Dental fluorosis caused by volcanic degassing in West Ambrym, Vanuatu

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ABSTRACT

Fluorosis, both dental and skeletal, is a disease afflicting millions of people worldwide and is caused primarily by the ingestion of fluoride-rich drinking water. Usually, this is groundwater that has leached fluoride from underlying rock deposits. In West Ambrym, Vanuatu, however, the indigenous people live in close proximity to a degassing volcano and harvest rainwater for their potable water needs. The current project investigated two hypotheses; firstly, that dental fluorosis existed in West Ambrym and secondly, that it was caused by the ingestion of rainwater contaminated by the degassing volcanic plume.

A dental survey was undertaken of children aged 6 to 18 years using the Dean's Index of Fluorosis. A total of 835 children participated; 253 of whom came from the target area of West Ambrym. For comparative analysis and a more regional perspective, the remaining 582 surveyed were from other nearby locations. Drinking water, non-drinking water and food samples were collected for fluoride analyses.

Dental fluorosis prevalence was found to be 96% in West Ambrym, 85% in Malakula, 71% in North Ambrym, 61% in Southeast Ambrym, 36% in Tongoa, 43% in an 'incidental islands' group, and 100% on Tanna. Drinking water samples from West Ambrym ranged from 0.7 to 9.5 ppm F (average 4.2 ppm F). Groundwater sources ranged from 1.8 to 2.8 ppm F (average 2.2 ppm F). Of the 158 drinking water samples, 99% were over the World Health Organisation recommended concentration of 1.0 ppm F. It was found that pH was not a suitable proxy for fluoride concentration. That painted and/or rusted corrugated iron roofing may play a role in lowering fluoride concentration of stored rainwater was a tentative finding. Coconut juice was a rich source of fluoride. Food samples ranged from < 6 ppm F to over 100 ppm F.

The current research has shown that the semi-continuously degassing of Ambrym volcano is introducing significant levels of fluoride into the drinking water of the local Ni-vanuatu. This geo-meteorological process has resulted in the development of widespread dental fluorosis in West Ambrym. The pathway of fluoride-enriched rainwater identified in this study has not previously been recognised in the aetiology of fluorosis. Defluoridation, or accessing an alternative water source, accompanied by modified rainwater harvesting practices, are means by which the prevalence of the disease can be markedly reduced.

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He aha te mea nui o te Ao?

Maku e kī atu, he tangata, he tangata, he tangata.

Māori Proverb

What is the most important thing in the world?

I say to you, it is people, it is people, it is people.

“At the beginning, this investigation was conceived of
as having but two purposes; the first to satisfy a scientific curiosity
as to what was producing this damage to the teeth, and, second,
if the cause could be found and if preventive measures could be
provided, to save future generations from this disfigurement;
a humanitarian effort”

Frederick S McKay, 1942

CHAPTER 1: INTRODUCTION

1.1 Introduction and objectives

Volcanoes can release significant quantities of fluorine compounds into the environment. Fluorine transported on volcanic ash has been implicated in animal morbidity and mortality as a result of pasture contamination, most notably in Iceland during the Laki fissure (1783-1784) and Hekla (1947 and 1970) eruptions (Thorarinsson, 1979), and the Ruapehu eruptions of 1995-1996.

In the Southwest Pacific, the island volcano Ambrym has been recognised as having one of the largest discharges of volcanic gases in the world (Bani *et al.*, 2006). Although these are dominantly sulphur compounds, it was recognised that airborne volcanogenic fluoride may be a significant component affecting the local population's health by becoming incorporated into drinking water supplies (Cronin *et al.*, 2002).

In humans, digested fluoride is deposited primarily in bones and teeth. Dental fluorosis, evidenced by white discolouration of teeth, is the first visible sign of prolonged over-exposure to ingested fluoride. Increased and continued over-exposure can result in damage to skeletal tissues. Numerous previous studies worldwide have elucidated that fluorosis is primarily a water-borne disease, where water with elevated levels of fluoride is used for drinking and cooking. Most of the known dental and skeletal fluorosis occurs in environments where communal drinking water supplies access groundwater that has leached fluoride from minerals in the underlying geological strata. Fluorosis is endemic in a number of countries because of this (e.g. in India and Africa), but can be a consequence of other causes such as indoor coal burning (e.g. in China). It can also be augmented by practices such as tea drinking, artificially fluoridated water supplies, and the use of fluoridated toothpastes or dentrifices.

Hence, the aim of this study was to elucidate whether the semi-continuous degassing of Ambrym volcano is causing dental fluorosis amongst the indigenous population of West Ambrym, Vanuatu. This has not previously been recognised as a pathway whereby fluoride enters potable water supplies with subsequent impacts upon health.

Three primary objectives were:

1. To determine the existence, and, if existent, the prevalence and severity of dental fluorosis in West Ambrym.
2. To ascertain the concentration of fluoride in drinking waters of West Ambrym.
3. Based on the outcomes of objectives 1 and 2, a third objective was to identify appropriate methods to reduce levels of fluoride in drinking waters, thereby reducing the fluorosis risk.

1.2 Study area – West Ambrym, Vanuatu

1.2.1 Geological and environmental setting

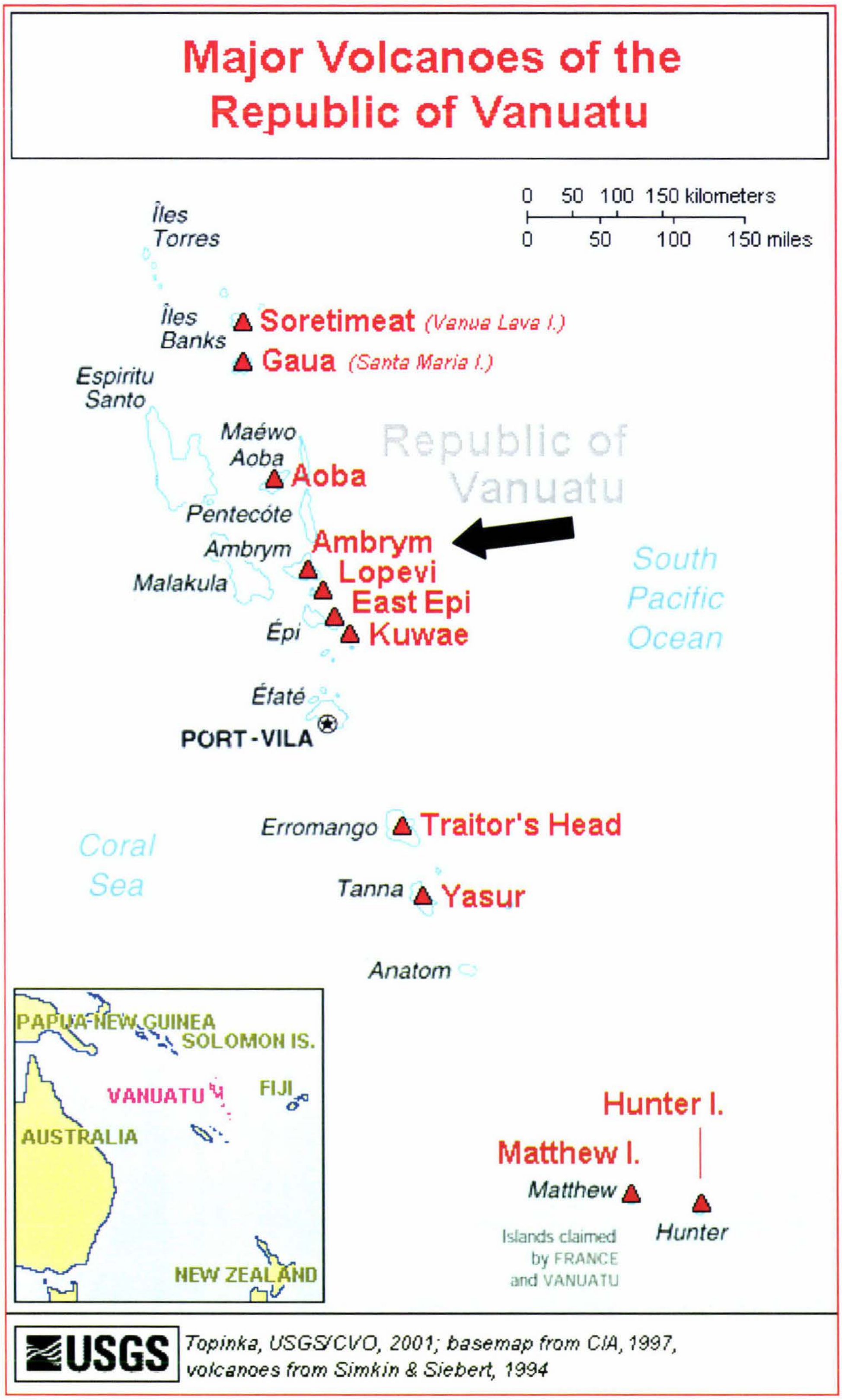
Ambrym is one of the 83 islands in the Y-shaped, northwest-southeast trending archipelago of Vanuatu, formerly known as the New Hebrides (Figure 1.1). Located on the Pacific Ring of Fire, between the Equator and the Tropic of Capricorn, these Melanesian islands are of both tectonic and volcanic origin. The dominant geological process in their genesis is the subduction of the Australian plate beneath the Pacific plate along the New Hebrides Trench (Pelletier *et al.*, 1998; Christova *et al.*, 2004; Schellart *et al.*, 2006).

Ambrym has several active vents located within a central, summit caldera and volcanic plateau, known as the 'Ash Plain' (Figure 1.2). Two of these vents, Marum and Benbow, rise to 1270 m and 1159 m a.s.l., respectively. Lava is basaltic andesite to basalt in composition (Monzier *et al.*, 1997), and the structural geology of this shield volcano is described in a paper by Robin *et al.* (1993). Protuberant headlands to the west, north, and southeast give the island its distinctive tri-lobate shape. Each region is thus identified according to this natural geographic division as West, North, and Southeast Ambrym, respectively.

Ambrym vents have been semi-continuously active for over two hundred years at least. Captain James Cook, when sailing past Ambrym on his second voyage in 1774, recorded that "we observed two very large columns of smoak, which I judge ascended from Volcanos (*sic*)" (Beaglehole, 1961). By January 2005, the Ambrym plumes were emitting SO_2 at a rate of 14 000 – 20 000 tonnes/day, with a fluoride output estimated to be up to 1100 tonnes/day (Oppenheimer, unpublished data, 2005). The Melanesian volcanoes, along with those of Iceland, appear to be some of the most fluoride-rich systems on Earth (Witham *et al.*, 2005).

Any rain that falls through a volcanic plume usually scavenges volcanogenic solutes and ash particles. Thus, the distribution and dispersion of volcanogenic fluoride in rainfall will naturally be influenced by wind strength and direction, as well as plume flux. The famous 'Southeast Trades' are the prevailing winds in Vanuatu. These predominate during the dry season from May until October and are known locally as the 'tokelau' (D. Charley, pers. comm. 2005). During the wet season, from November until April, winds are more variable and cyclones often occur. During each 12 month period, this wind variability ensures no area of Ambrym is entirely free from volcanic emissions.

Vanuatu's tropical to sub-tropical climate sustains lush forest vegetation; trees, ferns, and vines, as well as cash or subsistence fruit, and vegetable crops such as coconut, banana, and yam. Growth and productivity of horticulture is often compromised on Ambrym due to volcanic emissions causing acid rain and ash fall. An area of damaged vegetation can be seen in Figure 1.2b.



Topinka, USGS/CVO, 2001; basemap from CIA, 1997, volcanoes from Simkin & Siebert, 1994

Figure 1.1: Map of Vanuatu; attention is drawn to Ambrym and the other major volcanoes in this archipelago. Ambrym is located at 16°25' S and 168°07' E. Inset shows Vanuatu's location in the southwest Pacific. (Source: Smithsonian Institution)

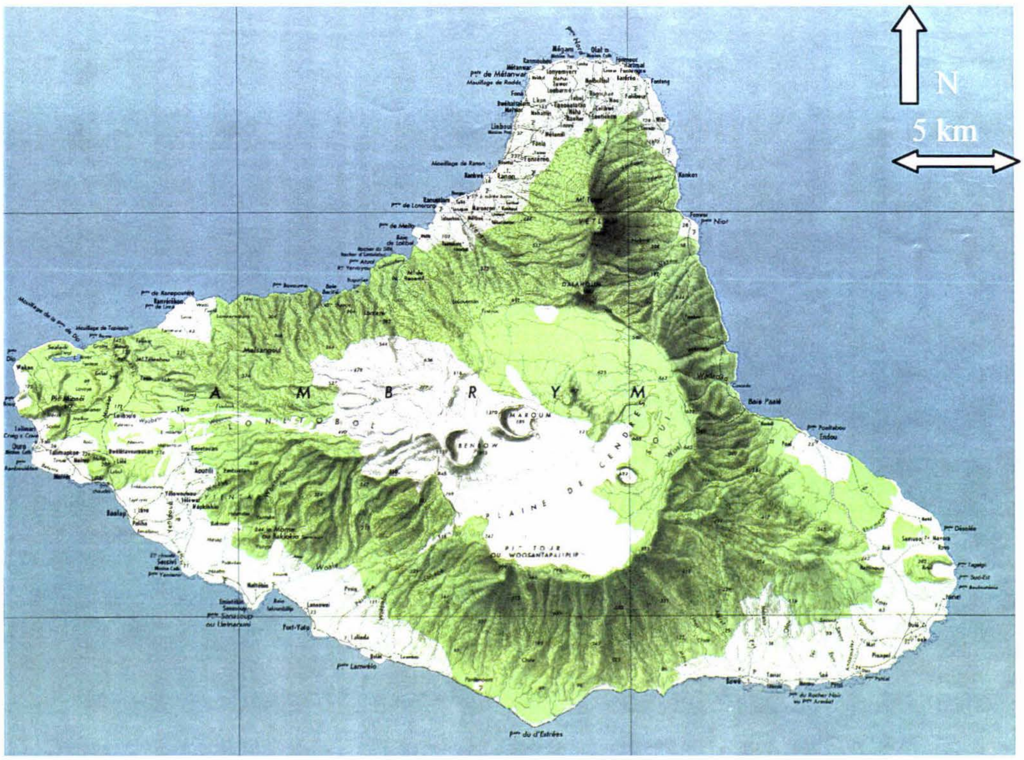


Figure 1.2a: Ambrym contour map. Note the central summit volcanic Ash Plain plateau ('Plaine de Cendres') and main vents of Benbow and Marum. (Source: The World of Maps).

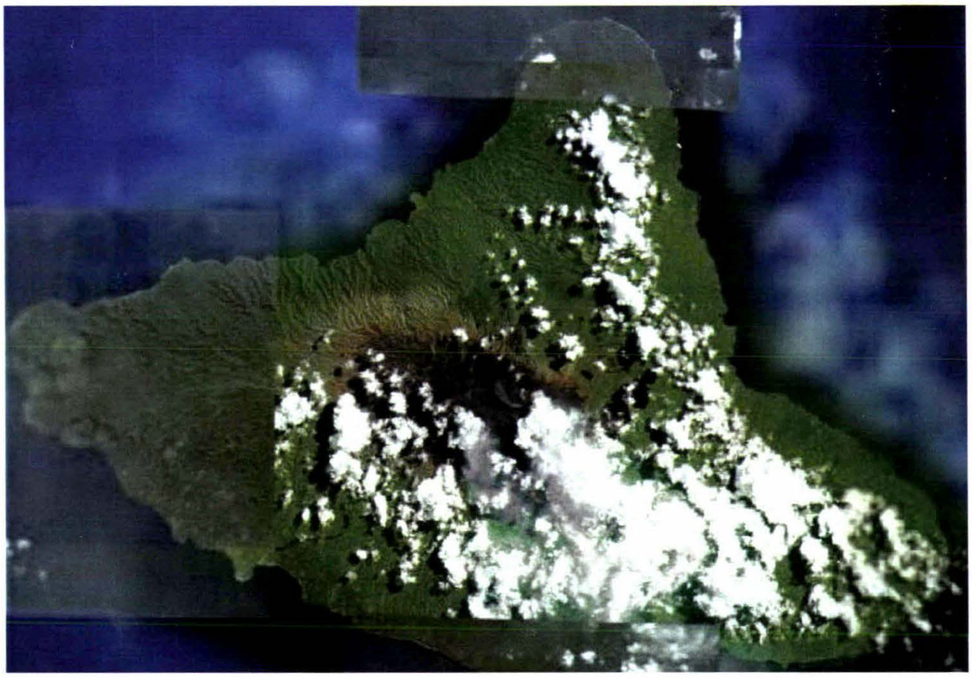


Figure 1.2b: Volcanic plume emanating from the vents in the dark brown Ash Plain is barely visible as it mixes with meteoric cloud. The pale brown and pale green area northwest of the Ash Plain indicates vegetation damaged by acid rain and volcanic emissions. (Source: Google Earth).

1.2.2 Sociocultural setting

The indigenous people of Vanuatu are called Ni-vanuatu or Ni-van, meaning 'of Vanuatu'. There are six provinces in Vanuatu. Ambrym is administered in the Malampa Province, along with the islands of Malakula, Paama, several smaller islands, and the now uninhabited Lopevi. Ambrym's population of over 7000 live a traditional lifestyle including subsistence farming and gardening. Rainwater is harvested by the majority of residents for drinking and cooking purposes and stored in tanks alongside households or in shared community tanks. About 20% utilise a piped water supply (Bakeo, 2000). Locally grown root crops and other vegetables, fruit, bread, and coconut are important staple foods (Carlot-Tary, 2000), while water, tea, and coconut juice are the most regularly consumed fluids (UNICEF, 2001). It is populations like this that live subsistence lifestyles and rely on local food and water sources that are often more at risk of elemental deficiencies and toxicities (Plant *et al.*, 1998).

Acid rain, ash fall, and successive volcanic eruptions and lava flows that have occurred within living memory have all damaged villages and forced evacuation and relocation (D. Charley, 2006; pers. comm.). Daily life for the Ambrym Ni-vanuatu, geographically at least, centres around this active, degassing volcano which is the heart and foundation of their island (Figure 1.3).

Figure 1.3: Degassing of Ambrym volcano with the two major plumes coming from the vents of Benbow and Marum. View is from West Ambrym, January 2005.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews two topics from what has in the past been studied as two quite separate sciences, geology and medicine. The first part introduces volcanic gases, their behaviour, and impact on the environment, while the second part covers in more detail the potentially debilitating disease of fluorosis.

Medical geology, or geomedicine, is an emerging field in the sciences and unites, broadly speaking, the disciplines of earth and health sciences. Up until the mid-1800's the relationship between natural environments and health was largely anecdotal (Mills, 1996), however records of this do exist that are much older. The first records linking geochemistry and health are attributed to Hippocrates and Plinyus the Elder (Deckers and Steinnes, 2004), and the Chinese have records linking health and the environment dating from the 4th century (Appleton *et al.*, 1996).

2.1 Volcanic gases

Volcanic gases are a component of all eruptions, but as they are often colourless and therefore unseen, they may be overshadowed, even in volcanic hazard planning, by the more spectacular eruption processes and products such as lava flows, tephra, and pyroclastic flows (Baxter, 2000). Significant gas emissions during an eruptive sequence, or during periods of relative quiescence, can potentially have impacts ranging from global climate to human health. Significant global cooling has been attributed to the widespread, dry, sulphuric fog from the 1783 Laki fissure eruption in Iceland (Thorarinsson, 1979) as well as an increase in mortality and morbidity as far away as England and France (Grattan *et al.*, 2005).

2.1.1 Composition of volcanic gas

Prior to the mid-1800's it was believed that each volcano emitted its own 'signature gas'. For example, SO_2 and HCl were believed to come from the Italian volcanoes of Mt Etna and Vesuvius, respectively, and CO_2 from Puracé in Colombia. It has only been in the last two hundred years, since French mineralogist Charles Sainte-Claire Deville ascertained that volcanic gases were in fact a mixture of gases of varying proportions, that they have become better understood (Delmelle and Stix, 2000).

Eight elements constitute the bulk of volcanic gases: hydrogen, oxygen, carbon, nitrogen, and sulphur, along with the halogens chlorine, fluorine and bromine (Delmelle and Stix, 2000; Aiuppa *et al.*, 2001). These combine to form a variety of gases; the halogens predominantly forming the acids HCl, HF, and HBr. Major gas species include H_2O, CO_2, and sulphur compounds (SO_2 and H_2S), with lesser amounts of gas species such as CH_4, H_2, HF, NH_3 (Mysen, 1988; Delmelle and Stix, 2000). Other elements can occur in minor or trace proportions such as helium, neon, argon, krypton and xenon, and trace metals can be found in high-temperature fumarolic discharges (Delmelle and Stix, 2000).

