

Dental fluorosis linked to degassing of Ambrym volcano, Vanuatu: a novel exposure pathway

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Abstract Ambrym in Vanuatu is a persistently degassing island volcano whose inhabitants harvest rainwater for their potable water needs. The findings from this study indicate that dental fluorosis is prevalent in the population due to fluoride contamination of rainwater by the volcanic plume. A dental survey was undertaken of 835 children aged 6–18 years using the Dean's Index of Fluorosis. Prevalence of dental fluorosis was found to be 96% in the target area of West Ambrym, 71% in North Ambrym, and 61% in Southeast Ambrym. This spatial distribution appears to reflect the prevailing winds and rainfall patterns on the island. Severe cases were predominantly in West Ambrym, the most arid part of

the island, and the most commonly affected by the volcanic plume. Over 50 km downwind, on a portion of Malakula Island, the dental fluorosis prevalence was 85%, with 36% prevalence on Tongoa Island, an area rarely affected by volcanic emissions. Drinking water samples from West Ambrym contained fluoride levels from 0.7 to 9.5 ppm F (average 4.2 ppm F, $n = 158$) with 99% exceeding the recommended concentration of 1.0 ppm F. The pathway of fluoride-enriched rainwater impacting upon human health as identified in this study has not previously been recognised in the aetiology of fluorosis. This is an important consideration for populations in the vicinity of degassing volcanoes, particularly where rainwater comprises the primary potable water supply for humans or animals.

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Introduction

Over 500 million people, almost 10% of the world's population, live in areas with associated volcanic risk (Baxter 2005), often drawn to the fertile soils around volcanoes for their high agricultural and horticultural production (Garrec et al. 1984; Neall 2006). Many of these populations live subsistence lifestyles relying on local food and water sources, and it is populations such as these that are often more at risk from elemental deficiencies and toxicities (Plant et al. 1998).

Volcanoes emit gases both during and between eruptions and many of the emitted species are environmentally significant (Thordarson et al. 1996; Gamble et al. 1999; Aiuppa et al. 2004; Witham et al. 2005). Their impacts range from influencing global climate to affecting human health (Thorarinnsson 1979; Sutton and Elias 1993; Allen et al. 2000; Baxter 2000, 2005; Grattan et al. 2005). This paper concerns one of these important volcanic gases, hydrogen fluoride, which is toxic to both animal and plant life (Baxter et al. 1981; Garrec et al. 1984; Delmelle et al. 2002). In humans and animals, excess intake of fluoride can cause both dental and skeletal abnormalities.

One of the most vigorous, persistently degassing volcanoes on Earth is on the island of Ambrym in Vanuatu. Its SO_2 emission has exceeded rates of 200 kg/s and though its fluoride emission has not been directly measured, its very high flux of bromine indicates a halogen-rich magma (Bani et al. 2009). Over 9,000 Ni-vanuatu, the indigenous people of Vanuatu, reside on Ambrym, many experiencing the volcanic plume overhead for most days of the year. Most potable water supplies are rainwater-derived and harvested using roof collection systems. When rain falls through the volcanic plume it can become enriched in fluoride (Cronin and Sharp 2002). The objective of this study was to investigate whether airborne volcanogenic fluoride is being dissolved in rainwater, thereby contaminating local drinking water supplies and impacting human health. The airborne volcanogenic fluoride is predominantly gaseous HF, while F compounds adhered to tephra are likely to contribute to a minimal extent. Since excess intake of fluoride causes visible dental anomalies, a dental survey was conducted using Dean's Index of Fluorosis (Dean 1934, 1942; Fejerskov et al. 1988). While West Ambrym inhabitants were the target population for this study, dental surveys were also undertaken in the two other localities of Ambrym, North and Southeast, as well as three other islands in Vanuatu; Malakula, Tongoa, and the island volcano Tanna.

Ambrym

The subduction of the Australian plate eastwards beneath the Pacific Plate has given rise to the New Hebrides Arc—the 83 islands in the Y-shaped archipelago of Vanuatu in the Southwest Pacific (Fig. 1a)

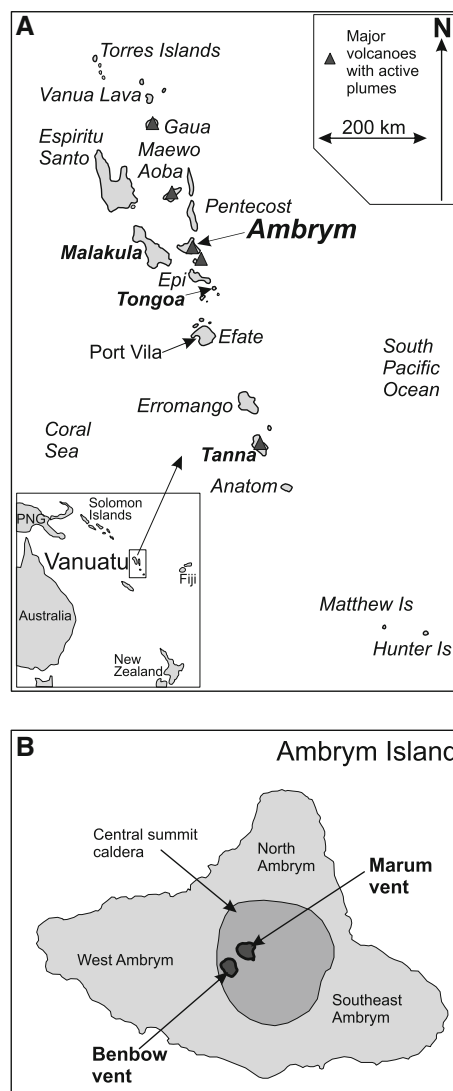


Fig. 1 a Map of the Vanuatu archipelago showing the positions of major volcanoes (*triangles*) and the island of Ambrym in the axis of the Y alignment of islands. b Ambrym island indicating the degassing vents of Marum and Benbow, the summit caldera, and the three localities of Ambrym

(Pelletier et al. 1998; Christova et al. 2004; Schellart et al. 2006). Ambrym lies at the fork in this Y; approximately 35 × 50 km in size, and its protuberant headlands to the west, north, and southeast give it a distinctive trilobate shape. Each region is thus identified according to this natural geographic division as West, North, and Southeast Ambrym, respectively. Several active craters are located within a central, summit volcanic plateau known as the Ash Plain, with two dominant vents, Marum and Benbow,

rising to 1,270 and 1,159 m above sea level, respectively (Fig. 1b). Magmatic eruptions have occurred within living memory, while earlier episodes of phreatomagmatism have also been recognised (Németh et al. 2009). The volcanic rocks range from basalt to basaltic andesite in composition (Monzier et al. 1997). Degassing has probably persisted for over 200 years at least; Captain James Cook observed ‘great columns of smook, which I judge ascended from Volcanos’ [*sic*] on his second voyage in 1774 (Beaglehole 1961). In January 2005, volcanic plumes from the Ambrym crater were emitting at an exceptionally high rate of 180–270 kg/s SO₂, and ~8–14 kg/s F (Bani et al. 2009).

