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