Many processes influence the chemical composition of gaseous volcanic emissions. On a broad scale is the regional tectonic and geologic setting, and magma type (Oskarsson, 1980; Witham *et al.*, 2005). Factors such as the solubilities of magmatic volatiles, chemical reactions, pressure, temperature, and presence of water (rainwater, hydrothermal, or groundwater) are the more dynamic variables (Delmelle and Stix, 2000). These processes vary as an eruption evolves and temporal changes in gas composition occur which can last from periods of hours to months (Gamble *et al.*, 1999; Aiuppa *et al.*, 2004).

2.1.2 Movement and transport of volcanic gas

A volcanic gas phase originates as magma ascends and undergoes a decrease in pressure. This allows volatiles to exsolve, expand, and evaporate (Wallace and Anderson, 2000). Gases may also be derived directly from the solid state under sharp gradients of decreased pressure or increased temperature (sublimation). These gases can then enter the Earth's atmosphere in a number of ways:

- as principal conduit and vent emissions. Gas emission from volcanic vents may be vigorous or subdued, from conventional explosive eruptions (Plinian and Strombolian) to passive degassing. Gases can also accumulate in solution at depth in crater lakes and be released in a single event, as was the case at Lake Nyos in the Cameroon, where over 1700 people were killed (Neall, 1996; Rice, 2000).

- from flank degassing and soil emissions. These gases are emitted along faults or fractures on the flanks of volcanoes, often emanating from fumaroles, and hot or cold springs. These gases tend to be cooler and less acidic species such as CO_2, CH_4, and H_2S (Delmelle and Stix, 2000). Groundwater, meteoric, or hydrothermal water that comes into contact with hot rocks at depth can also contribute volcanic gas emissions (Ferreira and Oskarsson, 1999). Soil emissions mainly consist of CO_2 (Baxter *et al.*, 1999), and, where these have ponded in depressions, they have been known to asphyxiate humans and animals (Thorarinsson, 1979; Baxter *et al.*, 1990).

- during the transportation and cooling of lava (Thordarson *et al.*, 1996). Further volumes of gases called 'laze' (lava haze) can be released if flowing lava comes into contact with, and boils, seawater (Sutton and Elias, 1993).

Although volcanic gases and aerosols arise from a localised, or point source, they have the potential to be widely dispersed. Gases injected into the troposphere come mainly from passively degassing volcanoes, while those reaching the stratosphere come from more energetic explosions that produce volcanic plumes with great column heights (Symonds *et al.*, 1988). The atmospheric residence times of different gaseous species are affected by a number of volcanological factors (Oskarsson, 1980; Allen *et al.*, 2002). Once in the atmosphere these gases may influence global climate (Tabazadeh and

Turco, 1993; Fiacco *et al.,* 1994; Graf *et al.*, 1998; Sadler and Grattan, 1999). Diurnal, seasonal, and atmospheric changes (such as wind direction and strength, which vary with altitude), as well as land topography all contribute to the complexity of plume dispersion. These factors can influence plume behaviour to create wind channels, turbulence, vertical mixing or ground hugging dynamics (Allen *et al.*, 2000; Delmelle *et al.*, 2002).

Volcanic gases are returned to terrestrial environments by wet and dry deposition. Dry deposition involves gases and aerosols adhered to particles of tephra, with tephra in the ash-sized fraction being particularly efficient carriers (Tabazadeh and Turco, 1993; Graf *et al.*, 1998; Aiuppa *et al.*, 2001). Rainfall is an important element-recycling process (Bellomo *et* al., 2003), and the chemistry of rainwater, including its acidity, is altered as volcanic gases become dissolved in it. This in turn can influence the chemistry of surface water and groundwater (Aiuppa *et al.*, 2001).

2.1.3 The fluorine cycle

Fluorine is ranked as the thirteenth most abundant element by weight in the Earth's crust (Mason and Moore, 1982). It is found in rock and soil, but is also present in fresh and salt waters, as well as the atmosphere (Murray, 1986; McGill, 1995). The hydrogeochemical cycle of fluorine is illustrated in Figure 2.1.

Fluorine-bearing minerals are found in a number of geological materials, mainly igneous rocks and limestones. In igneous rocks, fluoride is more abundant in granites (e.g. in the minerals biotite and hornblende), and in pegmatites and hydrothermal vein deposits (e.g. in fluorite). In sedimentary rocks, fluoride is adsorbed onto clays as well as found in limestones. Apatite (fluorapatite) is a fluoride-rich mineral found in both these rock types (Pellant, 2000; Edmunds and Smedley, 2005).

Weathering and breakdown of these rock deposits releases fluoride to soil and water. Anthropogenic contamination occurs from industrial sources such as brick and china-clay works, aluminium smelters, and mines (Fuge and Andrews, 1988), as well as through the application of phosphate fertilisers (Pickering, 1985).

Soil has been described as a "labile reservoir of chemicals" by Deckers and Steinnes (2004), and is more of a sink for fluoride than a source. The behaviour of fluoride in soil is influenced by soil type, pH, and fluoride concentration input. It tends to be retained in clay soils, those with organic matter, and, where sufficient aluminium and calcium ions are present, by becoming bound into complexes (Pickering, 1985; Davison, 1987).

Rainfall and ambient temperature also influence the distribution and movement of fluoride in the soil profile. Where fluoride is bound in soil complexes, water reaching the water table is low in fluoride, but where evapotranspiration is high, there can be an increase in water table fluoride concentration (up to five times in temperate climates, and 10-100 in semi-arid environments) due to capillary action. Deep bore water in non-volcanic terrains usually has higher fluoride concentrations than surface or shallow water due to its prolonged residence time and percolation in deep aquifers. Exceptions may be in volcanic areas where shallow groundwater receives hydrothermal inputs (Davison, 1987; Edmunds and Smedley, 2005).

Volcanic emissions, evaporation of marine aerosols, and anthropogenic sources all release fluorine into the atmosphere (Edmunds and Smedley, 2005).

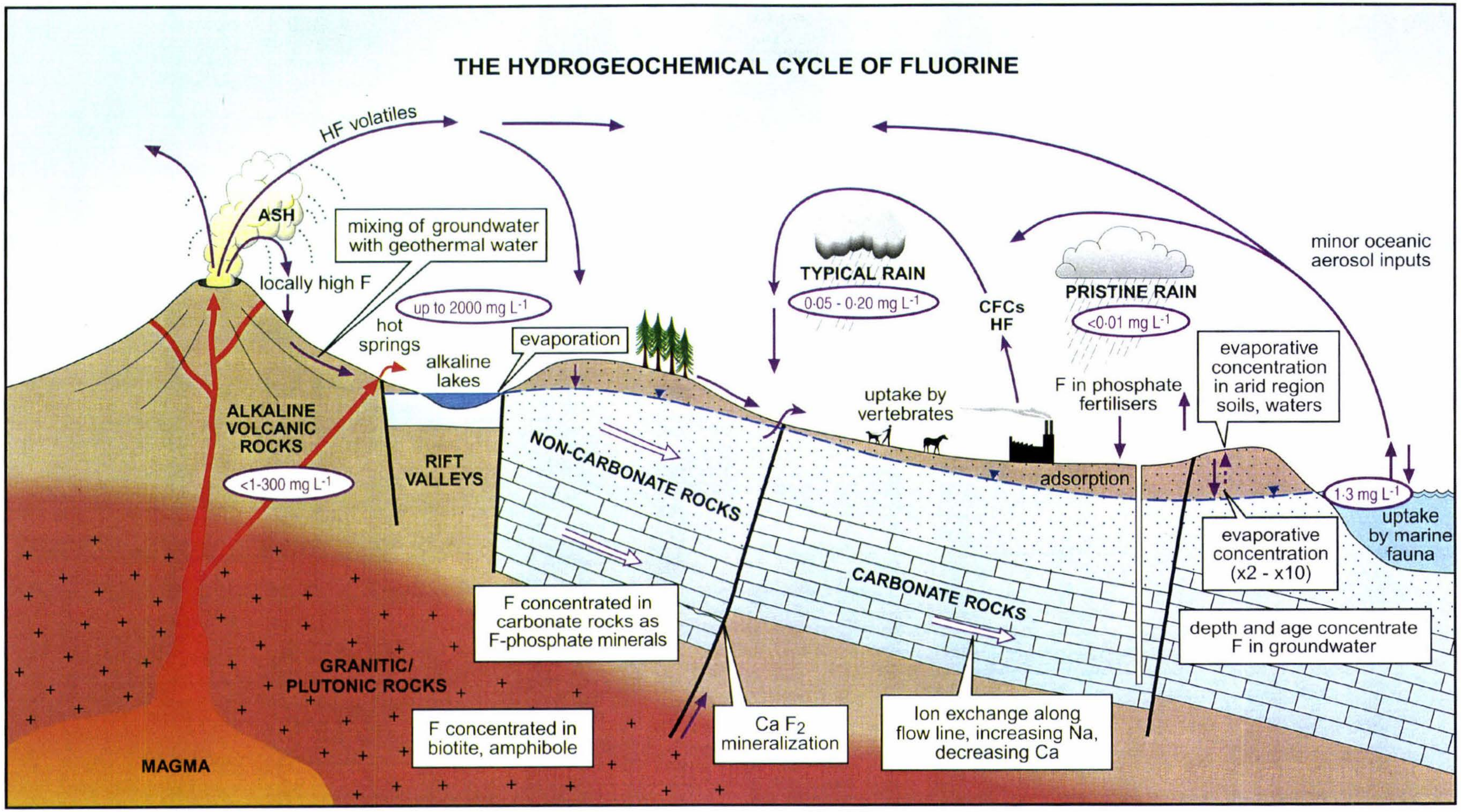


Figure 2.1: Representation of the hydrogeochemical cycle of fluorine. From Edmunds and Smedley (2005).

2.1.4 Volcanogenic fluorine

Fluorine dissolves in magma and forms a gas at relatively low magmatic pressures and temperatures (Delmelle and Stix, 2000), with hydrogen fluoride (HF) being the dominant gas species of fluorine by several orders of magnitude (Symonds *et al.*, 1988; Allen *et al.*, 2000). Although HF is < 1% of volcanic gas constituents, the annual global flux of volcanic HF was estimated to be 0.06 – 6 Tg (Tg = 10^{12} g), which is less than that emitted from anthropogenic sources (Symonds *et al.*, 1988). In the past, volcanic halogen emissions have received less attention than SO_2 (Garrec *et al.*, 1984), however HF is one of the most toxic and hazardous volcanic species, and is likely to be transferred from the atmosphere to Earth faster than SO_2 by dry deposition (Allen *et al.*, 2000). HF is also very soluble in water (Delmelle *et al.*, 2002) and so is readily dissolved in rainwater, as well as in groundwater along fractures and joints, and thence discharged in springs.

Fluorine can also be transported in particulate mineral form as well as gaseous HF in an eruptive column (Davison, 1987). Oskarsson (1980) found that the fluoride fraction in eruption products from the 1970 Hekla Plinian eruption were dispersed in three forms which were governed by different temperature zones within the eruption column. These fluoride products consisted of microscopic salt particles (mainly fluorite, CaF_2), as compounds adsorbed onto tephra particles (mainly calcium fluorosilicate, $CaSiF_6$), and as acid aerosols, which could also be tephra-adsorbed. NaF and AlF_3 were two other likely species, with most salts being adsorbed to tephra surfaces rather than trapped within vesicles (Rose *et al.*, 1973). Less energetic eruptions however, such as Strombolian and Hawaiian types, do not have the same dynamics and simply release volatiles directly into the atmosphere (Oskarsson, 1980).

Inverse relationships exist between tephra particle size and adsorbed fluoride concentrations (Rose, 1977; Taves, 1980). Thus, fluoride levels in ash samples have been found to increase with increasing distance from the vents, as the finer ash fraction is transported further. Fluorosis in grazing livestock has also been found to be more severe with distance (Thorarinsson, 1979; Rubin *et al.*, 1994), although Rose (1977) claimed to find smaller soluble salt concentrations in tephra with increasing distance from source. Note this is referring to *particulate* fluoride, or fluoride which is adsorbed to tephra particles.

2.1.5 Environmental and health impacts of volcanic gas

Volcanoes, like industrial sites, are point sources of fluoride. Concentrations of *gaseous* fluoride are high close to source, and decrease with increasing distance (Davison, 1987; Delmelle *et al.*, 2002). Volcanogenic gases, ash, and acid rain can have widespread effects. Damage to vegetation can have consequential impacts on local ecology and, more significantly, the local human and animal nutrition, and economy. Despite a rainfall of 1300 mm/yr, acid rain has lead to desert conditions in Ka'u Desert, Hawaii (Sutton and Elias, 1993). Man-made structures are also susceptible, particularly those constructed of metal or concrete which are liable to corrosion, such as machinery, vehicles (Sutton and Elias, 1993), and metal roofing which may corrode in less than six months (Delmelle *et al.*, 2002).

Different volcanic gas constituents are known to have particular impacts. Fluorine can affect the environment as the gas HF, or as fluoride compounds and aerosols adhered to particles of tephra. HF is phytotoxic and damages vegetation downwind of volcanoes at concentrations less than 1 ppb (10 – 10 000 times lower than concentrations of other pollutants), causing burning, and impairing photosynthesis, growth, and reproduction (Garrec *et al.*, 1984; Rai *et al.*, 1996; Allen *et al.*, 2000). Crops and short-lived species seem particularly susceptible, whereas it is suggested that longer-lived species, e.g. herbaceous and forest, seem able to adapt to prolonged elevated levels (Davies, 1982; Garrec *et al.*, 1984). Some plants are known bioaccumulators and are unaffected by high fluoride levels, such as the *Camellia* species, which is cultivated for tea drinking. Lichens, which do not have roots, have been used as bioindicators for monitoring airborne fluorine and pollutants (Davies, 1982; Garrec *et al.*, 1984; Notcutt and Davies, 1989; Weinstein and Davison, 2003).

Health effects caused by volcanic plumes are often anecdotal (Sutton and Elias, 1993; Allen *et al.*, 2002) and fatalities are probably under-reported because many "volcanic deaths" may be attributed to direct physical hazards (Baxter *et al.*, 1982). Respiratory effects from volcanic plumes are a common complaint (Sutton and Elias, 1993; Allen *et al.*, 2000), and acid rain is irritating to eyes and skin (Baxter *et al.*, 1982, 1990). The most acidic aerosols are those in the fine particle fraction, which are more likely to reach the deeper and sensitive tissues of human airways and cause pulmonary damage (Allen *et al.*, 2002). Volcanic emissions carried into an already polluted area such as a city, could have an even greater health impact (Durand and Grattan, 2001).

Volcanogenic trace metals can also be of concern to human health and these include chromium, nickel, cobalt, copper, zinc, arsenic, selenium, cadmium, tin, mercury, lead (Allen *et al.*, 2000) and radon (Baxter, 2000). The most important volcanogenic gases which are toxic to human health, however, are CO_2, SO_2, HCl, H_2S, and, the compound implicated in this study, HF (Baxter *et al.*, 1981; Delmelle *et al.*, 2002).

2.2 Fluorosis

This chapter has so far introduced fluorine from an earth science-environmental perspective. The second part of this chapter is concerned with fluorine from a health perspective. In the human body, fluorine is one of the most abundant trace elements, second only to iron. Due to its irrefutable ability to impede dental caries thereby improving dental health, it has been referred to by some authors as an essential trace element (e.g. Krishnamachari, 1986; Dissanayake and Chandrajith, 1999; Edmunds and Smedley, 2005). This is not widely accepted as it is contentious as to whether fluorine meets the six criteria necessary to be designated as an 'essential trace element' (Cerklewski, 1998), and 'possibly essential trace element' is suggested as a more appropriate term (Nielsen, 2000). Regardless of fluorine's formal status, the difference between the beneficial dose that impairs caries and the toxic dose that causes harm to teeth and bone is narrow (Krishnamachari, 1986; Plant *et al.*, 1998). The WHO guideline value for fluoride in drinking water is 1.5 ppm (mg/l), but it is recommended that other factors are taken into account when national country standards are being set, such as volume of water consumed (WHO, 2004).

Fluorosis is a preventable disease of teeth and bone and is caused primarily by the ingestion of fluoride-rich drinking water. Archaeological evidence suggests it has occurred in ancient communities such as at Herculaneum near Vesuvius (Torino *et al.*, 1995), a settlement which was later buried by the AD 79 eruption that also engulfed Pompeii, and on Bahrain Island, Bahrain during the Hellenistic-Tylos period around 250 BC – 250 AD (Littleton, 1999). Although fluorosis occurs in other animal species, where concern mainly rests with the impact on livestock, this chapter considers fluorosis as it affects humans. Particular attention is paid to dental fluorosis as it is this form of fluorosis which is assessed in the current study.

Fluorine is a highly reactive element, found mainly as the fluoride anion (F^-). It is in this form that it easily crosses cell membranes and becomes incorporated into body tissues, having a strong affinity for calcium (Berndt and Stearns, 1978; Krishnamachari, 1986). Naturally, different compounds (species) of fluoride do not all react in the same way. The complexity of this is well beyond the scope of this thesis, and indeed continues to pose challenges in the research field.

2.2.1 Biological pathway of fluoride in the human body

2.2.1 (i) Exposure

Exposure to fluoride can be through inhalation, dermal absorption, or ingestion. Inhalation of fluoride can occur in the vicinity of certain industries, coal combustion, or volcanoes releasing fluorine-bearing gases and particulates to the atmosphere (Murray, 1986).

Although most nutritional elements the body requires are obtained from food consumption, ingestion of drinking water is the main route and source for fluoride. Some foods and consumable products have been found to be elevated in fluoride. Richest food sources are tea and marine fish (particularly when the bones are also consumed), but infant formula (especially if reconstituted with fluoridated water), and fluoridated toothpastes have also been identified (Murray, 1986; Malde *et* al., 1997; Nielsen, 2000; Erdal and Buchanan, 2005). The amount of fluoride available from these sources is highly variable and although they are not consumed in the same quantities as water, they can have a significant impact (Lian-Fang and Jian-Zhong, 1995; Franco *et al.*, 2005; Whyte *et al.*, 2005). Although it is thought they may be partly responsible for the apparent increase in the mild forms of dental fluorosis over recent years, water is generally the major fluoride source (Browne *et al.*, 2005).

2.2.1 (ii) Absorption in the digestive tract and bioavailability

Of ingested fluoride, most absorption occurs in the stomach. Although the amount and rate is dependent on the composition of other food present, absorption of fluoride is usually rapid, and occurs by passive diffusion. In a fasted state most, if not all fluoride, is absorbed (Murray, 1986; Fejerskov *et al.*, 1988; Cerklewski, 1997). Absorption is reduced when food is present, particularly in the presence of the cations calcium, magnesium, and aluminium (McGill, 1995), as these form insoluble fluoride salts, especially in the alkaline small intestine, where fluoride absorption also takes place (Cerklewski, 1997). Calcium-deficient diets, such as those in India and Asian countries (Akiniwa, 1997) are a risk factor, particularly in children, to the effects of excess fluoride (Krishnamachari, 1986).

The amount of an element absorbed by the body depends on a number of complex variables (Plant *et al.*, 1998; Cornelius *et al.*, 2000; WHO, 2002). The amount of fluoride absorbed and its effects depends largely on the dose of fluoride, duration of exposure, the condition (e.g. age, nutritional status) of the individual (Krishnamachari, 1986; Den Besten, 1994; Murray, 1986), and the fluoride species (Cornelius *et al.*, 2000; Pennington, 2000). Synergistic and antagonistic interactions with other elements add to the complexity of fluoride's bioavailability, toxicology, and subsequent impact on health (Bogden, 2000; Yanez *et al.*, 2002; Deckers and Steinnes, 2004).

2.2.1 (iii) Distribution in the body

Approximately half of ingested fluoride (McGill, 1995) is sequestered into the mineralising tissues of the body with the majority being incorporated into bone, and a smaller but significant proportion into developing teeth (Fejerskov *et al.*, 1988; McGill, 1995). This proportion is higher in children because of the increased fluoride uptake by rapidly developing bone. Skeletal distribution of fluoride, in adults and children, is not homogenous (Murray, 1986; Cerklewoski, 1997). Incorporation of fluoride into teeth occurs only during their development and growth, prior to their eruption, whereas fluoride deposition in bone can occur throughout a life span. Bones and teeth are made of hydroxyapatite crystals ($Ca_5(PO_4)_3OH$) that form a rigid lattice-like structure (Glanze, 1990). It is the calcium in this mineral that the fluoride ion, with its small ionic radius and high electronegativity, has an affinity for. It can displace the hydroxyl (-OH) and form the more insoluble fluorapatite ($Ca_5(PO_4)_3F$), or it can occupy spaces within the hydroxyapatite crystal (Higden, 2003).

In soft tissues, fluoride usually occurs only in trace amounts (Inkielewicz *et al.*, 2003), but fluoride toxicity may also harm these tissues (Krishnamachari, 1986).

2.2.1 (iv) Elimination

In adults, approximately half of ingested fluoride is excreted in urine (Murray, 1986; Krishnamachari, 1986; Fejerskov *et al.*, 1988), and any undigested fluoride is egested in faeces (McGill, 1995).