Ambrym’s Ni-vanuatu live a traditional lifestyle of subsistence farming and gardening. Rainwater harvesting is practised by the majority of residents for drinking and cooking purposes (Bakeo 2000). The prevailing winds throughout the year are trade winds from the east to southeast. The southeast trade winds, locally known as ‘tokelau’, are predominant during the dry season from May until October. During the wet season from November until April, winds tend to be lighter and variable, and cyclones also occur. Rainfall distribution is determined by the seasonal winds and local topographic features (VMS 2007). The orographic rainfall patterns produce higher rainfall on Ambrym’s windward side during the wet season, while the leeward side, West Ambrym, is drier. These wind and rainfall distribution patterns naturally have a significant role in the dispersion and impact of volcanic emissions around the island. Acid rain and ash falls compromise horticultural growth and productivity (Cronin and Sharp 2002), while lava flows have occurred within living memory that have damaged villages and forced evacuation and relocation.

Malakula, Tongoa, and Tanna

Malakula is one of Ambrym’s closest neighbouring islands with a population of around 24,000, and is as little as approximately 27 km west of Ambrym. There is no degassing volcanic activity on this island, but its position and proximity to Ambrym means that at times, the plume is visible overhead. Almost 100 km southeast of Ambrym is the smaller island of Tongoa with a population of 2,400. This island is only exposed to the volcanic plume when winds are from the opposite direction to the dominant south-east trade

winds. This would usually occur during the wet season from November to May. Tanna has a population of around 28,000 and lies approximately 400 km south-southeast of Ambrym and is an island with its own active volcano, Yasur. Yasur, a cinder cone, also displays semi-continuous activity and has reportedly also caused acid rain and vegetation damage. This volcano appears to be a less fluoride-rich system than Ambrym volcano, and Yasur’s emission of gases is much less vigorous than Ambrym (less than 8 kg/s SO₂ in 2004/5 [Bani and Lardy 2007]). Malakula, Tongoa, and Tanna are also identified in Fig. 1a.

Volcanogenic fluoride and health

Volcanic gases show a wide range of compositions (Delmelle and Stix 2000; Aiuppa et al. 2001). Major gas species are H₂O and CO₂, while those present in smaller proportions include SO₂, H₂S, H₂, and halogen acids HCl, HF, and HBr (Delmelle and Stix 2000; Oppenheimer 2003). Those most toxic to human health include CO₂, SO₂, HCl, H₂S, and HF (Baxter et al. 1981; Delmelle et al. 2002; Hansell et al. 2006).

Aside from deaths caused by asphyxiation (Thorarinsson 1979; Baxter et al. 1990; Neall 1996, Rice 2000), health effects caused by volcanic plumes and gases are often anecdotal (Sutton and Elias 1993; Allen et al. 2002). Respiratory effects are a common complaint (Sutton and Elias 1993; Allen et al. 2000), acid rain is irritating to eyes and skin (Baxter et al. 1982, 1990), and elevated levels of trace elements have been recorded in urine output following acute volcanic gas exposure (Durand et al. 2004).

HF typically constitutes <1% of volcanic gas constituents, but the annual global flux is crudely estimated to be as high as 6 Tg (Symonds et al. 1988). A more robust estimate of the annual HF flux associated only with arc volcanism (i.e. which includes Ambrym) is ~0.5 Tg (Pyle and Mather 2009). The Melanesian volcanoes, along with those of Iceland, appear to be the most fluoride-rich systems on Earth (Witham et al. 2005).

HF is known to be highly phytotoxic and damages vegetation downwind of volcanoes at concentrations of <1 ppb, causing burning, and impairing photosynthesis, growth and reproduction (Garrec et al. 1984; Rai et al. 1996; Allen et al. 2000). It is very soluble in water (Delmelle et al. 2002), and thus is readily

dissolved in rainwater, becoming mobile and bioavailable.

Fluorine can also be transferred to the Earth's surface by dry deposition, i.e. as a gas or aerosol adhered to tephra particles (Allen et al. 2000). Fluorine transported on volcanic ash particles has been widely implicated in impacts on plant and animal health. The earliest record comes from widespread animal morbidity and mortality as the result of pasture contamination caused by the eruption of the Laki fissure between 1783 and 1784 AD. Similar effects occurred on a smaller scale during the 1947 and 1970 eruptions of Hekla (Thorarinsson 1979), Mt Hudson in 1991 (Araya et al. 1993), and Mt Ruapehu in 1995–1996 (Coote et al. 1997; Cronin et al. 1998).

As well as the high solubility of gaseous HF, previous work suggests that most F in Ambrym tephra is contained within the highly soluble phases NaF and CaSiF₆ (Cronin et al. 2003).

Fluorosis

Fluorine is ranked as the thirteenth most abundant element by weight in the Earth's crust (Mason and Moore 1982) and is the second most abundant trace element in the human body (Dissanayake and Chandrajith 1999; Edmunds and Smedley 2005). Due to its ability to impede dental caries, it has been designated as a 'possibly essential trace element' (Nielsen 2000). However, the difference between the beneficial dose that impairs caries and the toxic dose that causes harm to the mineralising tissues in the body is narrow (Krishnamachari 1986; Plant et al. 1998).

Fluorosis is a preventable disease of teeth and bones that afflicts millions of people worldwide. It is caused primarily by the prolonged ingestion of fluoride-rich drinking water, which is most often groundwater that has percolated through and leached volcanic and sedimentary deposits (McGill 1995; Krishnamachari 1986; Calderon 2000; WHO 2001; Ayenew 2008). Archaeological evidence suggests it occurred in ancient communities such as at Herculaneum near Vesuvius (Torino et al. 1995) and Bahrain Island, Bahrain c. 250 BC–250 AD (Littleton 1999).