2.2.2 Health effects of over-exposure to fluoride

As explained above, over-exposure to fluoride can be via inhalation, dermal contact, or ingestion. These over-exposures can be sudden, with acute consequences, or they can be prolonged with chronic consequences. In medicine, 'acute' refers to a sudden onset of a disease or symptoms of severe intensity, and usually subsides after a relatively short period. 'Chronic' refers to a slow and progressive, possibly insidious onset of a disease or symptoms, that may persist for a lifetime (Glanze, 1990).

2.2.2 (i) Acute health effects

Sudden over-exposure to fluoride can cause a range of acute physical reactions whether it is inhaled, through skin contact, or ingested. Due to its acidity, inhaled gaseous fluoride causes irritation to respiratory tract mucosa and asthma-like symptoms, usually associated with industrial or volcanic emissions. However, fluoride inhalation has been known to occur in domestic situations due to inhalation of cleaning-product fumes. In at least one case, it resulted in a chronic, asthma-like disease known as reactive airways dysfunction syndrome (Franzblau and Sahakian, 2003). Fluoride coming into contact with skin causes irritation and corrosion to mucus membranes, and severe burns which may affect subcutaneous tissue (Williams-Jones and Rymer, 2000).

Acute high level toxicity is rare and is usually due to accidental ingestion. This has occurred with dental supplements, or from inappropriately (accidentally) elevated water-fluoride concentrations in municipal supplies (Whitford, 1987; WHO, 2001). Signs and symptoms of acute fluoride poisoning increase in severity from salivation, nausea, vomiting, and abdominal pain, to seizures, diarrhoea, cardiac arrhythmia, coma, and death (Whitford, 1987; Akiniwa, 1997), which can occur within a matter of hours (Cerklewski, 1997). The amount of fluoride required to induce any of these symptoms is difficult to calculate as it is dependent on many variables as outlined in Section 2.2.1. A 'probably toxic dose' (PTD) has been proposed as the minimum dose which may induce toxicity responses, including death, and has been suggested to be 5 mg F/kg body weight. This does not mean that doses lower than this should be considered benign (Whitford, 1987).

2.2.2 (ii) Chronic health effects

Dental and skeletal fluorosis are the chronic forms of this disease, and result from a prolonged over-exposure to fluoride (Krishnamachari, 1986; McGill, 1995; WHO, 2001). Reports on industrial fluorosis (in Denmark), and endemic skeletal fluorosis (in India) started appearing in the literature in the 1930's (Krishnamachari, 1986).

Industrial fluorosis is an occupational disease caused by the inhalation of fluoride-bearing dust, fumes, and chemicals. Industrial fluorosis is due to *intermittent exposure* to *airborne* F (Krishnamachari, 1986), a detail that may be significant to those scientists whose occupation it is to periodically frequent degassing volcanoes. Industrial fluorosis has been associated with cryolite and fluorspar mines, and manufacturing industries producing aluminium, steel, glass, ceramics, fertilisers, and insecticides (Krishnamachari, 1986; McGill, 1995). The emissions from these industries have also been implicated in contamination of pastures causing toxicity to livestock (Thorarinsson, 1979; Rubin *et al.*, 1994; Deckers and Steinnes, 2004), and threatening fruit production in the horticultural industry (P. Paynter, pers. comm., 2006). Industrial fluorosis not only affects the musculo-skeletal systems, but also the respiratory-circulatory systems.

Endemic fluorosis occurs in many countries and exists in two forms: dental fluorosis and skeletal fluorosis. In medicine, 'endemic' refers to a disease that occurs *regularly* or *usually* amongst a population. 'Epidemic' on the other hand refers to a disease which has become prevalent among a population at a *specific time* (e.g. when there is an 'outbreak') (Glanze, 1990). Dental fluorosis is due to an accumulation of ingested fluoride in teeth (Pereira and Moreira, 1999; Aoba and Fejerskov, 2002). Skeletal fluorosis is a more severe form of fluorosis that occurs with longer periods and higher concentrations of fluoride ingestion (WHO, 2001). Dental fluorosis develops earlier than skeletal fluorosis and, because it manifests as tooth discolouration, is the *first visible sign of prolonged over-exposure to fluoride*. Thus, it could serve as a bioindicator, alerting to the possibility that skeletal fluorosis *may* develop. Note that skeletal fluorosis can occur in the absence of dental fluorosis, and vice versa. This is explained later in this chapter (Section 2.2.4).

The following sections will focus on the chronic endemic forms of fluorosis from prolonged over-exposure to fluoride as it is this aspect that this research is concerned with.

2.2.3 Dental fluorosis

2.2.3 (i) History of dental fluorosis research

In the early 1900's interest was growing into what was causing "mottled enamel", as it was then known. A Dr Eager seems to be the first to have reported on mottled enamel in 1901 (Dean, 1934). According to McKay (1942), nothing further appeared in the literature regarding mottled enamel until a study was commenced in the afflicted community of Colorado Springs, Colorado, where mottling of tooth enamel was considered a condition peculiar to that community, and the cause entirely unknown. Expansion of the study beyond Colorado's borders led to the discovery of other similarly affected communities in the United States. Two correlations became unequivocal as the study proceeded: mottled enamel was associated with a common water supply, and it only occurred in communities whose individuals were native-born or were raised on that water supply during the time of tooth development i.e. erupted (mature) teeth were not affected. These findings by Drs Black and McKay were in the first research article published on mottled enamel in 1916.

McKay (1942) recounts in his history, that it had been noted that deep wells, especially from coal mines and warm springs, caused the most marked aberrations, yet the standard chemical analysis being conducted on water samples remained unremarkable. A breakthrough was reached when the study included the community at Bauxite, Arkansas, an aluminium ore mining town owned by the Aluminium Company of America. The company had its own laboratory and resident chemist and were able to conduct more comprehensive water analyses. Finally, fluorides were found to be the unusually high and common constituent in drinking water from endemic areas (Churchill, 1931). Concurrent, separate laboratory studies on rats also pointed to fluoride as the causative agent in mottled tooth enamel (Smith *et al.*, 1931).

Smith (1942) reviewed other related research that occurred during that decade, all of which are relevant to research issues that continue today, such as the affinity of fluoride for bone, defluoridation methods, treatment of stained enamel, relationship between soil fluoride and plant uptake, fluoride-rich cooking water and food, and dietary uptake and output (bone, milk, urine) in cattle.

I include a paragraph here on dental caries, as it is one of the most well known and controversial issues to come out of this era of fluoride research. The observation that fluorotic teeth had a lower prevalence of dental caries sparked the continuing debate over an 'optimum level of fluoride' in public water supplies for caries prevention. There is confusion in the literature as to who is responsible for this finding. It has been attributed by some authors to Dean (in his 1934 and 1942 papers) (Whitford, 1987; Fejerskov *et al.*, 1988; Aoba and Fejerskov, 2002; Browne *et al.*, 2005) but this is not so. Dean (1936) attributed the fluorosis-caries link to an observation of McKay in a 1929 paper, and McKay (1942) acknowledged Dean *et al.* for furnishing the conclusive evidence. Smith (1942) acknowledged both McKay and Dean for their published work in this matter (in 1938 and 1939, respectively), as well as Cox, who appears to be the first to recommend it be added to public water supplies in 1939. More recent research maintains that the cariostatic effect of fluoride is due to its presence locally (topically) at the tooth surface, and *not* due to its incorporation into the tooth structure during development. Lower prevalence of dental caries can therefore be achieved without the risk of concomitant dental fluorosis (Fejerskov *et al.*, 1994; Palmer and Anderson, 2001; Aoba and Fejerskov, 2002). It appears this is not yet widely accepted.

2.2.3 (ii) Normal dental development

Humans boast two of several organs or appendages which exist simultaneously throughout a human lifetime. Human dentition however, is unique. Although there is a period of overlap, essentially the two sets of teeth occur consecutively; the deciduous or primary teeth erupt first, and are pushed out by the later developing permanent teeth.

Odontogenesis or tooth formation begins in the deciduous teeth first between about 12 – 16 weeks gestation (Thylstrup, 1979; Billings *et al.*, 2004). Calcification of permanent incisors begins at around 3 - 4 months of age, about the same time the deciduous molars are completing calcification (Browne *et al.*, 2005).

In basic terms, a tooth comprises four dental tissues (Figure 2.2). At least two dental tissues are known to be affected by excess fluoride, dentin (or dentine) and enamel (Horowitz *et al.*, 1984; Fejerskov *et al.*, 1988). Although the size of the dentin crystals appears to be unaltered, dentin fluoride concentrations increase, and Vieira *et al.* (2003; 2004) suggest that dentin may be the best biomarker of chronic fluoride over-exposure. This kind of microscopic examination of dentin can only be performed on extracted teeth, a level of invasiveness inappropriate for this study, and so will not be considered further.

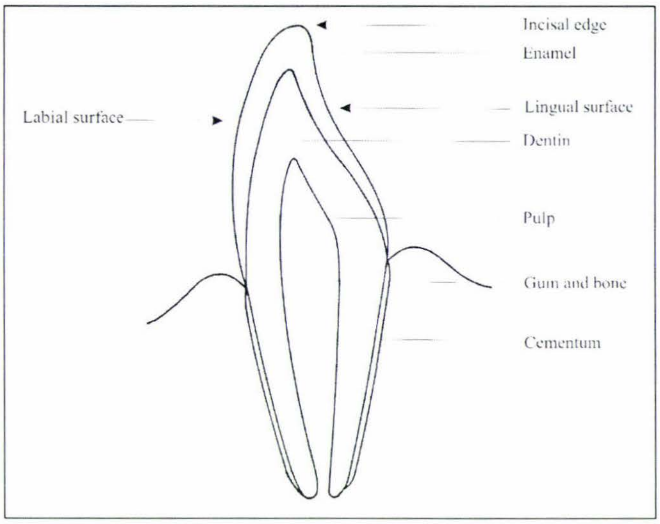


Figure 2.2: Diagrammatic cross-section of an anterior tooth, showing the four dental tissues. Tooth surfaces are also identified. Modified from Berndt and Stearns, (1978).

In dental fluorosis, the tissue most obviously affected by excess fluoride is enamel. Normally developed teeth have a translucent, semi-vitriform, smooth and glossy enamel, which is pale cream in colour (Black and McKay, 1916; Dean, 1934, 1936; Fejerskov *et al.*, 1988). The colour is attributed to the underlying dentin showing through the enamel, while the incisal edge appears almost glassy (Thylstrup, 1979). Not only are the changes caused by dental fluorosis most profound in the enamel, but, as it is the outermost tooth tissue, the changes are also most easily observable and measurable. Bearing this in mind, the description of tooth development to follow will concentrate on enamel development.

Normal enamel development occurs in two stages; a secretory stage and a maturation stage. In the *secretory* stage, ameloblasts (enamel-forming bodies) perform two functions: the production of enamel matrix (made up of proteins such as amelogenin and enamelin), and the initiation of mineralization (the production of hydroxyapatite crystals). In the *maturation* stage, mineralization (crystal production) proliferates, while the proteins and water are withdrawn from the enamel matrix (Soames and Southam, 1998). The hydroxyapatite crystals form a packed and ordered lattice of enamel rods. Micropores between the rods are a normal part of the lattice structure and give enamel its characteristic translucent appearance (Fejerskov *et al.*, 1988).

Enamel development is completed for the deciduous dentition by about one year of age (Billings *et al.*, 2004). Differing ages are given in the literature for the completion of enamel development in permanent teeth; an early estimate by Dean (1936) was eight years of age; Watts and Addy (2001) state until 12 years; and Billings *et al.* (2004) and Browne *et al.* (2005) at four to five years. Essentially, enamel development progresses up until some point prior to tooth eruption (Thylstrup, 1979). The important point to make here is that there is a long time period over which the developing teeth are susceptible to injury.

2.2.3 (iii) Histology and appearance of dental fluorosis

Systemic exposure to excess fluoride, causing dental fluorosis, is only one of a number of conditions that can disrupt the process of normal dental development (Black and McKay, 1916). Others include, for example, specific diseases that are congenital or genetic in origin (Soames and Southam, 1998; Watts and Addy, 2001), infection and trauma (Soames and Southam, 1998), or teratogenic agents such as certain drugs or heavy metals (Billings *et al.*, 2004).

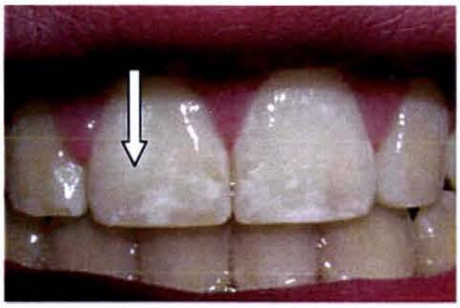
Disturbances of enamel development can occur during matrix production (in the secretory stage) and these generally produce *hypoplasias* of the enamel i.e. the tooth is incompletely formed or underdeveloped and the morphology of the tooth is affected *prior* to eruption. Disturbances that occur during mineralization (in the secretory and maturation stage) generally produce *hypomineralisation* of enamel (Soames and Southam, 1998) i.e. an increase in porosity which doesn't affect overall tooth form or structure.

Some literature continues to refer to the changes in dental fluorosis as hypoplasias (e.g. Murray, 1986; Den Besten, 1994; WHO, 1997). Fejerskov *et al.* (1994) maintain this is a misconception that has persevered over the years and that the changes are due to hypomineralisation (Horowitz *et al.*, 1984; Levy *et al.*, 2002). Dean (1936) initially assumed the onset of susceptibility to fluoride was from birth, but foetal exposure is now considered to be part of the aetiology of dental fluorosis (Soames and Southam, 1998; Levy *et al.*, 2002).

Hypomineralisation manifests as a subsurface porosity beneath an outer, highly mineralised enamel surface. The amount of fluoride ingested long-term has been shown to affect the degree and extent of subsurface porosities which are then filled with water and protein. The water and protein influence the way light is reflected off the tooth surface, and the resulting continuum of visible aberrations is one of the characterising features of dental fluorosis (Black and McKay, 1916; Thylstrup and Fejerskov, 1978; Fejerskov *et al.*, 1988) (Figure 2.3).

The aberrations are visible as an opaque or white discolouration ranging in size from small flecks or fine lines, to diffuse or scattered patches on tooth surfaces (Dean, 1934, 1936, 1942a; Horowitz *et al.*, 1984; Fejerskov *et al.*, 1988). The fine white lines are in fact 'a continuous narrow line of porosity along the surface enamel' (Thylstrup and Fejerskov, 1978) and indicate the incremental lines of enamel development, called the perikymata (Russell, 1961-62; Fejerskov *et al.*, 1988). These porosities are **pre-eruptive changes.**

Post-eruptive changes also occur in fluorotic teeth, and the expression of the changes depends on the degree of pre-eruptive porosity (Fejerskov *et al.*, 1988). Post-eruptive changes could be either a discolouration and/or loss of surface enamel.



a) Very mild/mild dental fluorosis. A horizontal line indicating the perikymata is barely visible (photograph by Hardy Limeback).

b) Mild dental fluorosis (photograph by Elke Babiuk).

c) Moderate dental fluorosis; erosion appears to be affecting the form of some teeth (photograph by Hardy Limeback).

d) Severe dental fluorosis, with apparent pitting (photograph by John Colquhoun).

Figure 2.3: Four photographs showing the patchy white opacities in very mild and mild dental fluorosis, and the thick chalky appearance and brown extrinsic staining in moderate and severe dental fluorosis. The classification used here is the Dean's Index of Fluorosis. (Source: Fluoride Action Network).

Discolouration is evident as a characteristic brown, dark brown, or black stain (Dean, 1934; Horowitz *et al.*, 1984; Fejerskov *et al.*, 1988). This has been described as the "internalisation of an extrinsic stain" (Watts and Addy, 2001) where the enamel proteins in the defectively-porous enamel have absorbed substances from the diet or from tobacco smoke inhalation (Fejerskov *et al.*, 1988; Soames and Southam, 1998).

Loss of surface enamel may be focal or general. Focal loss, known as **pitting**, results in small visible pits or holes, and these may be discrete or confluent (Thylstrup and Fejerskov, 1978). Pitting is due to mechanical damage during mastication and occurs when the subsurface porosity exceeds approximately 10-15%, although pore volumes have been discovered to be as high as 25% (Thylstrup and Fejerskov, 1978). General loss of surface enamel is due to abrasion or attrition of the outer porous surfaces. This occurs on the surfaces most prone to wear, particularly, although not limited to, the occlusal surfaces (Thylstrup and Fejerskov, 1978). In severe cases the form of the tooth may be affected. When surface enamel is lost, it is underlying near-normal enamel, and not dentin, that is exposed (Fejerskov *et al.*, 1988).

Dean (1934, 1936, 1942a) had accurately documented the brown-black discolouration and loss of surface enamel, but believed these to be pre-eruptive intrinsic stains and hypoplasias, respectively. However, the histological research of Thylstrup and Fejerskov (1978) strongly supported a theory proposed in 1933 that loss of surface enamel is a post-eruptive phenomenon.

A more detailed description of the appearance of dental fluorosis is given in Methodology (Section 3.1), as well as features that distinguish it from other enamel opacities.

2.2.3 (iv) Distribution of dental fluorosis within dentition

Because dental fluorosis occurs during tooth development, it is not uncommon for homologous teeth to exhibit similar opacities or aberrations (Russell, 1961-62; Thylstrup and Fejerskov, 1978).

However variation does exist in the dentition (Dean, 1934). Studies show a trend of increasing severity from anterior to posterior teeth (Thylstrup and Fejerskov, 1978; Pereira and Moreira, 1999; Griffin *et al.*, 2002). This reflects the varying periods of development with the bicuspids, cuspids, and second and third molars calcifying more slowly and hence erupting later than the incisors (Russell, 1961-62; Fejerskov *et al.*, 1988). A number of studies also show maxillary teeth are more likely to be affected than mandibular teeth (Thylstrup and Fejerskov, 1978; Griffin *et al.*, 2002; Hamdan, 2003), with the mandibular incisors being the least affected (Russell, 1961-62; WHO, 1997) (Figure 2.4).

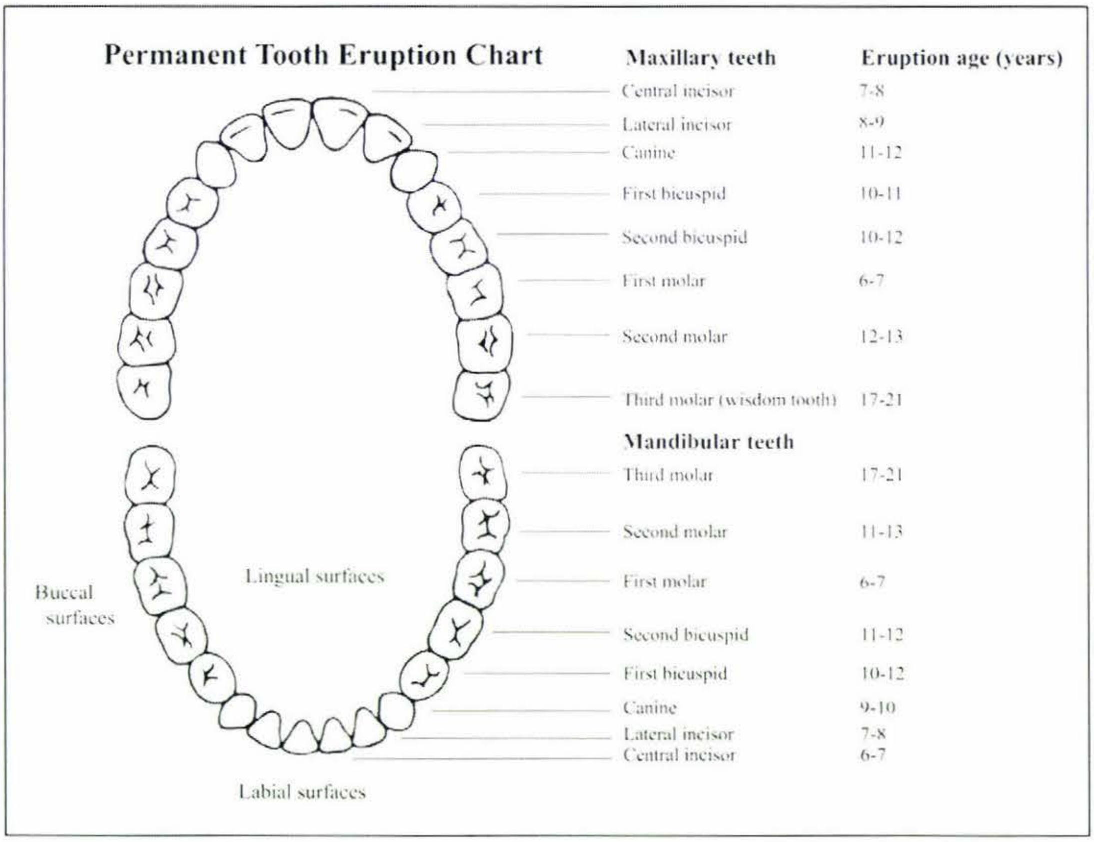


Figure 2.4: Diagram of the dentition showing position and age at time of eruption of maxillary (upper) and mandibular (lower) permanent teeth. This view is looking onto the occlusal surfaces and incisal edges of the teeth. The buccal surfaces (facing the cheek), and the labial surfaces (facing the lip) are also known as facial surfaces. Lingual surfaces face inwards, towards the tongue. Diagram modified from American Dental Association (Source: ADA, 2005).

Further, a study by Levy *et al.* (2002) suggests that fluorosis may not be simply a cumulative process, but that there may be certain critical periods when developing teeth are more susceptible to fluoride exposure.

The severity of dental fluorosis in deciduous teeth is less than that for permanent teeth (Dean, 1936, 1942a; Russell, 1961-62; Fejerskov *et al.*, 1988; Levy *et al.*, 2002). That permanent teeth are more susceptible to defects could be due to their later development in life (Billings *et al.*, 2004), or that deciduous teeth are somewhat protected by the placental barrier *in utero*, the shorter duration (and therefore exposure and accumulation period) of enamel formation, or the thinner depth of enamel (Murray, 1986).

2.2.4 Skeletal fluorosis

The current project is not researching the evidence of skeletal fluorosis in the Ambrym population, so normal skeletal development and the histology and appearance of skeletal effects will not be reviewed in detail. However, it is important to have some understanding of the potential seriousness of skeletal fluorosis as there are consequential questions that arise in environments with raised water fluoride concentrations and confirmed identification of dental fluorosis; is skeletal fluorosis in its infancy and currently asymptomatic, and, if the mitigating conditions remain the same or amplify, could skeletal fluorosis become a reality?

Skeletal fluorosis occurs with higher concentrations of fluoride ingestion, usually occurring over longer exposure periods. In its early stages, it may be asymptomatic, but in its severest form it is crippling, and can lead to incapacitation.

The aetiology is akin to that of dental fluorosis except in skeletal fluorosis the excess fluoride rapidly replaces the hydroxyl in the hydroxyapatite crystal of bone. The main difference is that it is only the *developing, pre-erupted* tooth that is susceptible to the accumulation of fluoride, whereas the skeleton remains susceptible throughout a lifetime. Further, the skeleton will also release fluoride (into plasma) during the normal processes of bone resorption (Fejerskov *et al.*, 1994; Stini, 1998). Therefore, dental fluorosis can occur without the development of skeletal fluorosis (because water fluoride concentrations are not high enough), and skeletal fluorosis can develop in those who do not have dental fluorosis (because they were not exposed to high water fluoride concentrations as a child). Dental and skeletal fluorosis can occur in children who consume water with sufficiently elevated water fluoride concentrations, even though the exposure period may only be a few years.

Early signs and symptoms of skeletal fluorosis are joint stiffness (decreased range of movement), pain (arthralgia), and back stiffness (McGill, 1995; Tekle-Haimanot *et al.*, 1995; WHO, 2001; Whyte *et al.*, 2005), which increase in severity as the disease progresses (Krishnamachari, 1986). There are four principal bone changes that occur in skeletal fluorosis and these can vary depending on the factors influencing its bioavailability and nutritional status of the individual (Section 2.2.1). These disorders are:

- **Osteosclerosis -** an increase in bone density
- **Osteoporosis** – a decrease in bone density
- **Osteomalacia** - a softening or decalcification of the bones
- **Exostoses** – periosteal bone growths

(Krishnamachari, 1986; Glanze, 1990; Heaney, 2000; Ando *et al.*, 2001).

Unlike dental fluorosis which does not show gender differentiation, many studies have shown that severe skeletal fluorosis predominantly affects males. However, females over 60 years of age can also suffer from the disease, and this suggests oestrogen plays a protective role in its development (Krishnamachari, 1986). This gender differentiation has also been recorded in paleopathological studies in skeletons dating from 2000 years ago (Littleton, 1999).

Skeletal fluorosis has been found where fluoride in drinking water is upwards of 4-6 ppm, and generally requires a longer exposure period of ten or more years to develop (McGill, 1995; Tekle-Haimanot *et al*., 1995). However, skeletal fluorosis has manifested in children less than 10 years of age, and this may reflect the added effect of a nutritionally deficient diet (Figure 2.5).

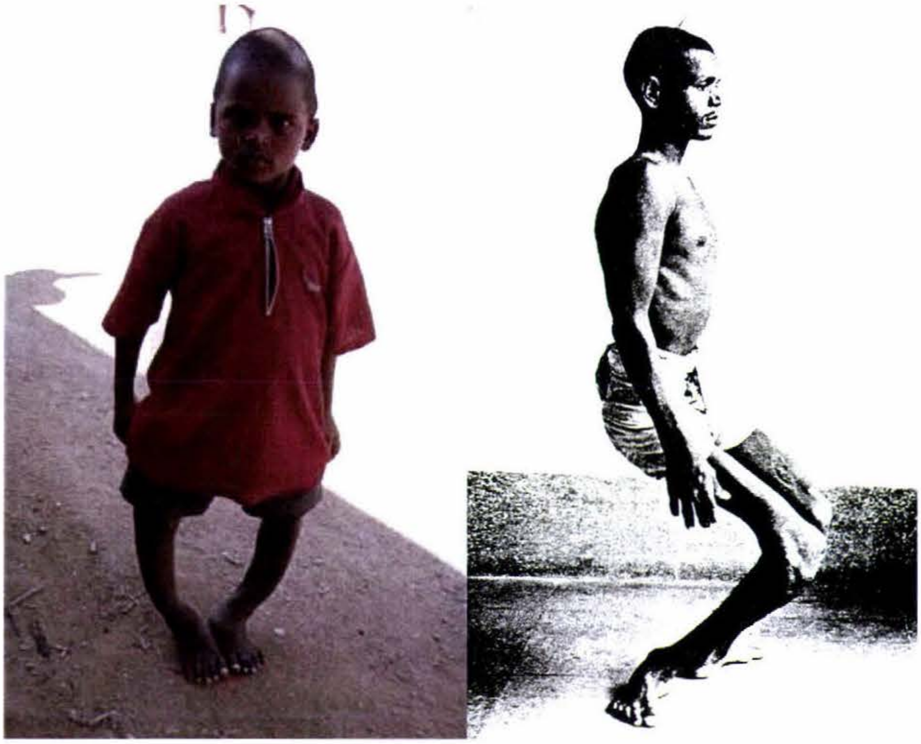


Figure 2.5: Photographs of skeletal fluorosis caused by ingestion of excess fluoride affecting a child, with bow-legs (genu varum) (from www.nofluoride.com), and an adult (from Krishnamachari, 1986).

Many studies have noted the osteosclerotic effects of fluorosis i.e. an elevation in bone mineral density (McGill, 1995; Yildiz *et al*., 2003; Whyte *et al*., 2005). However, increased bone mineral density does not necessarily equate with increased bone quality or strength (Alarcon-Herrera *et al*., 2001; Yildiz *et al*., 2003), and an increased incidence of bone fractures is associated with fluoride-induced changes in bone mineralization. A study in China showed that general bone fractures and hip fractures increased when water concentrations exceeded 4 ppm F. These results also suggested a deficiency effect at < 0.3 ppm, where general fractures increased (Li *et al*., 2001).

In its severest form skeletal fluorosis is crippling and can become incapacitating. Mineral deposits and exostoses penetrate muscles, tendons, and ligaments (McGill, 1995). Secondary neurological problems can develop if the spinal cord becomes ossified and mechanically compressed. This can further amplify disability (McGill, 1995; Tekle-Haimanot *et al.*, 1995), although nerve damage can relieve the sensation of pain (Reddy, 1998).

2.2.5 Environments of fluorosis

Most cases of dental and skeletal fluorosis are caused by the ingestion of fluoride-rich drinking water. Where this occurs naturally, it is generally due to the leaching of volcanic and sedimentary deposits (Calderon, 2000), although the leaching of Cenozoic mastodon tusks and bones was implicated in one community (Smith *et al.*, 1931). These fluoride-rich groundwaters can be transported via geological fractures and springs to surface waters, or they can be directly accessed by bores and wells.

Fluorosis is endemic in a number of countries due to this water - rock interaction and has led to the identification of fluoride 'belts'. Two extensive belts exist: one through Syria-Jordan-Egypt-Libya-Algeria-Sudan-Kenya, and another through Turkey-Iraq-Iran-Afghanistan-India, as well as belts in northern Thailand-China, Japan, and the Americas (WHO, 2001).

Fluoride-rich and fluoride-poor areas can be correlated with two over-arching variables (Keller, 1979; Subba Rao and John Devadas, 2003), which Dissanayake (1979) proposed could then be identified into 'geochemical provinces' and mapped:

1. Geology – parent rock, topography, and soil.
2. Climate – temperature and rainfall.

These factors have already been reviewed under 'the fluorine cycle' (Section 2.1.3). Maximum daily temperature has an apparent dual effect however, as not only does it influence the hydrogeochemical distribution of fluoride, it is also understood to cause an increase in fluid intake, and therefore an increase in total amount of fluoride consumed (Kailis and Silva, 1967; Grimaldo *et* al., 1995; van Palenstein Helderman *et* al., 1995; Murray, 1986).

A number of other environments have been identified where high-fluoride water was found *not* to be the main cause of endemic fluorosis. In China, millions of people suffer from dental and skeletal fluorosis (Dissanayake and Chandrajith, 1999; Ando *et al.*, 2001). Three different aetiologies have been identified - high-fluoride water (as discussed above), indoor coal combustion, and drinking of brick tea (Lian-Fang and Jian-Zhong, 1995). Where fluorosis has been found in low water-fluoride areas (< 1 ppm F) (Ando *et al.*, 2001), food preparation practices and food sources play a more significant role. Coal, particularly Chinese coal, is fluoride-rich (Zheng *et al.*, 1999; Finkelman *et al.*, 2002), as is the clay which is used as a binder in making coal briquettes (Dai *et al.*, 2004). Rural-dwelling Chinese burn these briquettes in indoor fires in order to dehydrate food. The fluoride released during combustion is then absorbed by the food, which is later consumed (Dissanayake and Chandrajith, 1999; Dai *et al.*, 2004). This practice not only enriches fluoride in the diet, but, as the fires are flueless, airborne fluoride can also be inhaled.

Countries in the East African Rift Valley (EARV) have high-fluoride groundwater due to the highly silica-undersaturated, phosphate- and fluorine-enriched magmas there. One study analysed 138 drinking water samples in Ethiopia and found 33% to be elevated in fluoride (over 1.5 ppm) (Reimann *et al.*, 2003). However dietary practices have also played a role in endemic fluorosis here. In Tanzania, magadi is a potash salt commonly added to food as a flavour enhancer, and this was found to be a main source of fluoride (Mabelya *et al.*, 1995; van Palenstein Helderman *et al.*, 1995). Malnutrition and dietary inadequacies are also linked to fluorosis (Smith *et al.*, 1931), and this could be a significant contributing factor in many of these developing countries.

Fluorosis does occur in developed countries, but on the whole it is only dental fluorosis that is noted, and this is usually mild (Figure 2.3). This perhaps explains the paradox that fluorosis is considered a cosmetic effect by the US Environmental Protection Agency whereas WHO deem it to be an adverse state of health affecting millions of people (Erdal and Buchanan, 2005). In developed countries, many civic water supplies are fluoridated for the public health benefit of decreased caries incidence, and it is believed to be of no concern at these concentrations (Calderon, 2000). Studies claim anecdotal reports of increased fluorosis but it is thought this is not due to water fluoridation alone, but to an increased availability of ingestible fluoride sources such as infant formula, fluoridated toothpastes and supplements, tea, and atmospheric discharge from industry.

2.2.6 Gap in knowledge

Over 500 million people live (with associated risk) in the vicinity of active volcanoes (Baxter, 2005) and this continues to grow with populations expanding onto fertile soils around volcanoes, the physical properties of which make ideal ground for agricultural and horticultural practices (Garrec *et al.*, 1984; Neall, 2006). Hydrothermal areas may be utilised for cooking food (Baxter *et al.*, 1999), or for their therapeutic properties.

In Section 2.1, volcanic gases and their environmental impact was introduced. In terms of health impacts of volcanic gases, respiratory related conditions such as asthma, silicosis, and asphyxia (suffocation) prevail as common complaints. No research has yet been done linking volcanogenic fluoride from a persistently degassing volcano to a chronic human health disease, namely, fluorosis. This study is one of the first to examine the relationship between volcanogenic fluoride and dental fluorosis in a population living in close proximity to an actively degassing volcano.

CHAPTER 3: METHODOLOGY

This chapter is divided into three sections for the methods employed in the dental survey, water collection, and food collection. All statistical analysis was carried out using the Microsoft Excel programme.

3.1 Dental survey

3.1.1 Introduction

As detailed in Chapter 2 (Literature Review), fluorosis research began almost 100 years ago. Almost 80 years ago, Dean developed the first measurement tool, a dental survey, for assessing the dental effects of over-exposure to fluoride. Since then, various dental surveys and methods have been developed depending on aims and desired outcomes of respective research projects. These can range from general to more specific objectives. For example, a general survey is used by the World Health Organisation (WHO) in order to design appropriate oral health programmes and monitor patterns of disease for target human population groups. These surveys encompass assessments of overall health and condition of teeth, gums, and bone (WHO, 1997). More specifically, and incorporated into the WHO dental survey, is a descriptive dental assessment tool for recording all aberrations of enamel, regardless of the aetiological agent. This enamel assessment tool is called the developmental defects of enamel (DDE) index.

The objective of the present study however, was to specifically assess dental fluorosis. Although dental fluorosis is a developmental defect of enamel, the DDE index does not assess this *per se*. Hence, for the purpose of this study, an aetiological index was required, i.e. an index designed specifically to assess those enamel defects which result from a chronic overexposure to, and accumulation of, fluoride.

Three main indices are used to study the prevalence of dental fluorosis in a community or population: the Dean's Index, the Thylstrup-Fejerskov Index (TF Index), and the Tooth Surface Index of Fluorosis (TSIF) (Clarkson, 1989; Riordan, 1994; MacKay and Thomson, 2005). A more recent index, the Fluorosis Risk Index (FRI), was developed in 1990 by Pendrys (cited in Rozier, 1994) but was unknown at the commencement of this study. The FRI was designed to elucidate associations between specific age-exposure periods and dental fluorosis. However the level of detail provided by the FRI was not required for the current study, and, due to variable water fluoride concentrations encountered on Ambrym, would not have been appropriate.

In addition to these indices, Cochran *et al.* (2004) developed a standardised method for dental photography which would allow the actual assessment (in conjunction with one of the indices above) to occur at a later time. This technique has very precise requirements in terms of equipment and procedure e.g. illumination strength, quality of film, angle, and distance of camera from subject. The authors claim it to be a useful tool for studying enamel defects because of its calibration, reproducibility, and capability for comparison of contemporaneous studies from different sites, as well as those conducted non-contemporaneously. However, this technique does appear to allow an opportunity for the introduction of substantial human and technical error. It was not considered an appropriate adjunct for the purposes of the current study because field conditions in the study area precluded the routine use of the technology required. Further, the advent and widespread use of digital photography necessitates some form of recalibration of the technique.

In order to select the most appropriate method of fluorosis assessment for the current study, a review of the three main indices was undertaken. This is presented in the following section.

3.1.2 Review of Fluorosis Indices

The Dean's, TF, and TSIF indices refer to conducting surveys in communities where the participants are lifetime residents and the water supply in use has not changed since the time of the participants' tooth development. Other studies have also dealt with a communal water supply which has remained unchanged for a number of years. Many of these studies seek to correlate water fluoride concentrations with prevalence of dental fluorosis in a community, so the unchanging water supply is imperative. This close correlation was not an aim of the current study, nor was it feasible as, on Ambrym, drinking water is contained in numerous household reservoirs which are heterogeneous with respect to condition, age, construction material, location, and input.

The three main fluorosis indices are listed below in their chronological order of development as it was implicit that each successive index was an improvement on the former. All three indices are useful and commonly utilized (Clarkson, 1989; Rozier, 1994), and are based on a visual assessment of dentition.

3.1.2 (i) Dean's Index of Fluorosis

The Dean's Index was developed by the dentist and epidemiologist H Trendley Dean before the relationship between dental health and fluoride was established. It was published as a paper entitled "Classification of Mottled Enamel Diagnosis" (Dean, 1934), and is based on macroscopic changes visible on the enamel surface. The six categories of Dean's Index are described in Table 3.1. In the original index, Dean (1934) included a seventh category he termed "moderately severe", but in his 1938 paper, this was incorporated under "severe". This revision is now the standard classification which is referred to as Dean's Index (Dean, 1942a).

Table 3.1: The six categories of Dean's Index (Dean 1934, 1942a).

Category	Descriptive criteria
Normal	Usual translucent enamel, smooth glossy surface. Pale creamy white colour. Non-fluorotic hypoplasias included here.
Questionable	Few white flecks to occasional white spots 1-2 mm in diameter.
Very mild	Small, opaque, paper white areas scattered irregularly or streaked. Small pitted or white areas may be found on cusps. < 25% tooth surface.
Mild	Chalky white, opaque areas. Faint brown stains sometimes apparent. Up to 50% tooth surface.
Moderate	Pitting often present. Brown stain (or white depending on endemic area), frequently a disfiguring feature. All surfaces affected.
Severe	Smoky white appearance. Diagnostic sign: Discrete or confluent pitting. Greater depth of enamel appears to be involved. Brown stain, deeper in hue and more widespread. Often have corroded-like appearance (hypoplasia*). All enamel surfaces affected.

*** Dean (1934, 1936, 1942a) used the term hypoplasia, to describe the change in tooth form, believing the corroded appearance of the enamel to occur prior to tooth eruption. However, Thylstrup and Fejerskov (1978) found these features to be post-eruptive, and therefore not strictly a hypoplasia.**

The Dean's Index was the first specific, visual dental health index developed, and so could be considered relatively basic and the prototype of later indices. MacKay and Thomson (2005) said of the Dean's Index it "... is regarded internationally as the historical golden standard for research into enamel defects". However, the "questionable" category has been the cause of some contention in the literature as to its usefulness. This will be discussed later in the chapter.

Dean specified that the preferred age group for a dental fluorosis study should be 12 to 14 years, by which time the permanent teeth of most individuals have erupted (excluding third molars or 'wisdom teeth'). Each tooth is classified according to one of the six categories. For simplicity, the classification reported is that which is assigned to each child. This is the category recorded for the two most severely affected teeth. It does not specify operating conditions, but Pereira and Moreira (1999) claim Dean examined teeth both wet and in natural light.

In an attempt to quantify dental fluorosis in a population, establish boundaries of what is publicly acceptable, and the relationship to water fluoride concentration, Dean (1942a) devised the **Community Index of Fluorosis (Fci)**. The detail of this calculation can be found in the Results (Section 4.1.4), suffice to say here that it is an average value based on the frequency that each category of fluorosis is recorded. Dean interpreted an Fci of 0.4 or less being of no concern (and 0.3 was associated with low prevalence of caries), but an Fci above 0.6 indicated dental fluorosis had become a "public health problem". Here, the term "public health problem" relates to the aesthetics of dental fluorosis. This does not acknowledge its histopathology, and, as it is an average, nor does it adequately acknowledge that some individuals may be suffering with the severest forms of dental fluorosis while others have none at all. Bearing this in mind, the Fci can still be useful as an overall, single-figure measure to compare the degree of fluorosis amongst populations.

3.1.2 (ii) Thylstrup-Fejerskov (TF) Index

Much of the literature, particularly dental, appears to be concerned with the presence and/or aesthetics of dental fluorosis, a view supported by Thylstrup and Fejerskov (1978). They appear to be among the first to correlate the histopathology of dental fluorosis with the macroscopically visible aberrations, although Black and McKay (1916) had initiated understanding into the histological changes in mottled teeth. The TF Index (Table 3.2) proposed by Thylstrup and Fejerskov (1978) was designed to be more diagnostically sensitive and address the apparent shortcomings of the classical Dean's Index.

Table 3.2: The original TF Index (Thylstrup and Fejerskov, 1978). A modified version was later published in Fejerskov *et al*. (1988).