Dental fluorosis is an accumulation of fluoride in teeth and is caused by ingestion of fluoride during the period of tooth development, i.e. prior to tooth

eruption (Pereira and Moreira 1999; Aoba and Fejerskov 2002). The fluoride becomes incorporated into the crystal lattice structure of the enamel and causes hypomineralisation which increases the porosity of the enamel (Horowitz et al. 1984; Fejerskov et al. 1994; Levy et al. 2002). This manifests as an opaque or white tooth discolouration ranging from small flecks or fine lines to diffuse or scattered patches on tooth surfaces. With time, food and other oral substances can fill the pore spaces and cause a brown staining to occur (Dean 1934, 1936, 1942; Horowitz et al. 1984; Fejerskov et al. 1988).

The amount of fluoride absorbed by the body depends on a number of complex variables to do with the health and condition of the individual (Krishnamachari 1986; Murray 1986; Den Besten 1994), the bioavailability of the fluoride compound (Cornelius et al. 2000; Pennington 2000), and synergistic and antagonistic interactions with other elements (Bogden 2000; Yanez et al. 2002; Deckers and Steinnes 2004). Malnutrition is a known risk factor in the onset of fluorosis (Smith et al. 1931), particularly if diets are deficient in calcium, magnesium, and aluminium (McGill 1995; Cerklewski 1997; Akiniwa 1997). The WHO general guideline for fluoride in drinking water is 1.5 ppm (mg/l) (WHO 2004), but in countries where the annual average maximum daily temperature is 22–26°C, such as in Vanuatu, a fluoride concentration of no more than 1.0 ppm in drinking water supplies is recommended (WHO 1971).

Methods

Three expeditions were made to Vanuatu to conduct dental surveys and collect water samples. The expeditions occurred in January 2005 to West Ambrym and Tanna; in April–May 2005 to West Ambrym, North Ambrym, and Southeast Ambrym; and in July 2005 to the islands of Malakula and Tongoa. Due to time constraints, water samples were only collected from the primary study area of West Ambrym during the January 2005 expedition. Discussion with local chiefs regarding selection of appropriate survey villages and schools was led by SJC and DTC, as random or statistical selection of sites was not feasible within this social environment or with the limited infrastructure and transport resources available.

Dental surveys

Dental surveys followed a quantitative observational epidemiological approach (Calderon 2000) and were undertaken using Dean's Index of Fluorosis (Dean 1934, 1942). The Thylstrup-Fejerskov (TF) Index (Thylstrup and Fejerskov 1978; Fejerskov et al. 1988) and the Tooth Surface Index of Fluorosis (TSIF) (Horowitz et al. 1984) were also considered for use in this survey. The TF and TSIF indices take into account histological changes in dental fluorosis which then allows for a tighter correlation between visible aberrations on the tooth surface and water fluoride concentrations. However, this level of detail was not required, and nor was it practical, for this study in a population with non-communal water supplies of varying fluoride concentrations.

Dean's Index selected as the most appropriate tool as it provides sufficient detail to determine dental fluorosis prevalence. Along with its simplicity (it has six categories and is recorded on a 'per child' rather than 'per tooth' basis) and utility (given the field conditions and transport, which was often on foot), it has the additional feature of the Community Index of Fluorosis (discussed later). The choice of Dean's Index here concurs with Pereira and Moreira (1999) who consider the Dean's Index to be most useful for comparative studies between current and historical prevalence. Pereira and Moreira (1999) also note that regardless of which index is used, there is a good correlation of prevalence estimates amongst all three.

Participants were children aged 6–18 years of age. Surveys were conducted outside in natural light which varied from clear days to overcast conditions. The survey was moved undercover during downpours of rain. Each child was seated facing the examiner (RJC), perpendicular to the incident sunlight, and asked to smile. The labial and occlusal surfaces of incisors, canines, and first bicuspid of both maxilla and mandible were the index teeth in this study, as these teeth are usually clearly visible when a person smiles (or grimaces!). Partial dentition examination has proved practical in other studies too (Tabari et al. 2000; Stephen et al. 2002; Hamdan 2003; MacKay and Thomson 2005). Teeth were examined wet and uncleaned. Where the tooth surface was obscured due to food or plaque, an attempt was made to remove it with a disposable soft paper tissue. If this was unsuccessful, the tooth was not examined. The child's

head and/or the examiner's head was 'rolled' so the line of sight varied when looking at the tooth surface, as recommended by Russell (1961). The Dean's Index has six categories of fluorosis assessment: normal, questionable, very mild, mild, moderate, and severe. Allocation to a category is based on the two most severely fluorotic teeth. Where these two teeth were not of the same category, the lesser category was assigned (WHO 1997). Data (home village, age, description of opacities, etc.) were recorded in field notebooks and later entered into Microsoft Excel spreadsheets.

In the target population of West Ambrym, index teeth of 253 children were examined; in North and Southeast Ambrym, 172 and 177 children had their teeth examined, respectively. Due to time and other constraints, the sample size was 98 on Malakula, and on Tongoa the sample size was 86; only a small survey was undertaken on Tanna with 26 participants. There were a further 23 children who were visitors to the villages when the dental surveys were being undertaken and so were 'incidentally' included in the assessment, and hence are referred to as the 'incidentals' group.

To gauge intra-examiner reliability, of the 253 West Ambrym children examined, 5% (13) were examined twice, during consecutive visits. The examiner (RJC) was unaware of the original assessment rating, and, due to the time interval between repeat examinations undertaken during different expeditions, the likelihood of rating recall was remote.

SJC wrote the ethics application, and approval was obtained from Massey University Human Ethics Committee (HEC:PN Application—04/157). Ni-vanuat consent was given at the levels of the Vanuatu Ministry of Health, village chiefs, parents, extended-family adults, schoolteachers, and the children themselves.

Water sampling

As dental (and skeletal) fluorosis is primarily caused by ingestion of fluoride-rich drinking water, drinking water samples from household rainwater tanks were collected from 18 villages in the primary study area of West Ambrym from the 9th to the 23rd of January 2005. It is estimated samples were taken from >90% of tanks in each village. Groundwater samples were also collected from three villages that had access to

either a spring or a piped, shallow aquifer supply. The local method of using a bucket, cup, or teapot to draw water from the tanks was used, and approximately 40 ml was transferred to polypropylene specimen containers. Specimen containers were first rinsed in surplus sample water prior to the analysis sample being collected. Samples were initially kept at ambient temperature and frozen on returning to New Zealand. No preservatives were added.