Numerical	**Descriptive criteria**	
Score	**Smooth surfaces**	**Occlusal surfaces**
0	Normal translucency of enamel remains after prolonged air drying.	
1	Narrow white lines located corresponding to the perikymata.	
2	More pronounced lines of opacity which follow the perikymata. Occasionally confluence of adjacent lines.	Scattered areas of opacity < 2 mm in diameter and pronounced opacity of cuspal ridges.
3	Merging and irregular cloudy areas of opacity. Accentuated drawing of perikymata often visible between opacities.	Confluent areas of marked opacity. Worn areas appear almost normal but usually circumscribed by a rim of opaque enamel.
4	The entire surface exhibits marked opacity or appears chalky white. Parts of surface exposed to attrition appear less affected.	Entire surface exhibits marked opacity. Attrition is often pronounced shortly after eruption.
5	Entire surface displays marked opacity with focal loss of outermost enamel (pits) < 2mm in diameter.	
6	Pits are regularly arranged in horizontal bands < 2mm in vertical extension.	Confluent areas < 3mm in diameter exhibit loss of enamel. Marked attrition.
7	Loss of outermost enamel in irregular areas involving < half of entire surface.	Changes in morphology caused by merging pits and marked attrition.
8	Loss of outermost enamel involving > half of surface.	
9	Loss of main part of enamel with change in anatomic appearance of surface. Cervical rim of almost unaffected enamel is often noted.	

The TF Index has the following features which the authors consider to be advances on the Dean's Index.

- A biological (histological) dimension. This is a defining characteristic of the TF Index. Using light microscopy, the authors characterised the histological changes associated with varying degrees of fluorotic enamel. These changes (surface and subsurface porosities) were correlated to the macroscopic observations which are visible on the tooth surface, and upon which a visual dental assessment is based.

- A more detailed breakdown of the more extreme signs of dental fluorosis (Dean's 'severe' category) into five categories (discussed further in Section 3.1.3; Table 3.4).

- The TF Index exhibits a tighter correlation between a wider range of water fluoride concentrations and degree of dental fluorosis prevalent within a population.

- Each tooth surface is assessed. In the original paper (Thylstrup and Fejerskov, 1978), the intention was to assess the clinical appearance of fluorosis for each tooth surface. Separate descriptions were given for smooth surfaces (buccal/labial, and lingual), and occlusal surfaces (Table 3.2). This allowed for within-tooth and within-dentition comparisons. This detail is omitted in a modified version (Fejerskov *et al.*, 1988) because at the time of eruption, all surfaces of a given tooth are equally affected, so it is sufficient that only the facial surfaces are used for classification.

- The absence of a 'questionable' category, although this was not explicitly claimed to be an improvement.

Thylstrup and Fejerksov (1978) presented their classification system, and except for drying of teeth, no other operational procedures were conditional. However, the following were the conditions they noted during their survey:

- Lighting: daylight.
- Equipment: portable chair, plane mirror, and probes.
- Dental preparation: Teeth dried with cotton wool and examined according to WHO (1971) [an earlier edition of WHO, 1997].
- Subjects: 212 children divided into two groups – those with all their permanent teeth erupted (except 3rd molar), and those with both deciduous and permanent teeth.
- Ages: approximately 12 to 15 years.
- Examiner reliability: practical difficulties precluded assessing it at the time. Inter- and intra-examiner reliability was later assessed using photographs of 125 buccal surfaces.
- Confidence in identification of opacities: was not specified.
- Examiners: the two authors.

In their discussion, these authors comment that occlusal surfaces are a poor indicator of fluorosis, as these are most prone to wear and opacities can therefore be lost by abrasion (Thylstrup and Fejerskov, 1978). This observation is taken into account in the modified TF Index (Fejerskov *et al.*, 1988) where the separate descriptive criteria for occlusal surfaces are omitted. This, along with the addition of a diagrammatic illustration for each category, appears to make the modified version a simpler and more useful tool.

3.1.2 (iii) Tooth Surface Index of Fluorosis (TSIF)

The TSIF (Table 3.3) proposed by Horowitz *et al.* (1984) was also designed to be more diagnostically sensitive and address the apparent shortcomings of the classical Dean's Index.

Table 3.3: Tooth Surface Index of Fluorosis from Horowitz *et al.* (1984).

Numerical score	**Descriptive criteria**
0	Enamel shows no evidence of fluorosis.
1	Enamel shows definite evidence of fluorosis, enamel areas with parchment white colour that total less than one-third of the visible enamel surface. This category includes fluorosis confined only to incisal edges of anterior teeth and cusp tips of posterior teeth ("snowcapping").
2	Parchment-white fluorosis totals at least one-third of the visible surface, but less than two-thirds.
3	Parchment-white fluorosis totals at least two-thirds of the visible surface.
4	Enamel shows staining in conjunction with any of the preceding levels of fluorosis. Staining is defined as an area of definite discolouration that may range from light to very dark brown.
5	Discrete pitting of the enamel exists, unaccompanied by evidence of staining of intact enamel. A pit is defined as a definite physical defect in the enamel surface with a rough floor that is surrounded by a wall of intact enamel. The pitted area is usually stained or differs in colour from the surrounding enamel.
6	Both discrete pitting and staining of the intact enamel exist.
7	Confluent pitting of the enamel surface exists. Large areas of enamel may be missing and the anatomy of the tooth may be altered. Dark-brown stain is usually present.

The TSIF has similar features to those of the TF Index which were considered to be advances on the Dean's Index. The authors claim these are:

- A more detailed breakdown into three categories for the more extreme signs of dental fluorosis (discussed further in Section 3.1.3; Table 3.4). The authors suggest that due to few allocations to category 6, a future modification might be to combine categories 5 and 6.

- An increased sensitivity of the index classifications to water fluoride concentrations. The eight categories of the TSIF allow statistical differentiation among different water-fluoride concentrations.

- Each tooth surface is assessed, i.e. three categories are recorded for the posterior teeth (buccal, occlusal, and lingual surfaces), and two for the anterior teeth (labial and lingual surfaces). This allows for within-tooth and within-dentition comparisons. The authors claim this is useful for determining the 'public health effect of fluorosis' because the labial surfaces of maxillary anterior teeth, which are of particular aesthetic importance, can be reported on separately.

- The absence of a 'questionable' category was to improve clarity regarding the presence or absence of fluorosis. However the authors found that the examiners in their study disagreed on a positive identification of fluorosis when using the TSIF, i.e. disagreement between allocating a score of 0 or 1.

The authors specified that only erupted unrestored teeth are to be examined. No other specific operating conditions were given, but the following conditions were employed during their survey:

- Lighting: artificial (but type not specified).
- Equipment: portable dental chair and plane dental mirrors.
- Dental preparation: not specified, although Pereira and Moreira (1999) claim teeth were examined wet.
- Subjects: 807 children. Always lived in respective communities and always used the community water supply. Only permanent teeth examined.
- Ages: 8 to 16 years.
- Examiner reliability: 111 (14%) were re-examined.
- Confidence in identification of opacities: referred to Russell (1961-62).
- Examiners: two National Caries Program dentists trained by the authors to use TSIF.

3.1.3 Comparison of the dental indices

All three indices are still currently utilised in dental research. Dean's Index e.g. Grimaldo *et al.* (1995); Ibrahim *et al.* (1997); Alarcon-Herrera *et al.* (2001); Grobler *et al.* (2001); Griffin *et al.* (2002), and the TF Index e.g. Mabelya *et al.* (1995); van Palenstein Helderman *et al.* (1995); Tabari *et al.* (2000); Rwenyonyi *et al.* (2000); Stephen *et al.* (2002); Hamdan (2003); Wondwossen *et al.* (2003); Vieira *et al.* (2004), appear to be referenced more frequently than the TSIF e.g. Clark (1995); Levy *et al.* (2002).

Pereira and Moreira (1999) suggest each index may be more appropriate depending on the research aim: e.g. the Dean's Index for comparative studies between current and historical prevalence; the TF Index for clinical or analytical epidemiological studies; and the TSIF for studies with an aesthetic perspective. However, all of the indices in the above studies appear to have been applied successfully irrespective of appropriateness to the research aim as suggested above. Further, a number of authors have compared and commented on two or more of the three indices (authors cited by Riordan, 1994; and Pereira and Moreira, 1999) looking at aspects such as practicality, statistical similarity, and usefulness. Amongst the three indices there is a good correlation of estimates regarding the prevalence of fluorosis, regardless of the degree of severity (Pereira and Moreira, 1999), but naturally, it is suggested that research ought to continue to assess the validity of fluorosis indices (Horowitz *et al.*, 1984; Clarkson, 1989; Rozier, 1994).

Most comment and criticism in the literature seems related to the Dean's Index, an observation also noted by other authors (Clarkson, 1989; Riordan, 1994). This is not surprising considering it is the pioneer of assessment tools in fluorosis research. The literature critiquing the Dean's Index comes largely from those authors who have sought to overcome its shortcomings by designing new indices i.e. Thylstrup and Fejerskov (the TF Index) and Horowitz et al. (the TSIF). The shortcomings of Dean's Index can be summarised as follows:

- There is no histological component. The Dean's Index does not correlate the various visible signs of dental fluorosis with the associated histopathology (Thylstrup and Fejerskov, 1978). These authors observe that Dean made the point in 1938 that this deficiency needed to be addressed.

- It lacks sensitivity to assess within-tooth and within-dentition variation because for simplicity, the classification allocated is *per child* (on the basis of the two most affected teeth), rather than *per tooth* (as in the TF Index and TSIF). Therefore, overall severity in the individual child is not reflected. Information on the distribution of fluorosis within the dentition, or on different surfaces of the same tooth, is not collected in the Dean's Index, but it is in the original TF Index and the TSIF (Thylstrup and Fejerskov, 1978; Horowitz *et al.*, 1984).

- Extreme signs of fluorosis are grouped into one category. The lack of classification refinement for the more extreme signs of fluorosis means the Dean's Index is unable to distinguish between communities with different water-fluoride levels at higher fluoride concentrations (Thylstrup and Fejerksov, 1978; Horowitz *et al.*, 1984). Where Dean has one 'severe' category, the TF and TSIF have five and three categories, respectively (see Table 3.4). This increases sensitivity to statistically enable correlations between water-F concentrations and the level of dental fluorosis experienced by a community.

Table 3.4: Comparison of the categories of the TF Index and the TSIF that correspond to the descriptive categories of Dean's Index. Note especially the number of categories that correspond to Dean's 'severe' category. A similar reconciliation of the TF Index and TSIF with Dean's Index is given by Griffin *et al.* (2002).

Dean Index	T-F Index	TSIF
Normal	0	0
Questionable		
Very mild	1, 2	1
Mild	3	2
Moderate	4	3, 4
Severe	5, 6, 7, 8, 9	5, 6, 7

- The inclusion of a 'questionable' classification. Dean himself states that "the classification of 'questionable' is often a baffling problem" (Dean, 1934). Although this is not specifically mentioned by Thylstrup and Fejerskov (1978), Fejerskov *et al.* (1988) concur with Dean's comment. The matter is directly addressed in the TSIF by Horowitz *et al.* (1984) who claim that the 'questionable' classification is "difficult to define or interpret precisely".

However, Dean explained that the questionable category is for those instances where the examiner cannot confidently assign a category of either 'normal' or 'very mild' due to the presence of small white spots or flecks. The confirmation that these opacities are fluorotic is only resolved once the entire population has been classified. He explained:

"...no attempt is made to diagnose these small white spots or minute white fleckings as the earliest signs of mottling of the enamel by examination of the person *per se. Recourse is always made to group study*...Thus, in areas of questionable endemicity, this classification becomes a valuable adjunct. Should an unusually large number of cases be classified as 'questionable' when, at the same time, a smaller percentage is likewise showing the milder forms of mottling of the enamel [*cf. an absence of milder forms* - RJC], we are justified in assuming that we are dealing with what is probably a "border-line" area, an area where the causative factor in the mottling is present in the water supply quantitatively somewhere between the maximum harmless amount and the minimum amount capable of producing the very mild and the mild type of mottled enamel (Dean, 1934) (emphasis mine). NB: when Dean wrote this, it was not yet established that fluoride was the causative factor of what was then still known as 'mottled enamel'.

In the current study, Dean's 'questionable' category was found to be most useful; his description of 'questionable' is precise, and flecks or spots of 1 – 2 mm were commonly observed in the field. The enamel was not 'normal' translucent, but was also not severe enough to be classed as 'very mild' (or '1' had the TF Index or TSIF been employed).

Fejerskov *et al.* (1988) comment that the intuitive feelings of Dean have been validated in later studies, that the prevalence of 'questionable' was found to be related to water fluoride concentration, and former doubts about the 'questionable' category are no longer justified.

Despite the limitations outlined above, Dean and the Dean's Index have maintained a place of respect in the dental fraternity, as expressed by the following excerpt from Fejerskov *et al.* (1988):

"Given the knowledge about the histopathological features of dental fluorosis available during his time, and given the spectrum of dental fluorosis with which Dean principally dealt, it is quite remarkable, and a tribute to his intellect, that he was able to develop a classification system which subsequent advances in scientific research have been able to substantiate as reflecting, broadly, the biological changes which occur in enamel as a result of fluoride ingestion."

Other points noted in reviewing the Indices include:

- Assessment is partly a subjective process. The TF includes relative terms such as "narrow white lines" and "more pronounced white lines", whereas the Dean's Index and the TSIF classify according to the clinical appearance and the estimated proportion of tooth surface area involved. This attempt to estimate affected surface area brings in an element of objectivity, which can ease somewhat the difficulties of classification.

- Fewer options in the Dean's Index means it is simpler and quicker when assigning a tooth to a category. That the original TF Index included a classification for occlusal surfaces which was omitted in the modified version, and that the TSIF suggested an amalgamation of categories 5 and 6, and that Dean amalgamated 'moderately severe' and 'severe' demonstrates that in the field, a simple tool with few categories is preferable. Rozier (1994) affirms the continued use of the Dean's Index since the 1930's is testimony to its simplicity and utility.

3.1.4 Selection of fluorosis index for this study

The suitability of a particular index is dependent on the objectives of a given study and the level of detail required. In the current study, general considerations to meet the aim of this research included:

- Simplicity - This was not an exhaustive analytical project in a technically- or economically-advanced environment to further elucidate the intricacies and complexities of fluorosis. A robust method that would determine the prevalence and severity of dental fluorosis in remote communities, and that could easily be utilised by other lay people was considered preferable, should the Malampa Provincial Council decide to commence an ongoing monitoring programme.

- Resources issues:
  - Time – Field work was limited to the available time allocated in Vanuatu. This was often compromised by local influences such as reliability of transport from one village to another, and dependence on daylight hours. Ideally, interruption of school time and usual village life would be minimal.
  - Technology – power supply is sporadic or non-existent in many villages. Field conditions and transport (often on foot) precluded the use of more than basic, unpowered equipment. For example, Russell (1961-62) recommends the use of a colour-correct examination lamp, and Thylstrup and Fejerskov (1978) and Horowitz *et al.* (1984) used portable dental chairs in order to view all tooth surfaces. I required a dental assessment that would be as stress free for each child as possible. By excluding the use of specialised equipment (e.g. cheek retractors, dental probes, sterilising equipment), the potential for fear and negative emotional/psychological impact was greatly reduced, thereby increasing co-operation and fostering positive researcher-participant relationships.

Bearing in mind the aim of this research and the above general considerations, it was deemed that the Dean's Index was the most appropriate fluorosis index to use for this study because of the following reasons:

- The current research was not required to distinguish severity of fluorosis amongst different community water fluoride concentrations, but to ascertain the existence and, if existent, prevalence of dental fluorosis. Dean's Index, with six categories, provided sufficient detail for this to be investigated. It is the recommended index for use in current and historical prevalence studies (Pereira and Moreira, 1999), and is the index incorporated into WHO oral health surveys (WHO, 1997).

- Dean's Index is calculated on a per child (individual) basis, which is the unit of observation in epidemiology (Calderon, 2000). Further, it has the additional provision of the Community Index of Fluorosis (Fci), to gauge dental fluorosis severity within a community and to facilitate comparison with other communities. The objectives of the study did not require an analysis of within-tooth or within-dentition variation, so the detail of the TF Index and TSIF was not required.

- As time was limited in Vanuatu, a time-efficient method was required.

- The survey could be conducted easily without the use of specialised equipment.

3.1.5 Differential diagnosis of opacities

In order to ascertain the prevalence of dental fluorosis within a community, it is crucial that there is confidence in recognising fluoride-induced opacities. Dental opacities can be caused by agents other than fluoride e.g. antibiotics, genetic disorders, and other developmental defects of enamel. Soames and Southam (1998) and Watts and Addy (2001) claim that other types of hypomineralised and hypoplastic enamel are clinically and histologically indistinct from fluorotic enamel. For example, they claim the appearance of the genetic disease amelogenesis imperfecta is very similar to dental fluorosis. However, amelogenesis imperfecta has a yellow-brown range of discolouration (Soames and Southam, 1998; Watts and Addy, 2001), and the difference in tooth form is a true hypoplasia, present at the time of eruption (Soames and Southam, 1998). Fejerskov *et al.* (1988; 1994) maintain the characteristics of fluorosis are quite distinct from both amelogenesis and dentinogenesis imperfecta. The criteria, as described by Russell (1961-62) are still referenced in fluorosis research today (e.g. Levy *et al.*, 2002), and became an important complementary reference for this current study. The features of fluorotic and non-fluorotic opacities are presented in Table 3.5.

Table 3.5: Characteristics of milder degrees of fluoride induced opacities and those which are non-fluoride related in origin. Modified from Russell (1961-62) and Fejerskov *et al.* (1988).

Characteristic of opacity	**Dental fluorosis opacities**	**Other enamel opacities**
Form	Spots or flecks, fine lines (reflecting the perikymata) or patches. "Snowcapping" on cuspal tips or incisal edges.	May be symmetric, round or oval.
Demarcation	Usually difficult to determine, can fade imperceptibly or be diffuse.	Usually well marked, clearly visible.
Colour	Opaque, white, parchment-white, chalky (remembering normal enamel is translucent and glossy); can vary in intensity. Difficult to photograph.	White opaque or creamy-yellow to dark reddish orange at time of eruption; pinks, lemon-yellows; milky-yellow, grey, light yellow-brown uniformly throughout mouth.
Area affected	Can affect entire tooth surface (of all surfaces); often enhanced near cusp tips or incisal edges.	Usually centrally located on smooth surfaces, especially labial.
Teeth affected	Usually homologous teeth.	Usually incisors; commonly on single tooth but may affect homologous teeth.

3.1.6 Field methods used in this study

3.1.6 (i) Ethical approval

Ethical approval for this dental study was obtained from the Massey University Human Ethics Committee (HEC: PN Application – 04/157). A formal application was lodged with the Vanuatu Department of Health which was followed up and confirmed although no written approval was received. Consent and support from the indigenous Ni-vanuatu was obtained verbally after a full discussion and description of what the study was for, who would see the results, and how the data would be used and reported. In Vanuatu, verbal agreements are more traditionally and culturally appropriate and acceptable. Discussions occurred at various social and administrative levels: government departmental/ministerial, with local village chiefs and elders, and on an individual basis.

Initially, discussion and information-sharing occurred with the Department of Geology, Mines and Water Resources (DGMWR) in Port Vila. Prior to this project, a good working relationship had been established between research staff from Massey University, New Zealand, and staff at the DGMWR. Douglas Charley, a respected man amongst the Ni-vanuatu islanders, a chief from the island of Tongoa, and seismologist at DGMWR was instrumental in facilitating the research project.

Meetings were also held with a team from the Vanuatu Ministry of Health, including the Minister of Health, and a World Health Organisation representative and dental officer. The New Zealand Embassy in Port Vila was also informed.

On the islands, discussion (in Bislama, the Ni-vanuatu lingua franca) with local chiefs and elders occurred in each village. Although permission was granted at all levels, at any time permission could be withdrawn by either the villagers or Government.

During the school holiday surveys (January), parents and extended-family adults of the children were present during the assessment of children's teeth. Consent and support was also obtained from headmasters and teachers during the school term surveys (April/May and June). If a child was too shy or distressed to participate in the survey, then that child was omitted from the survey and/or their photograph was not taken. No record was kept of unexamined children; during the community-based survey it became apparent that children may have kept their distance upon our arrival and subsequently withdrawn into the bush to avoid the dental survey. Hence, total target population numbers are not known. Only once during school visits was a child not examined. On three occasions a child's photograph was not taken due to distress.

3.1.6 (ii) Field methods

Three expeditions, as outlined below, were made to Vanuatu in 2005 for the collection of water samples, and to conduct dental surveys using a quantitative observational epidemiological approach (Calderon, 2000).

January:	West Ambrym; Tanna.
April/May:	West Ambrym; North, and Southeast Ambrym.
July:	Malakula; Tongoa.

The target population for this study was the inhabitants of West Ambrym. It is the people in this region, and their drinking water supplies, which are most easily accessible and frequently exposed to Marum and Benbow's contaminants, as the dispersion of the volcanic plumes are governed by the predominant southeast winds. Surveys conducted in the other locations were for comparative analysis; Malakula lies downwind of Ambrym and Ambrym's volcanic plume has been sighted overhead there; Tanna is similar to Ambrym in that it too has an active volcano, Yasur; North and Southeast Ambrym, and Tongoa, were considered to be control population groups.