Water analysis was carried out in March 2005 at an accredited Environmental Chemistry laboratory, Manaaki Whenua Landcare Research, using standard Ion Chromatography techniques on a Lachat IC5000. The water samples were analysed using an anion column (150 × 5.5 mm) with suppressed measurement. The total run length per sample was approximately 12 min with a pump speed of 2.20 ml/min, 100 µl sample loop, and a sodium bicarbonate/sodium carbonate eluent. The standard range for fluoride analysis was 0.1–5.0 mg/l.

Plume analysis

Plume studies were also undertaken during the January expedition to ascertain elemental fluxes, including fluoride, emanating from the Ambrym volcano. The results of these studies are published in Bani et al. (2009).

Results and discussion

To ascertain intra-examiner reliability, 5% of West Ambrym children were surveyed twice and agreement of scores occurred nine times out of 13 (69%). A disagreement of scores occurred four times (31%) and for each of these, the category allocated on the second expedition was the next higher category than that defined on the earlier visit. Looking at the conditions when these children were surveyed, for each child, poorer light conditions were recorded on the first expedition and bright sunshine on the second. This change in lighting is a reasonable explanation as to why some opacities were imperceptible on the first occasion, but were visible on the second. As the brighter conditions allowed for a more accurate assessment of the tooth surface, it is this category which was used in the final data analysis.

Fluorosis prevalence and severity

The prevalence results of the Dean's Index survey are recorded in Fig. 2, with the highest prevalence figures found in the primary study area of West Ambrym and also the volcanic island Tanna. The prevalence was 96% in West Ambrym and 100% in Tanna. It should be noted the sample size in Tanna was much smaller, and all the children came from villages within 4 km of Yasur. This may at least partly explain why all children surveyed exhibited signs of dental fluorosis. In comparison, the closest villages surveyed on Ambrym were around 10 km away from the volcanic vents.

While these prevalence figures are high, similar levels of endemicity were found in United States communities where fluoride concentrations in drinking water ranged from 1.3 to 2.3 ppm (Dean 1942), and in a South African community where the fluoride concentration in drinking water was 3.0 ppm (Grobler et al. 2001).

The prevalence in North Ambrym and Southeast Ambrym was 71 and 61%, respectively. A prevalence of 43% was recorded for the incidentals group of children (which also had a very small sample size), and 36% on Tongoa.

Prevalence figures give no indication of the spread of severity within a community. The graphs in Fig. 3 illustrate the component categories (i.e. levels of severity) which make up the prevalence statistic for each location surveyed. For visual clarity, two graphs are presented; those with the highest prevalence are graphed in Fig. 3a, and those with a lower prevalence and a mode of normal are presented in Fig. 3b.

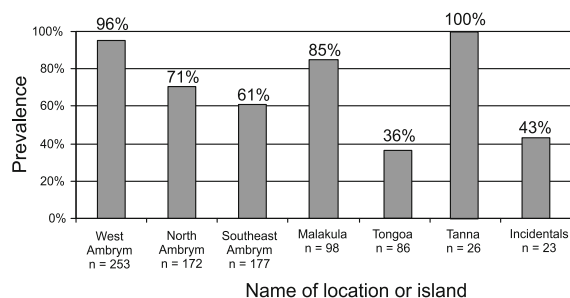


Fig. 2 Prevalence of dental fluorosis and sample size for each surveyed location. Total sample size was 835. The incidentals group comprised 23 children who took part in the dental survey but were not local to those villages. These children who were 'incidentally' surveyed had grown up on the islands of Espiritu Santo, Pentecost, Emae, Efate, Nguna, and Futuna

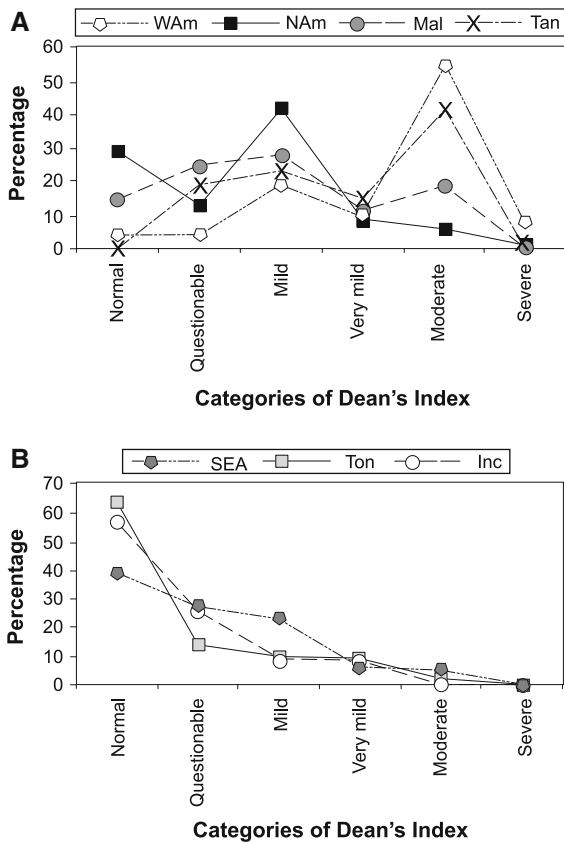


Fig. 3 Percentage of each of the categories of the Dean’s Index for each location surveyed. **a** Locations found to have the highest prevalence of the surveyed locations: West Ambrym (WAm), North Ambrym (NAm), Malakula (Mal), and Tanna (Tan). **b** Locations found to have lower prevalence figures: Southeast Ambrym (SEA), Tongoa (Ton), and the incidentals group (Inc)

West Ambrym, North Ambrym, Malakula and Tanna had the highest prevalence (Fig. 3a). Negatively skewed distributions occurred in the results for West Ambrym and Tanna only where the majority of the results were in the moderate category. It was only in West Ambrym that more than half of the population were recorded as falling into the second most-severe category of moderate. This is 13 times more than those without any sign of the disease. The number of children in the normal and questionable categories equals the number of those in the severe category. North Ambrym modes occur in the normal and very mild categories, while the modes for Malakula are questionable and mild. There is a high proportion of moderate fluorosis in West Ambrym and on Tanna, while Malakula has less than 20% in this category, and North Ambrym <10%.

Southeast Ambrym, Tongoa, and the incidentals group had the lowest prevalence statistics, and all shared a similar positively skewed distribution with the mode being in the normal category (Fig. 3b). Moderate dental fluorosis was recorded in 5% of Southeast Ambrym children, 2% from Tongoa, whilst there were no recorded cases in the incidentals group. No severe cases were observed in any of these three sample groups.

Previous studies have found that the negatively skewed distributions occur in communities with higher drinking water fluoride concentrations leading to more severe forms of dental fluorosis, whereas populations with low drinking water fluoride concentrations produce positively skewed distributions of fluorosis, i.e. where fluorosis is more common in the milder forms (Grimaldo et al. 1995; Ibrahim et al. 1995; Grobler et al. 2001; Griffin et al. 2002). Although drinking water samples in this study were only from West Ambrym, it is likely that lower water fluoride concentrations would be found in the locations exhibiting a positive skew (i.e. North Ambrym, Southeast Ambrym, Malakula and Tongoa), based on considerations such as the distance and direction of villages relative to the degassing vents, prevailing wind direction, and rainfall patterns.

For the three Ambrym locations, Malakula, and Tongoa, a geographical and meteorological effect can be inferred when comparing those locations in relation to Marum and Benbow. West Ambrym likely has a prevalence of 96% because of its close proximity to Marum and Benbow, being directly downwind of them and having the lowest rainfall on the island. The villages surveyed in North Ambrym and Southeast Ambrym are within 15 km of the active vents, but the volcanic plume is less frequently directed to these parts of the island by the prevailing wind, and for Southeast Ambrym in particular, a higher rainfall is experienced due to the orographic effect of the summit caldera in which Marum and Benbow reside. For the island of Malakula, the survey area was selected at the northeast tip of the island which is northwest of Ambrym’s vents and directly downwind during the tokelau winds, but 50 km away.

Tongoa is nearly 100 km from Ambrym, and to the southeast, so the prevalence of dental fluorosis here was unexpected. However, a satellite image has revealed Ambrym’s plume extending well beyond Tongoa on at least one occasion (NASA 2004; Bani



Fig. 4 Examples of severe fluorosis in children from West Ambrym. The entire tooth surface is affected. The tooth has lost its translucent lustre and appears a thick chalky white colour; the brown stain is of a deeper hue than is seen in the moderate cases. Erosion has affected the surfaces and form of some teeth. **a** An 11-year-old boy where pitting can be seen on the upper central incisors. **b** A 10-year-old girl

et al. 2009) and this, along with the prevalence of dental fluorosis in the incidentals group, suggests harvesting rainwater on other islands in the archipelago within the plume's reach may contribute to milder forms of dental fluorosis. However, more thorough surveys and investigations would be needed on each island to confirm if Ambrym's plume was the fluoride donor because groundwater is the main drinking water source on some islands and this too could be enriched in fluoride.

Over all results, there were 20 severe cases recorded. Two examples of severe dental fluorosis observed during this study are shown in Fig. 4 (milder forms are not illustrated here as they are difficult to capture in a photograph without specialised equipment). Nineteen of these were children from West Ambrym, whilst one child came from a village in North Ambrym. This child was seen during a survey in West Ambrym and it is possible that he had lived for a considerable time in West Ambrym during the period of tooth development. In Vanuatu,

it is not uncommon for a child to live with relatives for schooling, as is the case for most of those in the incidentals group. No severe cases were seen from the other island locations.

Age and gender

This study incorporated a wider age range (6–18 years) than that suggested by Dean (1942) due to the difficulty in obtaining a sufficient sample size within the specified age range of 12–14 years. An analysis of age was undertaken from the West Ambrym data set to ascertain if the use of a wider age range affected the results. The greatest difference in our study between those in the specified age range (12–14 years) and those outside it was in the severe category where 8% more cases were seen in those outside the specified age range (Table 1). However, a chi-squared test revealed no statistically significant difference in the severity of fluorosis between those aged 12–14 years and those outside that age range ($\chi^2 = 9.03$, $P = 0.108$, $df = 5$). Since the fluorosis results of our study remain unchanged despite the inclusion of a wider age range than the recommended 12–14-year age group suggests that the water fluoride concentrations during the period of tooth development of the West Ambrym children were at least over 2 ppm (Dean 1942; Fejerskov et al. 1988; Ibrahim et al. 1997).

Similar numbers of boys (116) and girls (137) participated in the survey with no difference in severity between the genders, a finding that concurs with other studies (Dean 1936; Thylstrup and Fejerskov 1978; Hamdan 2003).

Geographical distribution in West Ambrym

The Community Index of Fluorosis (Fci) is a value Dean (1942) developed to represent the overall

Table 1 The spread of fluorosis prevalence in West Ambrym grouped according to whether the children fell into the specified age range (12–14 years) or outside of that (<12 and >14 years)

Age group (years)	Normal		Questionable		Very mild		Mild		Moderate		Severe		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
12–14	6	7	3	4	19	23	6	7	45	56	2	2	81	32
<12, >14 ^a	5	3	6	3	29	17	19	11	95	55	18	10	172	68
Total	11	4	9	4	48	19	25	10	140	55	20	8	253	100

^a Of this age group, 163 were aged 6–11 years and nine were aged 15–18 years

Table 2 Calculation of the Community Index of Fluorosis (Fci) for Port Vato, based on the Dean’s Index results of 12 children

Dean’s Index category	Weight (w)	Frequency (f)	Frequency × weight (f×w)
Normal	0	1	0
Questionable	0.5	0	0
Very mild	1	7	7
Mild	2	2	4
Moderate	3	2	6
Severe	4	0	0
Total		(n) 12	17

degree of severity of fluorosis within a community according to the equation $Fci = \Sigma(f \times w)/n$. For each category of fluorosis, the number of cases recorded is the frequency (f). This is multiplied by the allocated weight (w) for that category. The allocated weight is an arbitrary number Dean assigned to each category. The frequency-by-weight (f×w) calculations are summed, and that total is then divided by the sample number (n) to give the Fci for that community. Table 2 is an example of the Fci calculation for Port Vato. Thus,

$$\begin{aligned}
 Fci(\text{Port Vato}) &= \Sigma(f.w)/n \\
 &= 17/12 \\
 &= 1.4
 \end{aligned}$$

Dean (1942) considered that an Fci above 0.6 indicated dental fluorosis was a “public health problem”, while an Fci of zero indicated an absence of the disease.