Clinical examinations were community-based in January, school-based in April/May, and conducted in both settings in July. The villages and schools were chosen once on the ground in Ambrym following discussion with the elders and chiefs, taking into account such factors as accessibility, availability of transport, and community size. To have randomly selected and requested access to specific villages and schools prior to our arrival in person would not have been appropriate within the context of this social environment. Further, experience has taught that had specific prior arrangements been made, intervening issues such as transport difficulties or relatively impromptu community events may have superseded such arrangements.

Natural sunlight was chosen as the means to illuminate dentition due to reasons in Section 3.1.4. Other studies have also used natural light (Kailis and Silva, 1967; Ibrahim *et al.*, 1997; Tabari *et al.*, 2000). Where artificial light has been used, it has often not been specified (Horowitz *et al.*, 1984; Pereira and Moreira, 1999), but illumination source and strength can influence the visibility of dental opacities (Russell 1961-62). During periods of rain, the study was moved under shelter or indoors, with the children facing a window for maximum illumination. Such exceptions to direct natural sunlight, including when conditions were overcast, were recorded.

Each child was sat facing the examiner (RJC), perpendicular to the incident sunlight, and asked to smile. Teeth were examined wet and uncleaned. Where the tooth surface was obscured due to food or plaque build-up on the teeth, 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 (1961-62). The village where the child grew up was also recorded, as this was not necessarily the village or school in which they were seen.

Age is a proxy measurement of whether teeth were of mixed dentition (deciduous and permanent) or permanent only. Children 6-12 years are likely to have mixed dentition, and those 12-14 years are likely to have permanent, relatively pristine, dentition. Above 14 years, the dentition is permanent, but has had more time to be affected by other post-eruptive factors such as abrasion, trauma, and decay. When conducting the dental survey in the current study, children as young as five years presented due to parental encouragement or being in a school class with older children. However, children without permanent maxillary central incisors were not examined. The youngest child examined was reported to be six years old, which is around the expected age for these teeth to erupt.

The current study then, assessed mixed dentition, i.e. both deciduous and permanent teeth. This is important to note as deciduous teeth tend to exhibit a lower severity of fluorosis than permanent teeth (Dean 1934, 1936, 1942a; Fejerskov *et al.*, 1988). However, including children less than 12 years has been found to make little or no difference where the water is relatively high in fluoride i.e. over 2 ppm (Dean, 1942a; Fejerskov *et al.*, 1988; Ibrahim *et al.*, 1997).

Conversely, in a study of 8 to 16 year olds by Horowitz *et al.* (1984), younger children scored higher levels of fluorosis than the older age group. It was suggested that abrasion of the enamel surfaces in the older children caused the fluorotic enamel to be imperceptibly worn away (Thylstrup and Fejerskov, 1978; Horowitz *et al.*, 1984), particularly in the milder forms (Fejerskov *et al.*, 1988). Initial suggestions of remineralization 'correcting' fluorotic opacities (Thylstrup and Fejerskov, 1978; Horowitz *et al.*, 1984) have not since been scientifically validated (Fejerskov *et al.*, 1988).

As it had been decided to exclude the use of technical equipment, the incisors, canines, and first bicuspids on both right and left sides of the maxilla and mandible became the index teeth to examine in the current study, as these teeth are usually clearly visible when a person smiles (or grimaces). Partial dentition examination rather than full dentition examination has proved practical in other studies too e.g. Tabari *et al.* (2000); Stephen *et al.* (2002), Hamdan (2003), and MacKay and Thomson (2005). Although for this study labial surfaces were the target surfaces to observe, observations of the occlusal and lingual surfaces were also made when possible. The raw data (recorded observations) were then classified according to Dean's Index of Fluorosis, and all information was entered twice into Excel spreadsheets. Where the two most severely fluorotic teeth were not of the same category, the lesser category was assigned (WHO, 1997). A digital image was taken of each child's anterior dentition as a photographic record only. This was not used for classification purposes because milder degrees of dental fluorosis typically do not photograph well.

As food is not considered to be a major source of fluoride to the human body, a dietary questionnaire/food preparation survey was not conducted. However, some food samples were collected and analysed for fluoride. This is detailed further in Section 3.3 of this chapter.

Dental survey techniques are considered to be 'non-invasive' techniques. In medicine, this refers implicitly to the physical dimension of the human body. It does not encompass those impacts that may be imposed upon the mental, emotional, spiritual, or cultural dimensions of human well-being when an assessment or intervention is performed. This researcher is mindful that the present study may potentially have impacted upon these non-physical dimensions of human well-being.

3.1.7 Intra-examiner reliability

Along with the other indices, the aim of the Dean's Index is to objectively and quantitatively classify levels of fluorosis from qualitative descriptions. The nature of the expression of excessive fluoride on developing dentition is somewhat like a fingerprint – easily recognisable, yet each one is different. These combinations of striations or scattered, patchy areas with indistinct lines of demarcation can make classification difficult.

As there was only one examiner (RJC) there is no issue regarding inter-examiner reliability. Other studies have gauged intra-examiner reliability by re-examining approximately 5 % (e.g. Tabari *et al.* (2000); MacKay and Thomson (2005)) to 10% (e.g. Grobler *et al.* (2001); Levy *et al.* (2002)), and up to 15% (e.g. Horowitz *et al.* (1984); Cochran *et al.* (2004)) of subjects or photographic images. Thylstrup and Fejerskov (1978) and Hamdan (2003) did not specify the percentage of those re-examined.

In the current study, 5% (13 children) were examined twice, and the classification of these repeat examinations was used to gauge intra-examiner reliability. The examiner was unaware of the original assessment rating, and, due to the time interval between repeat examinations and the sheer numbers examined, the likelihood of rating recall was remote.

3.1.8 Sources of error

As with any research, particularly that which contains elements of interpretation and subjectivity, there are a number of sources of error. In this study, error could lead to under- or over-reporting of the prevalence and severity of fluorosis. Most sources of error have been alluded to already in this chapter, and include:

- Definition/interpretation of a positive identification of fluorosis. Dean considers small white flecks or spots to be the earliest sign of fluorosis whereas the other indices do not, as has been explained earlier in the chapter.

- Subjectivity: The indices are subjective by nature (Cochran *et al.*, 2004) and variations can arise in agreement between examiners (Dean, 1942a; Stephen *et al.*, 2002), despite the intended clarity of category definitions. Allocating a category by estimating the proportion of tooth surface area affected by opacities is on a scale of millimetres, with borderline cases being particularly difficult to categorise. This is complicated by the nature of opacities e.g. that they may be scattered patches with imperceptible borders (Table 3.5).

- Light source: Different types of light emit different wavelengths which mean the same tooth can exhibit different colours under different lighting conditions, a phenomenon known as metamerism (Watts and Addy, 2001).

Natural sunlight also varies depending on the time of day and how much atmosphere it must penetrate (Watts and Addy, 2001), which is therefore influenced by latitude and season. Other studies have also used natural sunlight, although two specified shaded sunlight (Ibrahim *et al.*, 1997; Rwenyonyi *et al.*, 2000). This examiner found the fine striations and pale opacities to become imperceptible in shade, so direct sunlight was always used where possible. Russell (1961-62) observed that the milder forms of fluorosis are often missed as they are essentially invisible in weak light, and 'burned out' in very strong light, and recommended the use of a colour-correct lamp. However, in this study the milder forms were observable in the lighting conditions encountered during the surveys.

- Dental preparation: Enamel opacities are more visible if teeth are dried (Fejerskov *et al.*, 1988; Cochran *et al.*, 2004) and in this study teeth were examined wet to keep examination interventions to a minimum. However, cleaning and drying of teeth is less important in areas of high endemicity (Fejerskov *et al.*, 1988).

- Partial dentition. In the current study only partial dentition was surveyed, omitting second molars which generally have a more severe degree of dental fluorosis.

- Bias may be associated with selection of the villages and schools visited in the survey.

- The 'most important objective' as perceived by the examiner, can lead to differences in operating conditions (Cochran *et al.*, 2004). For this examiner, the most important objective was to gather survey data from a large number of children within the limited time frame while having a minimal impact (psychosocially) on the children and communities. The Dean's Index was employed without the need to impose changes in operating conditions to accommodate this objective.

3.2 Water sampling

Eighteen villages in West Ambrym were visited from 9 to 23 January 2005, and drinking water supplies were sampled during this time. Approximately 40 ml samples of drinking water were taken from an estimated >90% of tanks in each village.

The local method of using a bucket, cup or teapot to draw water from the tanks was used to obtain a sample for analysis. Stream, pipe (shallow aquifer), and spring water samples were collected from source. Rainwater samples were collected in Petri dishes, or from that pooled in leaves, before being transferred to polypropylene specimen containers (LabServe LBS30130 and LBS3712Y). Coconut milk and green coconut water (GCW) samples were also collected. The specimen container was rinsed in surplus sample water before the analysis sample was collected.

A GPS location, description of the tank and system of collection was recorded for each sample. The pH was ascertained on location using a handheld Eutech Instruments pHScan WP2 Meter (accuracy +/- 0.1pH).

Samples were 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 x 5.5mm) with suppressed measurement. The total run length per sample was approximately 12 minutes with pump speed of 2.20mL/min, 100uL sample loop and a sodium bicarbonate/sodium carbonate eluent. The standard range for fluoride analysis was 0.1-5.0 mg/L. The error estimate for fluoride is 3%RSD, with values of +/- 0.05-0.1ppm.

3.3 Food sampling

Samples of locally grown produce were collected and stored in press-lock plastic bags. Samples from January 2005 were stored fresh after attempts to dry naturally were essentially unsuccessful. Samples from April/May 2005 were oven-dried slowly on a low heat on returning to Port Vila before being transported back to New Zealand. Further convective oven-drying was carried out at 65° C for three days on returning to New Zealand.

Food samples were crushed using mortar and pestle and stored in press-lock plastic bags. Analysis was carried out by Glenys Wallace in January 2006 at Massey University using a sodium hydroxide fusion method for total fluoride, modified from Frankenberger *et al.* (1996), and McQuaker and Gurney (1977).

CHAPTER 4: RESULTS

Three sets of data were collected. The principal set of data is the dental survey of West Ambrym children. The other two sets of data are the analyses of dietary sources of fluoride: principally, drinking water samples from West Ambrym, and secondly, a variety of locally-grown produce.

4.1 Dental survey

In order to ascertain the influence of volcanogenic fluoride on the health of the residents of West Ambrym, a dental survey was conducted using Dean's Index of dental fluorosis and the methods outlined in Section 3.6. A total of 253 school-aged children from 37 West Ambrym communities were surveyed. The sample comprised 137 girls and 116 boys. Five percent of children were surveyed twice to gauge intra-examiner reliability, and agreement of scores occurred nine times out of 13 (69%). However, conditions varied between each examination which was separated by a period of three months. There were four children who were allocated a different category of fluorosis on the two separate survey occasions; for each of these children, the category allocated on the second visit was the next more severe category than what had been allocated on the first visit. Looking at the conditions when these children were surveyed, for each child, poorer light conditions were recorded on the first visit, and bright sunshine on the second. This change in lighting is a reasonable explanation as to why some opacities were imperceptible on the first visit, but were visible on the second visit. 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.

4.1.1 Prevalence

Before prevalence could be calculated, the status of Dean's 'questionable' category had to be decided. As explained in Methodology (Section 3.3), recourse is made to the group results to determine this (Dean, 1934). Given the preponderance of evidence for dental fluorosis that was found in the sample population, it is inferred here that fluoride *was* the aetiological agent in the 'questionable' cases, and therefore these cases contribute positively to the prevalence statistic in the current study. Research since Dean's time has validated that 'questionable' cases are due to fluoride ingestion (Fejerskov *et al.*, 1988). Further, the 'questionable' category comprises only a small component (4%) of the population and if any other factor were responsible for the appearance of the teeth, this would not materially affect the overall conclusion from the data. The collated data revealed that the prevalence of dental fluorosis in West Ambrym was 96%, and only 4% showed no evidence of the disease. Distribution of the severity of dental fluorosis in the West Ambrym sample population is presented in Figure 4.1.

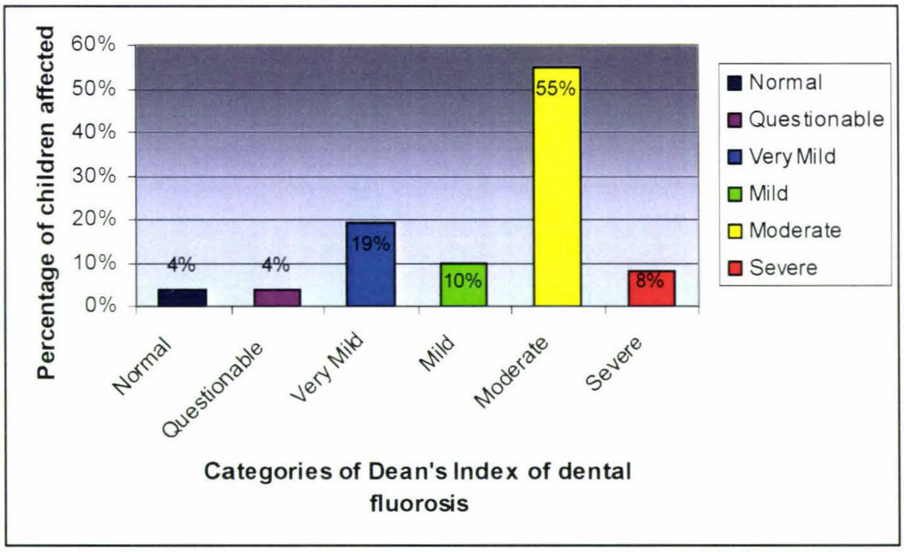


Figure 4.1: Results of the dental survey of West Ambrym children classified according to Dean's Index of dental fluorosis (n=253).

The distribution pattern of dental fluorosis in West Ambrym is bi-modal (Figure 4.1). The two modes are the 'very mild' and 'moderate' categories, with the latter being almost three times that of the former. 'Moderate' accounts for over half of the population surveyed, and was observed 13 times more frequently than those without any sign of the disease. The percentage of all children in the 'normal' and 'questionable' categories together is the same as those in the 'severe' category. Figures 4.2 and 4.3 are examples of moderate and severe dental fluorosis seen in children who participated in the West Ambrym survey. Examples of the less severe categories of dental fluorosis are not included here because these do not show up well without the use specialised photography. See Figure 2.3 for examples of the 'very mild' to 'severe' categories from the Fluoride Action Network.

a) Ten year old girl.

b) Nine year old boy.

c) Thirteen year old girl.

Figure 4.2: Photographs from the current study; examples of moderate fluorosis from West Ambrym showing the variation that can be seen in a single category. White mottling of the entire enamel surface is seen in figure a, while figure b and c exhibit some brown staining. Tooth form is unaffected in these cases.

a) Eleven year old boy.

b) Eleven year old boy. Pitting of the central upper incisors, with evidence of attrition on the cusps of the upper canines.

c) Ten year old girl.

Figure 4.3: Photographs from the current study; examples of severe fluorosis from West Ambrym. The entire tooth surface is affected. The tooth has lost its translucent lustre and appears a thick chalky white colour; and 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.

4.1.2 Age

The ages of the children surveyed ranged from six to 18 years with an average age of 10.8 years. Dean (1942a) specified that for a standardised and accurate measurement of dental fluorosis in a population, surveys should consist of children between 12 and 14 years of age (inclusive). Children from a wider age range were examined in this study because of the difficulty in obtaining a sufficient sample size within the specified age range. In order to determine if the sample age selection was critical, the results from the 12-14 year old group were compared with children outside that age range (Table 4.1).

Table 4.1: Number and percentage of West Ambrym children in each category of Dean's Index of fluorosis

Age group (years)	Normal		Question-able		Very mild		Mild		Moderate		Severe		Total	
12-14	6	7%	3	4%	19	23%	6	7%	45	56%	2	2%	81	32%
<12, >14*	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%

*** of this age group: 163 were aged 6 to 11 years; 9 were aged 15 to 18 years.**

The greatest difference between the groups is in the 'severe' category where 8% more cases were seen in the "<12, >14" year old children. Overall, a chi squared test (χ^2 = 9.03, P = 0.108, df = 5) revealed there is no statistically significant difference in the severity of fluorosis between the two age groups and combining data from children of all age groups did not invalidate the outcome of the survey.

4.1.3 Gender

Similar numbers of girls (137) and boys (116) took part in the dental survey, and each gender contributed a similar proportion to each category of fluorosis. The distribution of dental fluorosis within each gender is presented in Figure 4.4.

A bi-modal distribution of dental fluorosis is evident in both genders and is similar to the results for the overall population shown in Figure 4.1. Clearly, the percentage of boys and girls in each category are not significantly different.

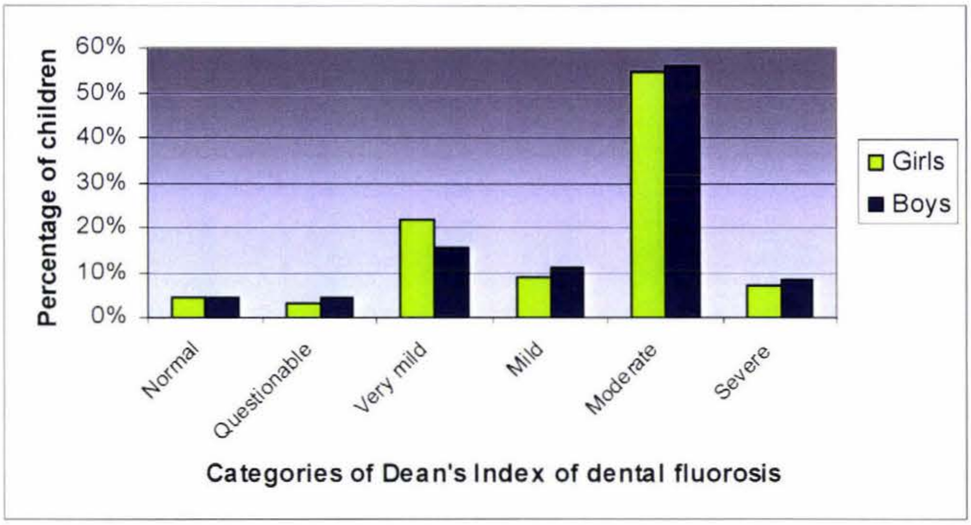


Figure 4.4: Distribution of dental fluorosis in the sample population of girls (n=137) and boys (n=116) of West Ambrym.

4.1.4 Geographical distribution in West Ambrym

The 253 children surveyed came from 37 villages in West Ambrym. The number of children surveyed from each village ranged from one to 21.

Dean developed the weighted Community Index of Fluorosis (Fci) to determine whether the effects of fluoride on dentition were at such a level as to be deemed a public health issue (discussed in Chapter 3). It can also be used, as it is here, to compare degrees of severity of dental fluorosis (as opposed to prevalence only) between different communities.

The Fci is determined as follows: the number of children recorded in each category (based on the severest category for two teeth) is the frequency (f) for that category. The sum of these frequencies is therefore the sample number (n). For each of the six categories, the frequency (f) is then multiplied by an allocated weight (w). These weights are listed in Table 4.2. The frequency-by-weight (f.w) calculations are summed and divided by the sample number (n) to give the Fci. Table 4.2 is an example of the Fci calculation, and Table 4.3 lists the Fci for each village in West Ambrym that had children participate in the survey.

Table 4.2: Calculation of the Community Index of Fluorosis (Fci) for Port Vato, based on the dental survey of 12 children from this village.

Dean's Index Category	Weight (w)	Frequency (f)	Frequency x 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

The number of children surveyed, the sample size (n), is the sum of the frequency column.

Fci $= \Sigma (f.w)/n$

$= 17/12$

$= 1.4$

An Fci of zero indicates an absence of dental fluorosis. An Fci of 0.4 was deemed of no concern, but above 0.6 indicated dental fluorosis at a 'public health problem' level (Dean, 1942a). A village with six children surveyed, with one in each category would have an Fci of 1.75. The Fci was calculated for villages that had at least five children surveyed; villages with smaller sample sizes are excluded here due to the likely effect of outlier values. The lowest Fci values in West Ambrym 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) (Table 4.3). The modal Fci is high at 2.4.

The Fci of villages with sample sizes of five or more were plotted on a map of West Ambrym (Figure 4.5).

Table 4.3: The Fci* of West Ambrym villages.