The 253 West Ambrym children in this survey came from 37 villages, with the number of participants from each village ranging from one to 21. The Fci was calculated in this study for villages that had at least five children surveyed; villages with smaller sample sizes were excluded due to the skewing effect of possible outlier values. The geographical distribution can be seen in Fig. 5. The lowest Fci values were for the villages of Port Vato (1.4) and Lalinda Presbyterian (1.6), and the highest Fci values were for the villages of Yaou (3.6) and Vetap (3.3). The modal Fci was also high at 2.4.

West Ambrym is a relatively small, homogenous, geographic field, and the variables and confounders contributing to fluorosis in this study are many (see under ‘Fluorosis’ and ‘Fluorosis prevalence’) and beyond the scope of this study. However, the village Fci values did show a distribution pattern in which West Ambrym could be divided into zones (Fig. 5). The high zone, with an Fci range of 2.6–3.6, is situated southwest of the volcanic vents; the intermediate zone, with an Fci range of 1.8–2.6, is located west of the volcanic vents; and the low Fci zone, with an Fci range of 1.4–1.9, lies south southwest of the

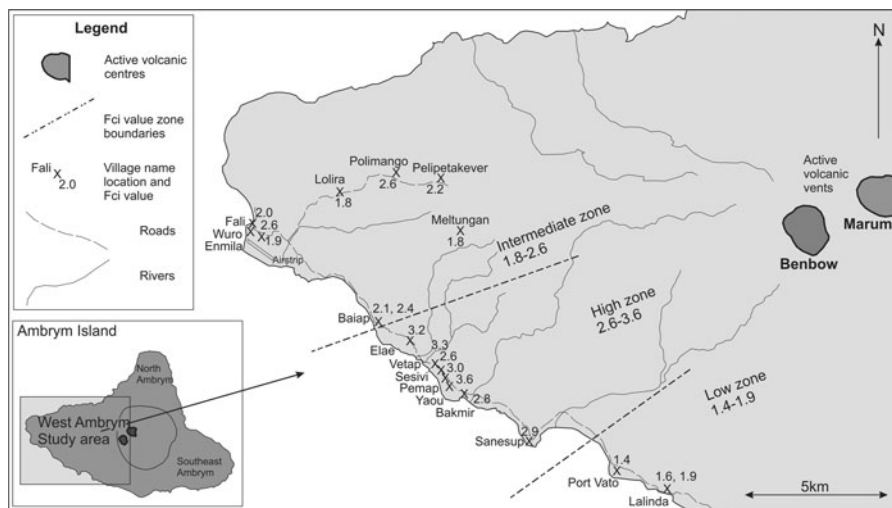


Fig. 5 Location of communities in West Ambrym with calculated Fci values. Villages with small sample sizes (<5) were excluded because these Fci values were less likely to be a useful indicator of community severity of dental fluorosis. The villages of Baiap and Lalinda had two values, one each for the

separate Presbyterian and SDA (Seventh Day Adventist) communities. The distribution of the Fci values were able to be grouped into zones of relative severity. Note the terms ‘high’, ‘medium’, and ‘low’ are relative and that Dean (1942) deemed all Fci values greater than 0.6 to be unacceptable

volcanic vents. (Note that these terms, ‘low’, ‘intermediate’, and ‘high’ are relative, and the Fci values here are all well above those which Dean deemed acceptable.) This pattern seems to reflect the dominant wind direction and plume deposition, bearing in mind there are other influences like topography, wind channels, and diurnal and atmospheric changes (Allen et al. 2000; Delmelle et al. 2002). Since the manifestation of dental fluorosis is subject to many variables, not all of which have been accounted for in this study, these zones cannot necessarily be used to predict future relative risk.

Water fluoride concentrations

Of the 158 drinking water samples collected in West Ambrym in January 2005, 152 came from household rainwater tanks, which are the dominant source for potable water supplies. Drinking water samples from rainwater tanks ranged from 0.7 to 9.5 ppm F (average 4.2 ppm F). Groundwater sources (spring or piped from shallow aquifers) ranged from 1.8 to 2.8 ppm F (average 2.2 ppm F). The recommended concentration of F in drinking water in a climate such as Vanuatu’s is 1.0 ppm (WHO 1971), and only two samples (1%) had 1.0 ppm F or less. These came from rainwater tanks distal to the degassing volcanic vents and at low elevation (<20 m above sea level).

In comparison, in a previous study by Cronin and Sharp (2002), seven drinking water samples from Tanna were analysed for fluoride and concentrations in all samples were found to be within acceptable WHO limits.

Geographical distribution of F in drinking water of West Ambrym

Figure 6 illustrates the range of fluoride water concentrations in each village, including the four groundwater samples. Wide variability is seen in the range and average drinking water fluoride concentrations within each village, and amongst all villages. The group of villages from Valemalmal to Sulol are also those linearly west of the vents. The more easterly villages from Lalinda to Baiap SDA are those situated along the coast. The highest single fluoride concentrations came from the villages of Pelipetakever (9.5 ppm), Sesivi (9.2 ppm), Meltungan (9.0 ppm), and Sanesup (7.8 ppm). Except for

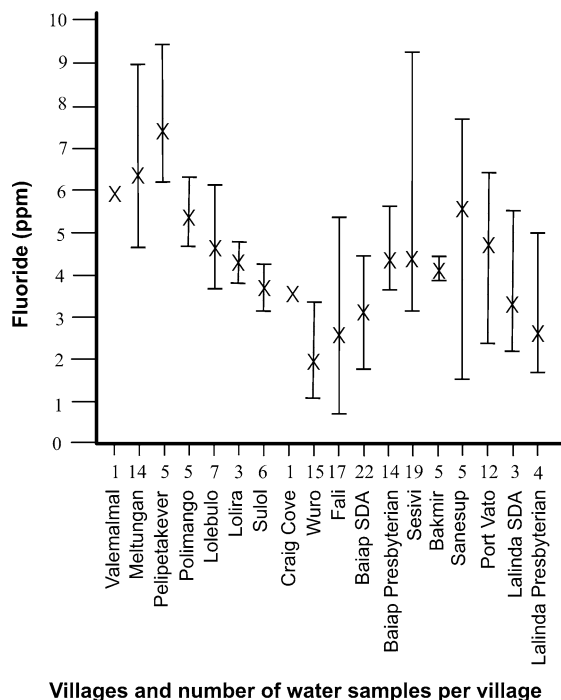


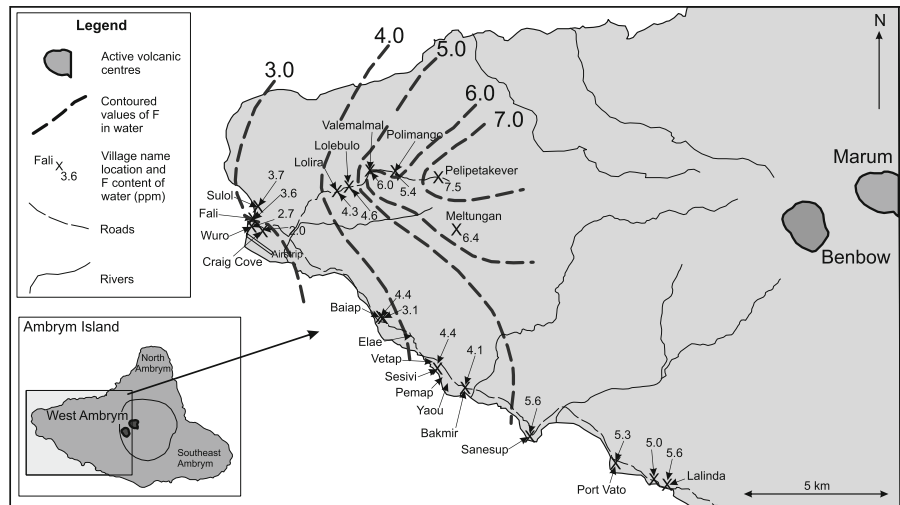
Fig. 6 The range of fluoride concentrations of drinking water samples from West Ambrym villages with the ‘x’ indicating the average concentration. The number on the x-axis is the number of water samples taken in each village ($n = 158$)

Sesivi, these villages also had the highest average fluoride concentrations: Pelipetakever (7.5 ppm), Meltungan (6.4 ppm), Sanesup (5.6 ppm), and also Polimango (5.4 ppm). The lowest single fluoride concentrations were found along the coast in Fali (0.7 ppm), Wuro (1.0 ppm), Sanesup (1.6 ppm), and Lalinda Presbyterian (1.8 ppm). Similarly, the lowest average fluoride levels were in Wuro (2.0 ppm), Fali (2.7 ppm), Lalinda Presbyterian (2.8 ppm), and Baiap SDA (3.1 ppm). Of the two villages that only had one water sample, inland Valemalmal had the highest with 6.0 ppm F, whilst Craig Cove, the commercial centre near the coast, recorded 3.6 ppm F.

The widest range of fluoride concentrations within a village was seen in the coastal villages of Sanesup (range of 6.2 ppm F) and Sesivi (range of 6.1 ppm F).

The average fluoride concentration of rainwater tank samples for each village was plotted on a map of West Ambrym (Fig. 7) (this excludes the four groundwater samples). A geographical distribution pattern was evident for fluoride concentration in drinking water. The highest concentrations were

Fig. 7 Location of sampled villages in West Ambrym with average fluoride concentrations for rainwater tank samples only (in ppm) for each village. Contour lines denote approximate concentration boundaries. Sample sizes for each village are as in Fig. 6 except for the following villages where the groundwater analyses have been excluded: Port Vato ($n = 10$), Lalinda Presbyterian ($n = 1$), and Lalinda SDA ($n = 2$)



found in those villages closest and immediately west of the vents, reflecting wind-induced plume dispersal.

The highest average fluoride concentrations are found in those villages closest to Marum and Benbow, and closest to being downwind of the predominant wind direction. For those villages linearly west of the vents (Fali to Pelipetakever) the fluoride concentration clearly increases as distance to the vents decreases, and as elevation increases. Strong correlations exist between fluoride concentration and distance ($r = 0.94$; $P = 0.00007$), as well as between fluoride concentration and elevation ($r = 0.90$; $P = 0.0004$). These are confounded however because of an even stronger correlation between distance from vents and elevation ($r = 0.97$; $P = 0.00004$).

Similarly, for the coastal villages, which are all <60 m above sea level, lower fluoride concentrations are seen in the western villages (Craig Cove) which increase towards the east (Lalinda). This increase in fluoride concentration along the coast from west to east is correlated with a decrease in distance to the vents ($r = 0.90$; $P = 0.0002$).

The above correlations are tentative because the amount of data collected for the number of geographical variables operative (e.g. distance, elevation, and wind direction) is insufficient for any more accurate, multi-variate analysis.

Fci and water fluoride concentrations

There were 16 villages that had both drinking water sampled and children who participated in the dental

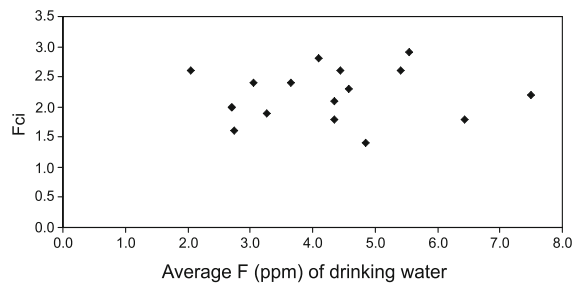


Fig. 8 Community Index of Fluorosis (Fci) versus the average fluoride concentration in the drinking water of that same village community. There were 16 villages that had both dental surveys undertaken and water samples collected

survey. To ascertain if any dose–response relationship existed, average village drinking water fluoride concentration and Community Index of Fluorosis (Fci) were compared (Fig. 8). No correlation was found between these two variables ($r = 0.03$, $P = 0.9$).

This result was not unexpected and a number of factors can account for this. Firstly, and most significantly, the water results from our study are *recent* concentrations. Further, they are only a *snapshot* of concentrations which vary markedly from tank to tank, as well as over time, and which were averaged to give one value for each village. Correlations between severity of fluorosis experienced by a community and drinking water fluoride concentrations can only be found in communities that have had an unchanging water source, and whose survey participants have been lifetime residents. This is because of the latency between fluoride exposure

(to developing teeth) and the observable biological response (dental fluorosis).