Village	Sample size (n)	F_{ci}
Baiap Presbyterian	12	2.1
Baiap SDA	17	2.4
Bakmir	13	2.8
Elae	9	3.2
Enmila	5	1.9
Fali	11	2.0
Lalinda Presbyterian	17	1.6
Lalinda SDA	21	1.9
Lolira	5	1.8
Meltungan	10	1.8
Pelipetakever	11	2.2
Pemap	7	3.0
Polimango	5	2.6
Port Vato	12	1.4
Sanesup	15	2.9
Sisevi	9	2.6
Vetap	9	3.3
Wuro	21	2.6
Yaou	5	3.6
Total (n)	214	

*** Most of the children from villages with smaller sample sizes (< 10) were seen during the school-based surveys, and this may account for the very small sample sizes in particular. However, some villages may comprise only a few households, so the small number of actual children surveyed may be a significant proportion of the total possible sample population for that village.**

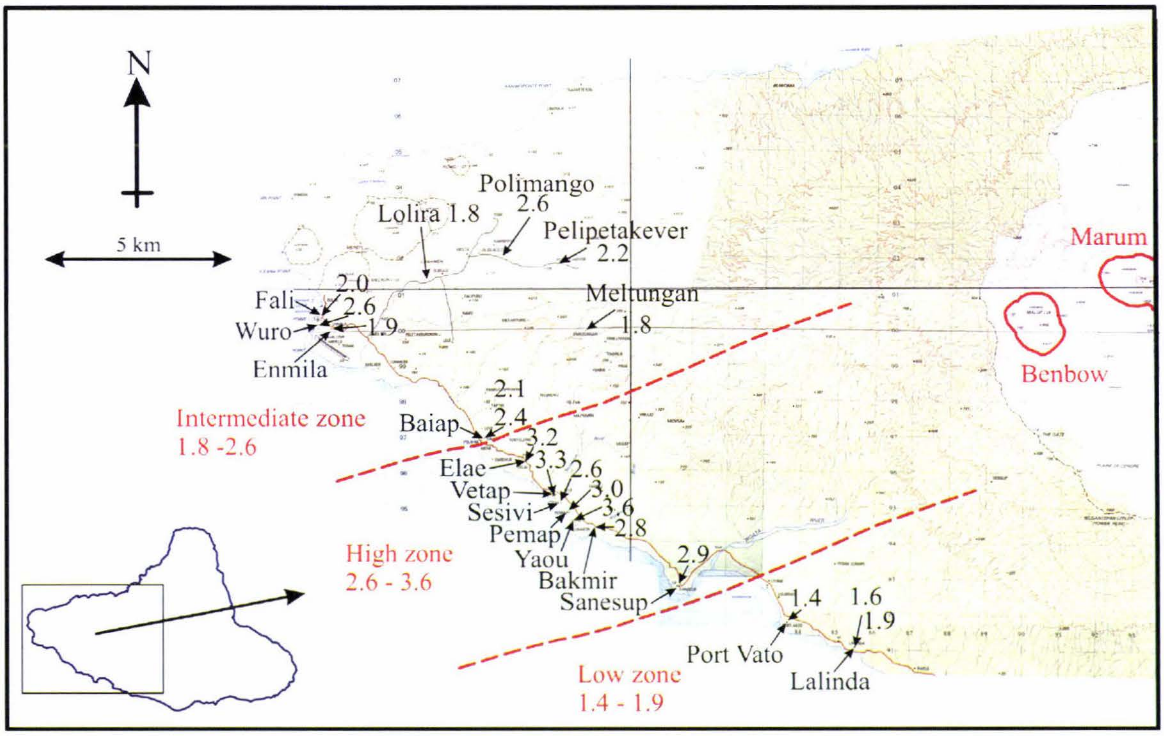


Figure 4.5: Location of communities in West Ambrym with calculated Fci values. Villages with small sample sizes (<5) are excluded as Fci is less likely to be a useful indication of community severity of dental fluorosis. The villages of Baiap and Lalinda have two values, one each for the Presbyterian and SDA (Seventh Day Adventist) communities.

No simple or direct pattern is seen in the spread of the Fci values in Figure 4.5. Dividing the area into zones is a means of classification that may reflect the most meaningful distribution of the Fci values. The high Fci zone centres on the pocket of villages N-SW of the vents with Fci values over 3.0: Elae, Vetap, Pemap, and Yaou. Bracketing these villages together with the villages of Sesivi, Bakmir, and Sanesup gives an Fci range for this zone of 2.6 to 3.6. The intermediate zone lies north of this, encompassing the villages of Fali, Wuro, Enmila, Lolira, Polimango, Pelipetakever, and Meltungan, and has an Fci range of 1.8 to 2.6. The low Fci zone sits south of the high Fci zone, and includes the villages of Port Vato, Lalinda SDA, and Lalinda Presbyterian. The low zone has an Fci range of 1.4 to 1.9. Note that 'low' here refers to this zone's relative values. These are still well above Dean's 0.4 threshold of acceptability.

4.1.5 West Ambrym and other locations in Vanuatu

To compare the level of dental fluorosis in the target population of West Ambrym with other areas in Vanuatu, additional dental surveys were undertaken at five other locations. No detailed analysis of this data is presented here; overall prevalence only is discussed in order to place the West Ambrym data into a regional perspective. These locations were: the two other regions of Ambrym, North and Southeast, (sample sizes of 172 and 177, respectively); Malakula (sample size of 98); and Tongoa (sample size 86). Only a small survey was undertaken at Tanna with 26 participants. The 'incidental islands' group is a collection of 23 children who were surveyed on the aforementioned islands, but were not local to those islands, having grown up on the islands of Santo, Pentecost, Emae, Efate, Nguna, and Futuna. Overall results of the dental surveys are presented in Figure 4.6.

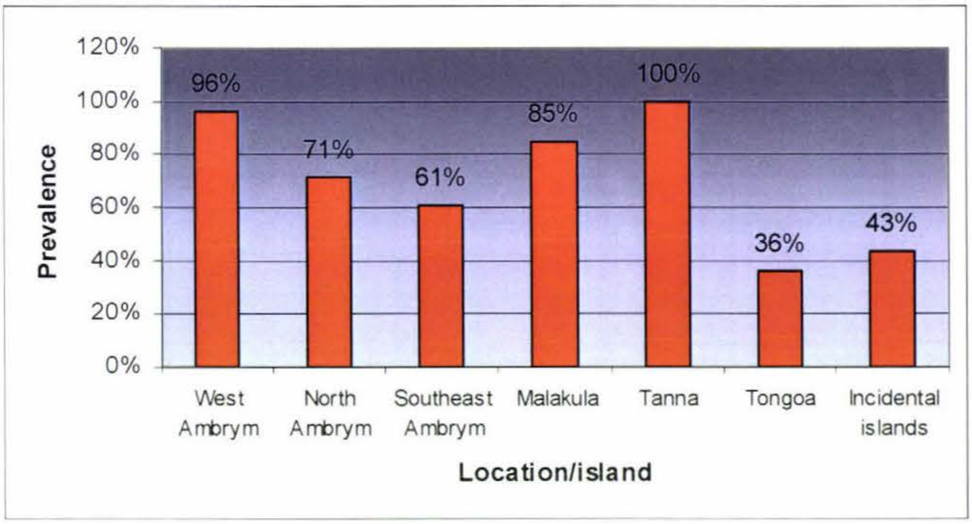


Figure 4.6: Prevalence of dental fluorosis for West, North, and Southeast Ambrym, and other islands in Vanuatu.

The highest prevalence of dental fluorosis is exhibited in Tanna but this result is tempered by the small sample size. For the regions in the vicinity of the degassing vents of Marum and Benbow, West Ambrym had the highest prevalence of dental fluorosis (96%). The regions of North and Southeast Ambrym also recorded high prevalence figures (71% and 61%, respectively). This gives a total prevalence for Ambrym of 77%. The study on the island of Malakula showed a prevalence of 85%, higher than for North and Southeast

Ambrym, but lower than West Ambrym and Tanna. In contrast, a prevalence of 36% was recorded for Tongoa, and 43% from the incidental data gathered from the other island locations.

A prevalence statistic, however, gives no indication of the degree of severity of a disease, it merely records its presence or absence. The graphs in Figure 4.7 illustrate the component categories of the prevalence statistic for each location surveyed. For visual simplicity, two graphs are illustrated here instead of one. The text however refers to both graphs as collated overall results.

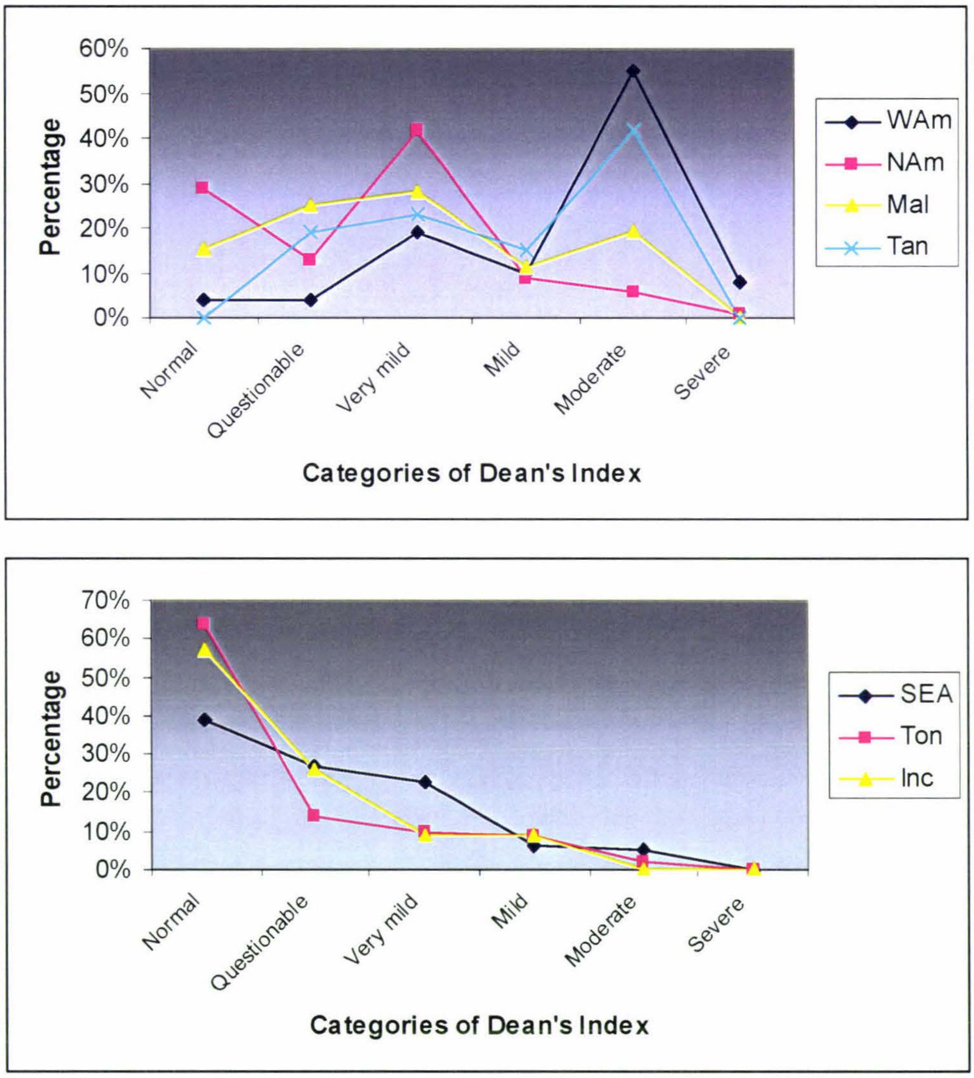


Figure 4.7a, b: Distribution of Dean's Index categories of dental fluorosis for a) locations with a bi-modal distribution: West Ambrym (WAm), North Ambrym (NAm), Malakula (Mal), and Tanna (Tan); and b) locations with a declining distribution: Southeast Ambrym (SEA), Tongoa (Ton), and the "incidental islands" (Inc) group.

Along with West Ambrym, bi-modal distributions are seen in North Ambrym, Malakula, and Tanna (Figure 4.7a), although the North Ambrym peaks occurred in the 'normal' and 'very mild' categories. These four locations also had the highest prevalence (Figure 4.6). Of particular note was the high proportion of 'moderate' fluorosis in West Ambrym and on Tanna. Malakula ranked third in this category, but had less than 20% recorded cases. Over 50% of children surveyed were classified as 'moderate' in West Ambrym, whilst 'mild' and 'moderate' accounted for more than half of the children on Tanna. In contrast, the bulk of Malakula's dental fluorosis was comprised of the milder categories, namely 'questionable' and 'very mild'.

The three sample populations with the lowest prevalence statistics all had a unimodal distribution, with 'normal' being recorded most often for children from Tongoa, the incidental islands group, and Southeast Ambrym (Figure 4.7b). 'Moderate' dental fluorosis was recorded in 5% of children from Southeast Ambrym, in 2% from Tongoa, whilst there were no cases in the incidental islands group. No 'severe' cases were recorded in any of these three sample groups.

Over all results, there were a total of 20 'severe' cases recorded. Nineteen of these children were from West Ambrym, whilst one child came from a village from North Ambrym. An interesting observation was the low variability in percentages in the 'mild' category; amongst all locations, the incidence was between 6 and 15%.

4.2 Water analyses

The great majority of Ambrym inhabitants are dependent upon rainwater for drinking and cooking purposes (Bakeo, 2000) and this is usually harvested from the roofs of their houses. Drinking water samples, as well as fresh rainwater and stream samples, were collected from West Ambrym only. The samples were analysed for F, Br, Cl, I, and pH. The results for F and pH only are presented here as these were most relevant to the study objectives.

4.2.1 Fluoride and pH of drinking water

In West Ambrym 158 drinking water samples were collected from 18 villages for fluoride analysis. Two sources of drinking water were identified, rainwater and groundwater. Most households rely on rainwater, which is stored in a large tank alongside each dwelling. In addition, three villages (Lalinda Presbyterian, Lalinda SDA, and Port Vato) have piped communal water supplies which access shallow aquifers. Springs located outside two villages (Lalinda Presbyterian and Port Vato) are used infrequently as a drinking water source.

The fluoride concentration and pH measurements from all West Ambrym drinking water sources have been collectively grouped in Figures 4.8a and b, respectively. The graphs reveal a relatively normal distribution for fluoride which is slightly skewed towards higher concentrations, whilst the distribution of pH skews towards lower values of pH.

F concentration ranged from 0.7 to 9.5 ppm. Both the highest and lowest concentrations are from rainwater tank samples. The mode is in the 3.0-3.9 ppm F range, and the average concentration is 4.1 ppm F. The World Health Organisation (1971) recommends no more than 1.0 ppm F in drinking water in countries where the annual average maximum daily temperature is 22 – 26° C. Only two West Ambrym samples (1%) had 1.0 ppm or less of fluoride. These came from rainwater tanks in Fali (0.7 ppm F), and Wuro (1.0 ppm F), two villages distal to the degassing volcanic vents and at low elevation (< 20m a.s.l.).

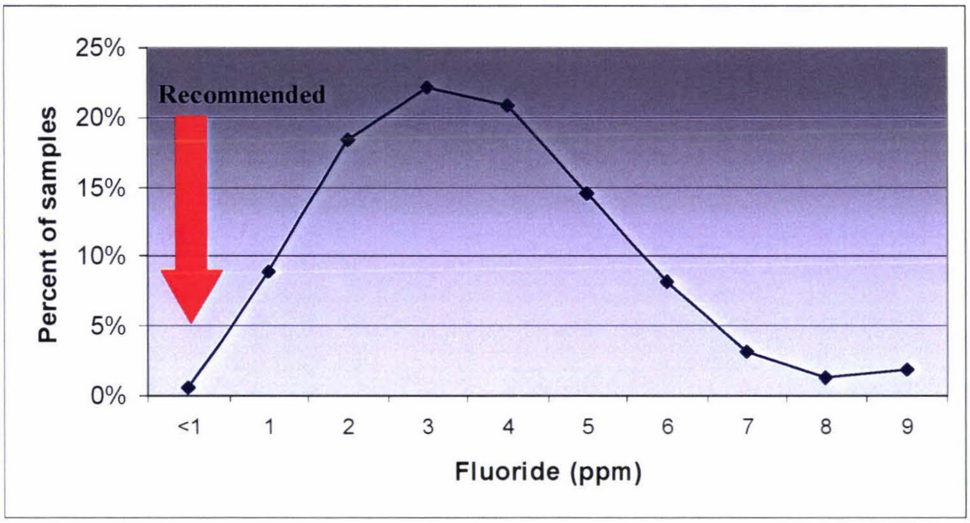


Figure 4.8a: Fluoride concentrations in all drinking water sources (rainwater and groundwater) in West Ambrym. Graph derived from data in Appendix 2 (n = 158).

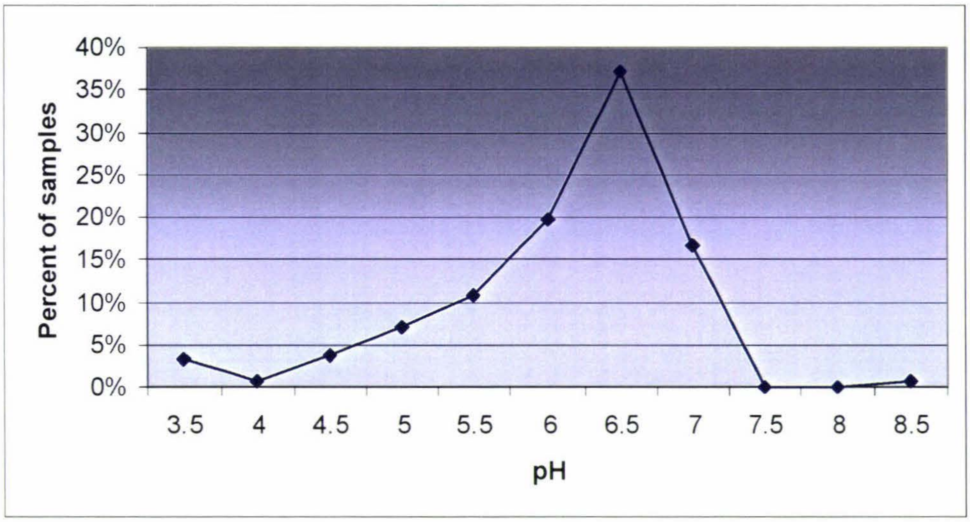


Figure 4.8b: pH measurements in all drinking water sources (rainwater and groundwater) in West Ambrym. Graph derived from data in Appendix 2 (n = 156).

The pH of rainwater stored in tanks ranged from 3.6 to 8.6, with an average of 6.3, and showed a trimodal distribution. The main mode is at pH 6.5. The second, more acidic mode is at pH 3.5. The samples with pH 3.5 and 4.0 are all measurements from water in fibreglass tanks. The third, outlier mode was a single analysis of 8.5 from a relatively new concrete tank, constructed in August 2004. The highest desirable pH in drinking water is 7.0 – 8.5 (WHO, 1971). The relationship between fluoride levels and tank materials are further explored in Section 4.2.4.

To determine if an association exists between these two variables, pH was plotted against fluoride concentration for all drinking water samples (Figure 4.9). Coastal rainwater and stream water samples have also been plotted. No correlation exists between pH and fluoride for rainwater and groundwater samples (r = 0.12), nor for groundwater samples only (r = 0.55). The freshly fallen coastal rainwater samples show an apparent correlation, but larger sample sizes would be required to confirm this.

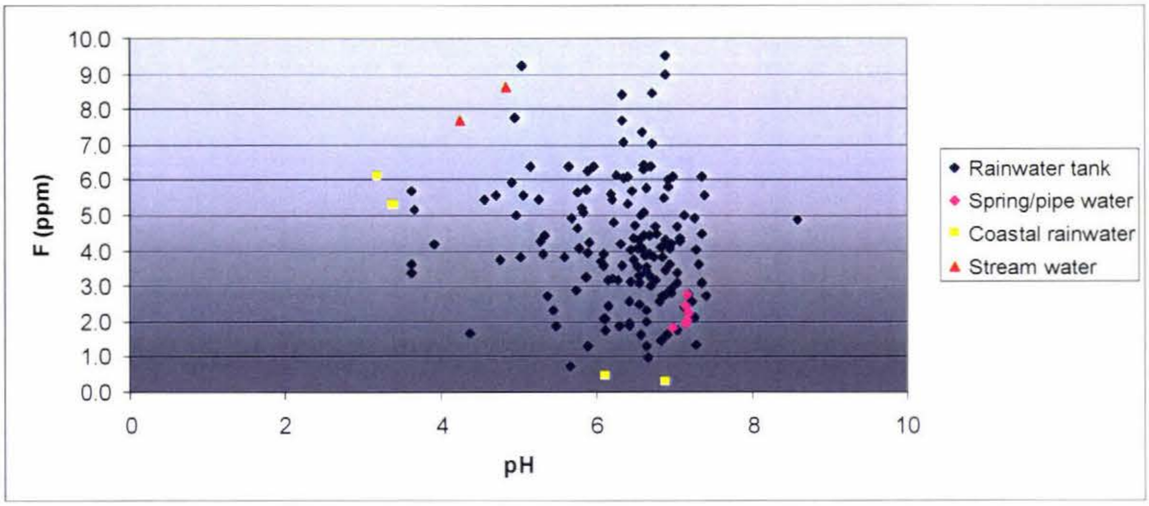


Figure 4.9: pH versus fluoride concentration of rainwater tank samples (n=150), spring/pipe water (n=6), coastal rainwater (n=4), and stream water on the caldera flanks (n=2). The clustered distribution suggests no correlation exists, and this was confirmed by statistical analysis (see text, above).