Individuals within a homogenous population (e.g. in terms of socio-economic status and ethnicity), and even twins (Black and McKay 1916), who drink from the same, unchanged water supply can exhibit different degrees of severity. The variation can be attributed to individual metabolism and sensitivity, dietary differences and water consumption (Dean 1942; Krishnamachari 1986). The measurement of confounders such as these was beyond the purpose and scope of our study. The complexity of variables involved in the development of dental fluorosis is emphasised by Den Besten (1994) who claims that its use as a biomarker to retrospectively ascertain individual levels of fluoride exposure is not feasible.

General discussion

Dental fluorosis can impact significantly upon the biological and psychosocial dimensions of health. Little seems to be published regarding the prognosis of fluorotic teeth, but, depending on severity, the teeth are more fragile (at least superficially), and may be prone to premature loss (Black and McKay 1916; McGill 1995). The repercussions of diminished dental integrity can include a compromised dietary intake, with possible ensuing nutritional deficiencies, as well as discomfort or chronic pain. One of the benefits though, is that fluorotic teeth tend to have very few caries. Two dental health studies have been conducted in Vanuatu and, while fluorosis was not assessed, they did reveal very low figures for DMFT (decayed, missing, filled teeth) (Norman-Taylor and Rees 1964; Deong 1991). An anthropological study on skeletal remains in Vanuatu has recorded finding fluorotic-like staining on dentition (Weets 1996) indicating high fluoride intakes may have been common in the past. On the other hand, we note that the strength of the plume emitted from the Ambrym craters is variable over time. A surge in emission appears to have begun towards the end of 2004, with peak SO₂ fluxes of ~180–270 kg/s, corresponding to an order of 10% of the total global anthropogenic output of SO₂, an astonishing figure for a single volcano. By mid-2005, SO₂ fluxes had decreased to levels of 23–58 kg/s. These are still very substantial and may be more representative of the time-averaged

emission from Ambrym; but the fluctuation highlights that there is much to be learnt about the relationship between the volcanic degassing, climate, the use of food and water resources of the inhabitants of the island, the exposure to fluoride in the environment, and the resulting prevalence and severity of dental fluorosis.

Several studies have considered the psychosocial impact of fluorotic teeth which encompasses issues of self-esteem, employment prospects, and negative value judgments and assumptions by others (Smith 1942; Riordan 1993; Dissanayake 1996; Robinson et al. 2005). Clearly there is a greater impact for those who suffer from the more severe forms of dental fluorosis. A study on psychological well-being that was conducted amongst Ni-vanuatu youth revealed that those in the Malampa Province (in which Ambrym is located) reported feelings of unhappiness, severe sadness, and depression, although the figures for Malampa were the lowest of the six provinces of Vanuatu (UNICEF 2001). This was a broad study however and it is not known if one island contributed more heavily than the others to the provincial figures, or what was the cause of the feelings. Anecdotally, discussion with a West Ambrym man revealed that those children with marks on their teeth didn't like to be different—a common and natural desire of human nature. Whilst working with a local clinic nurse in North Ambrym, RJC pointed out two children with moderate dental fluorosis. The nurse commented that these children had “West Ambrym teeth”, and was apparently unaware of the cause.

Skeletal fluorosis is known to occur where fluoride in drinking water is 4–6 ppm and above. It generally requires an exposure period of 10 years or more (McGill 1995; Tekle-Haimanot et al. 1995), but it has manifested in children less than 10 years of age, possibly where nutritionally deficient diets have a role in the aetiology (Krishnamachari 1986). Early signs and symptoms of skeletal fluorosis are joint stiffness, pain, and back stiffness, while in its severest form it can become crippling (WHO 2001; Whyte et al. 2005). While this study did not investigate skeletal fluorosis, and certainly no signs were apparent during our visits, it bears consideration as, along with the positive identification of dental fluorosis, almost half of the potable water samples collected in this study exceeded 4 ppm F, the level at which skeletal fluorosis can develop.

Mitigation

Two main courses of action are available, but not always feasible, to address the issue of high-fluoride drinking water: defluoridation of existing water supplies, and, the preferred option, because of its long-term sustainability and cost-effectiveness, the establishment of an alternative low-fluoride water source (WHO 2001; Frencken and Smet 1990). Modification to rainwater harvesting practices, such as covering tanks, installing filtering devices to prevent tephra accumulation in the reservoir, and disconnecting tanks when the volcanic plume and rainfall are contemporaneous are small, simple measures that could potentially be adopted. Previously, the Department of Geology, Mines and Water Resources in Port Vila have broadcast temporary tank disconnection advice during periods of increased volcanic activity. These mitigation measures are means by which the prevalence and severity of the disease can be markedly reduced, if not eliminated, from future generations.

Conclusions

A high prevalence of dental fluorosis exists in West Ambrym (96%), with over half the children surveyed exhibiting moderate and severe forms of the disease. Dental fluorosis in North Ambrym (71%), Southeast Ambrym (61%), Malakula (85%), and possibly Tongoa (36%) and the incidentals group (43%) may also be attributable to Ambrym's volcanic plume. Tanna's prevalence of 100% is most likely due to its own fluoride-rich volcanic source, Yasur.

The division of West Ambrym into zones of fluorosis based on the Fci values is not an indicator of areas of future risk due to the high variability in water fluoride concentrations and confounders such as dietary habits and other variables discussed previously and beyond the scope of this study.

In contrast to most other known environments of fluorosis where the pathway from parent rock to groundwater to drinking water is well established, the fluoride donor in this setting is the gas plume of the island volcano, Ambrym. The airborne volcanogenic fluoride from the semi-continuously degassing vents becomes incorporated into rainwater which in turn is harvested by the local people for their potable water

needs. This environmental pathway has not previously been recognised in fluorosis aetiology and is a physical and psychosocial health consideration for any population harvesting rainwater in the vicinity of a semi-continuously degassing volcano, whether the water be for human or animal consumption.

Areas of further research include investigation of food sources and bioavailability of fluoride, particularly from coconut juice which can make up a large part of daily fluid intake; dietary practices; the possibility of skeletal involvement; and suitability of catchment surfaces and water storage materials.

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