4.2.2 Geographical distribution of F in drinking water

(i) Village drinking water – all sources

The collated results of the drinking water analyses in Section 4.2.1 have been re-assembled in order to compare fluoride concentrations amongst villages. For each village the range and average fluoride concentration is presented in Figure 4.10.

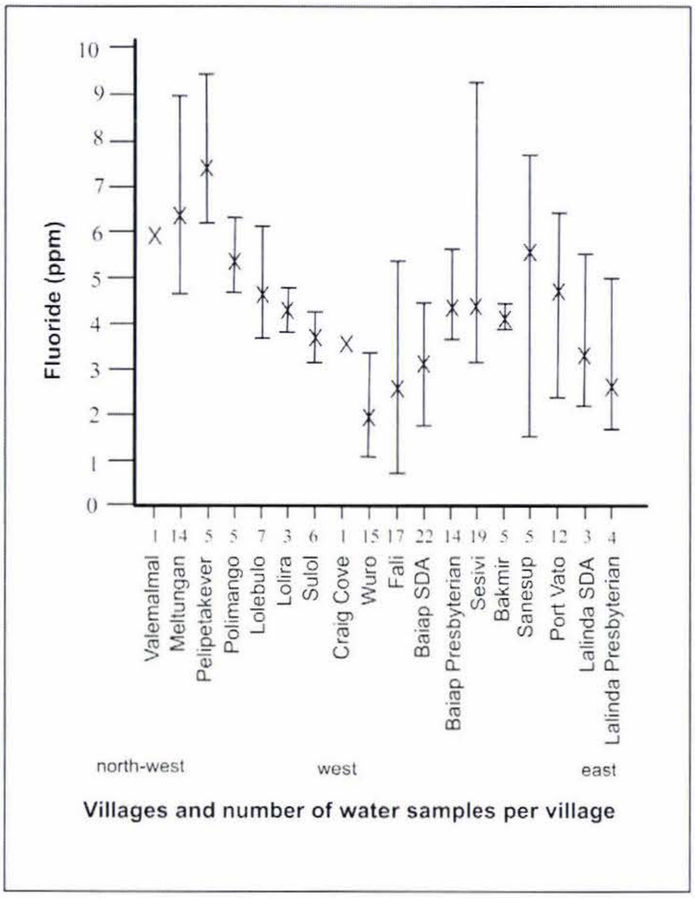


Figure 4.10: Upper, average, and lower fluoride concentrations of drinking water samples from West Ambrym villages. The number on the x-axis is the number of water samples taken in each village (n = 158).

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 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).

(ii) <u>Village drinking water - tank rainwater only</u>

The average fluoride concentration of rainwater tank samples only for each village is plotted on the map in Figure 4.11.

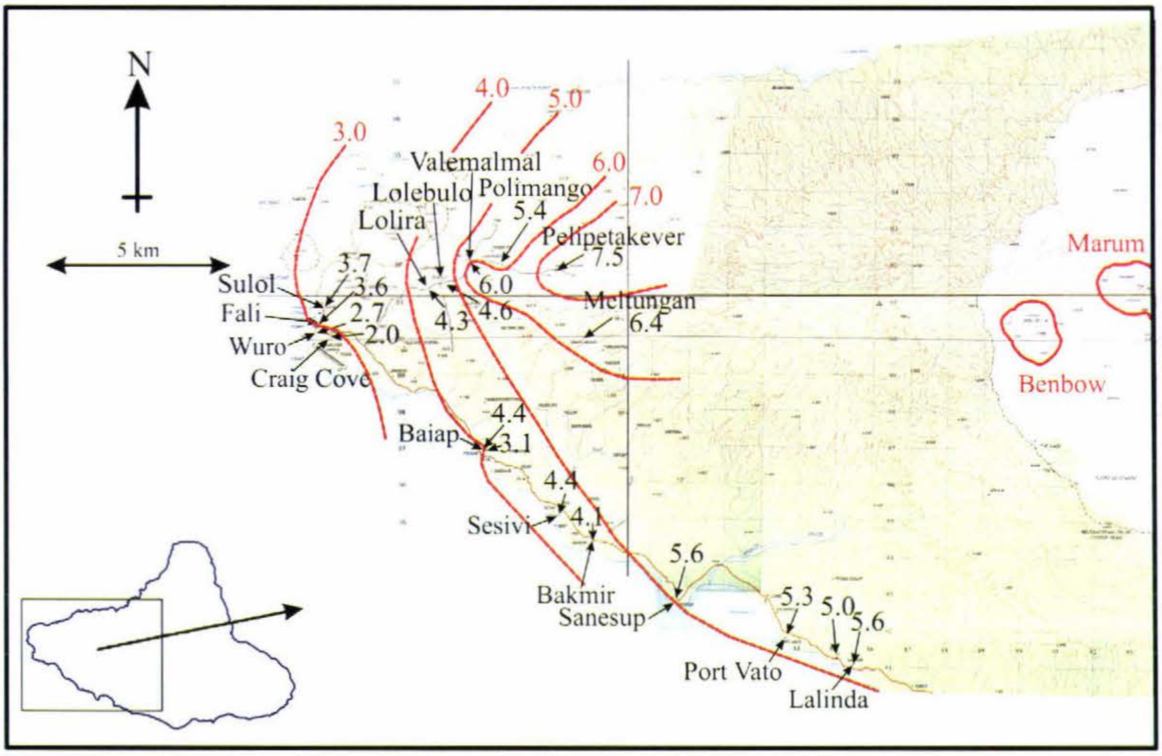


Figure 4.11: Location of sampled villages in West Ambrym with average fluoride concentrations for rainwater tank samples only (in ppm) for each village. Contour lines denote approximate concentration boundaries. Sample sizes for each village are as in Figure 4.10 except for the following villages where the groundwater analyses have been excluded: Port Vato (n= 10), Lalinda Presbyterian (n = 1), and Lalinda SDA (n = 1).

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. As distance away from the vents and distance away from the predominant wind direction increases, average fluoride concentration decreases.

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 a.s.l., 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 ($r = 0.90$; $p = 0.0002$). Interestingly, it also corresponds with an increase in distance away from the immediate area downwind of the prevailing wind direction.

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.

4.2.3 Fluoride and pH of drinking water by source

To investigate the effect of source on fluoride concentrations of drinking water, the data in Appendix 2 were categorised into groundwater and rainwater sources, as presented in Table 4.4.

Table 4.4: Fluoride concentration and pH measurements of rainwater stored in tanks and shallow aquifer sources in West Ambrym.

Water source	**Number of samples (n=158)**	**F concentration (ppm)**		**pH**	
		Range	**Average**	**Range**	**Average**
Spring/pipe water	6	1.8-2.8	2.2	7.0-7.2	7.1
Rainwater	152	0.7-9.5	4.2	3.6-8.6	6.3

Of the 158 drinking water sources sampled, 96% came from rainwater that was harvested and stored in tanks. The fluoride level in these samples ranged from 0.7 to 9.5 ppm, with a mean fluoride concentration of 4.2 ppm. Generally, piped water is not stored in tanks. One exception to this was a tank from Lalinda SDA (R05-116) that contained rainwater and pipe water. This sample had a *relatively* low tank water fluoride concentration of 2.1 ppm. This is the same as the piped supply sample (R05-115; 2.1 ppm F) at this location and suggests a large proportion of this water was from the piped source, particularly as the other rainwater tank water sample here (R05-114) registered 5.6 ppm F.

Only 4% of all drinking waters sampled were not derived directly from rainfall but came from local groundwater sources, either spring or piped (shallow aquifer) water. Fluoride concentrations in these groundwaters ranged from 1.8 to 2.8 ppm, with a mean concentration of 2.2 ppm. Although this is a very small sample size, the fluoride results are in a substantially narrower and lower concentration range than the rainwater tanks. Overall there is a marked difference of 2.0 ppm between the average fluoride concentrations from rainwater sources and groundwater sources.

Although overall, groundwater had a lower average fluoride concentration than the rainwater samples, there were 32 (21%) rainwater samples with a fluoride concentration less than the upper spring/pipe concentration of 2.8 ppm F, and 9 (6%) were less than the lower spring/pipe concentration of 1.8 ppm F.

According to the local residents, two other villages have previously had piped water supplies. Baiap SDA had a supply that dried up within the last six years, and the piped supply at Sanesup was damaged during Cyclone Ivy in February 2004.

4.2.4 Rainfall catchment surfaces and tank material

The data from Appendix 2 was collated according to the type of surface material used to intercept rainfall (usually the household roof) to ascertain if this had any bearing on fluoride levels in water supply. The results are presented in Table 4.5.

Table 4.5: Rainfall catchment surfaces recorded in the sampling of West Ambrym drinking water.

Catchment material	Sample size	%	Sample size	%	Avg F (ppm)	Avg pH
Corrugated iron	71 †(70)	50%			4.5	6.31
“ “ with rust	36 †(35)	26%			3.9	6.30
“ “ with paint	28	20%			3.5	6.28
“ “ with both rust and paint	6	4%			3.9	6.35
Corrugated iron sub-total	141 †(139)	100%	141	96%	4.1	6.32
Other			6	4%	4.1	6.77
TOTAL			147	100%		

† Sample size of pH data.

Of the 147 recorded surfaces, 96% had corrugated iron roofing, half of which were uncorroded and unpainted (‘unadulterated’). The other half were corrugated iron surfaces that had some degree of rust only (26%), some which were painted only (20%), and some which were both rusted and painted (4%). The highest average fluoride concentration of the tank water came from the ‘unadulterated’ corrugated iron (4.5 ppm), while the lowest average fluoride concentration was from water off the painted roofs (3.5 ppm).

Six (4%) samples were recorded as having ‘other’ catchment surfaces. Three were metal roofs (two “coloursteel” and one aluminium), and one was recorded as being made of concrete. A yellow tarpaulin was used to intercept rainfall for one tank, and bamboo for another. Although the sample size here is small, it is worth noting that the pH of water from these surfaces was more neutral than the pH of water from the corrugated iron surfaces. The differences in average fluoride concentrations between these groups are not significant.

Tank material is an important factor due to the long contact time of water during storage. Three types of storage material were identified. The main material for construction of water storage was concrete (92% of the survey samples). Newer materials being used for tank construction are fibreglass and plastic. These comprised only 5% of the survey sample. One storage tank was made of aluminium. Three samples were obtained where material was not identified. Again, the data from Appendix 2 was collated, and is presented here in Table 4.6 according to the type of tank material utilised.

Table 4.6: Fluoride concentration and pH measurements of drinking water stored in tanks of different composition.

Tank material	Number of samples n=152	F concentration (ppm)		pH	
		Range	Average	Range	Average
Concrete	140 (*138)	1.0 – 9.5	4.1	4.7-8.6	6.4
Fibreglass/plastic	8	0.7 – 5.7	3.6	3.6–7.3	4.5
Aluminium	1	5.4	5.4	4.6	4.6
Not recorded	3	5.2 – 9.2	6.8	5.0-6.9	5.9

*** 138 for pH data.**

Concrete tanks had the widest fluoride concentration range, from 1.0 to 9.5 ppm, and an average fluoride concentration of 4.1 ppm. A pH of 4.71 was the most acidic of the samples from concrete tanks, and a tank constructed in August 2004 had the most alkaline pH of 8.58.

For the fibreglass and plastic tanks, the fluoride concentration ranged from 0.7 to 5.7 ppm, with an average of 3.6 ppm. The pH ranged from 3.61 to 7.28, with an average of 4.5, somewhat more acidic than the samples from the concrete storage tanks. The six most acidic samples from all drinking water sources came from fibreglass tanks with pH between 3.61 and 4.37.

The one storage tank made of aluminium contained water with a fluoride concentration of 5.4 ppm, and a pH of 4.6.

No statistical analysis was carried out on materials because of small sample sizes.

4.2.5 Fluoride and pH of non-drinking water sources

To investigate this relationship further, water samples were collected from other locations closer to the volcanically active craters of Benbow and Marum, supplemented by rainwater samples at more distal village locations. The results are presented in Table 4.7.

Table 4.7: Fluoride concentrations and pH of non-drinking water samples collected from West Ambrym.

Water sources	Site	Sample series number	Fluoride (ppm)	pH
Rainwater	Ash Plain	R05-2	89	2.55
Rainwater (leaf)	Caldera flanks	R05-3	104	2.36
Rainwater (leaf)	Caldera flanks	R05-4	100	2.53
Rainwater (leaf)	Caldera flanks	R05-5	72	2.51
Stream	Caldera flanks	R05-1	8.6	4.84
Stream	Caldera flanks	R05-6	7.7	4.24
Rainwater	Fali	R05-34	0.3	6.89
Rainwater	Lalinda Presbyterian	R05-110	0.4	6.12
Rainwater	Lalinda Presbyterian	R05-112	5.3	3.38
Rainwater	Craig Cove	R05-62	6.1	3.19

The eight rainwater samples display a wide range of fluoride concentrations from 0.3 ppm to 104 ppm. Three of the four highest concentrations (72, 100 and 104 ppm) were in rainwater collected from fallen large concave leaves lying on the ground on the flanks of the caldera. The period over which the water collected here is unknown, but may have accumulated over a period of < 24 hours to several weeks. The 104 ppm sample contained ash particles which are likely to have had fluoride adhering to their surfaces. Dissolution of the fluoride from the ash surfaces would contribute to the water fluoride concentration. The fluoride concentration in one 'pure' rainwater sample collected on the caldera Ash Plain was 89 ppm. These samples were the most acidic with pH < 2.6. Contrasting this are the rainwater samples collected in villages 10 to 20 km distant from the vents of Marum and Benbow, where fluoride concentrations varied between 0.3 and 6.1 ppm. Two of these samples are also markedly acidic with pH < 3.4, and fluoride concentrations of 5.3 and 6.1 ppm; the rainwater samples with < 1 ppm F had a more neutral pH. Samples R05-110 and R05-112 are rainwater collected from the same location at different times, but with quite contrasting values for fluoride and pH.

Samples of proximal stream waters, at 615 and 650 m asl, had much lower fluoride concentrations at 8.6 and 7.7 ppm.

4.3 Food analyses

Although water is the main means by which humans ingest fluoride, food can provide an additional source. As an adjunct to the water-fluoride data, a number of foods commonly consumed in Vanuatu were sampled from various locations in Ambrym. The principal items analysed for fluoride were coconuts, sweet potato, bananas, manioc, and taro. Results of these analyses were provided by the Fertiliser and Lime Research Centre, Massey University, and are presented in Table 4.8.

Table 4.8: Fluoride concentrations of foods commonly consumed by Ni-vanuatu.

Sample-foods	**Village**	***Region**	**Field sample number**	**F (ppm)**
Banana	Sanesup	WA	R05-266	ND
" "	Ulei	SEA	R05-329	ND
Coconut flesh	Craig Cove co-op	WA	R05-60	64
" " "	Meltungan	WA	R05-61	70
" " "	Fanrereo	NA	R05-224A	67
" " "	Fanrereo	NA	R05-224B	20 - 50
Corn	Polimango	WA	R05-167	ND
Island cabbage	Ulei	SEA	R05-337	16
Kumara	Fanrereo	NA	R05-222	ND
" " , orange	Ulei	SEA	R05-339	15 - 34
" " , red	Polimango	WA	R05-171	16 - 37
" " , white	Polimango	WA	R05-172	30
" " , white	Ulei	SEA	R05-338	ND
Manioc	Fonteng	NA	AN58	ND
" "	Sanesup	WA	R05-269	68
" " (peeled)	Ulei	SEA	R05-336	31
Navelle nuts	Falebulo	NA	AN100	35
Taro	Ranon	NA	AN101	ND
Taro	Pelipetakever	WA	R05-164	35 - 46
Yam	Ranon	NA	AN102	75
Yam	Endu	SEA	R05A-303	118
Sample-fluids				
†GCW	Craig Cove co-op	WA	R05-58	4.0
GCW	Meltungan	WA	R05-59	5.5
GCW	Lalinda Presbyterian	WA	R05-111	10.0

***WA = West Ambrym; NA = North Ambrym; SEA = Southeast Ambrym. ND = not detected (< 6 ppm).**
† GCW = green coconut water.

The lowest fluoride concentration is found in taro, while the highest values are found in yams. The range of fluoride concentration in each food group was about 40 ppm. This is not too dissimilar to coconut flesh (50 ppm), but the range for sweet potato is much smaller (20 ppm). The peeled manioc had a lower fluoride content than the unpeeled sample, but it also came from the Southeast which is an area less exposed to volcanic emissions.

Tentative comparisons only can be made between food type and region due to the variability and numbers of samples collected. In West Ambrym, the food fluoride contents range from ND - 70 ppm, with an average of 37 ppm; for North Ambrym the range is ND – 75 ppm, with an average of 30 ppm. Southeast Ambrym has the widest fluoride concentration range from ND - 118 ppm, an average of 32 ppm. Where more than one food type was sampled from different regions, it was the sample from West Ambrym that had the highest fluoride content (coconut flesh, kumara, manioc, and taro). Comparing average concentration of root vegetables (kumara, manioc, taro, and yam) with the non-root foods (coconut flesh, cabbage, and navelle nut) reveals little difference in fluoride content, 35 and 48 ppm, respectively.

The green coconut water (GCW) samples had fluoride concentrations ranging from 4.0-10.0 ppm. The lower value here is similar to the average for all rainwater tank samples (4.1 ppm) while the upper is higher than all of the drinking water samples.

CHAPTER 5: DISCUSSION

Fluorosis, both dental and skeletal, is primarily a water-borne disease where fluoride-enriched water is used for drinking and cooking. Fluorosis can also be due to other causes such as indoor coal burning, and it can be caused or augmented by dietary practices such as tea drinking. Most of the known dental and skeletal fluorosis occurs in environments where drinking water is obtained from groundwater which has leached fluoride from minerals in the underlying geological strata. This however, is not the situation in West Ambrym. Here, the Ni-vanuatu reside under the combined volcanic plume of Marum and Benbow for many months of the year, and harvest rainwater for their potable water needs. Generally, rainwater is a pure form of water, and harvesting it is considered an ideal method for providing or supplementing potable water supplies (McGill, 1995; SOPAC, 2004a). However, where harvesting occurs in proximity to a degassing volcano, fluoride, along with other plume elements, may become incorporated into the rainwater. The current study has investigated the relationship between dental fluorosis and airborne volcanogenic fluoride in drinking water in West Ambrym.

5.1 Dental

5.1.1 Prevalence and severity

The target population for this reconnaissance study was the West Ambrym Ni-vanuatu, because this region has the largest and most accessible population to be frequently affected by the volcanic plume. In this study I determined the Dean's Index for 253 children who ranged from six to 18 years. The prevalence of dental fluorosis in West Ambrym was found to be 96%, which included 4% in the 'questionable' category. This figure may seem unusually high, but Dean (1936) remarked that the prevalence of dental fluorosis in endemic areas could reach 100%; and found this level of endemicity in communities with fluoride concentrations in drinking water from 5.7 to 14.1 ppm (Dean, 1942a). Figures similar to the prevalence in West Ambrym were found in a South African community (95%) with water levels of 3.0 ppm F (Grobler *et al.*, 2001), and in four American communities (94-97%) with water fluoride levels from 1.3 to 2.3 ppm F (Dean, 1942a).

In this study, no differences in the distribution of dental fluorosis severity were found with regard to age (group) or gender. This supports previous research that neither gender is more susceptible to dental fluorosis than the other e.g. Dean (1936), Thylstrup and Fejerskov (1978), and Hamdan (2003). That the survey results were unaffected by the inclusion of a wider range of children than those aged 12-14 year only suggests that the water fluoride concentrations in West Ambrym are high (Dean, 1942a; Fejerskov *et al.*, 1988).

For a study such as this, looking at disease in a population, one might expect distribution of severity to conform to a unimodal, bell-shaped curve. The results from West Ambrym revealed a bi-modal distribution with peaks in the 'very mild' and 'moderate' categories. However, bimodal distribution patterns are apparently unremarkable in the literature, and have occurred in other population studies (Dean, 1942a; Grimaldo *et al.*, 1995; Grobler *et al.*, 2001). The Dean's Index was also the *modus operandi* used by these investigators. The bi-modal nature of the distribution of severity may be an indication of the other variables or confounders present that contribute to the existence of dental fluorosis, such as individual metabolic differences and diet. It may also be a function of the difficulty in the assessment of tooth opacities, with many cases being borderline between two categories, especially between the categories of 'mild' and 'moderate' for example (see also 3.1.8 Sources of error).

The severity of dental fluorosis in West Ambrym can be looked at in two ways; the categories that comprise the prevalence statistic, and the Community Index of Fluorosis (Fci). Despite its bi-modal nature, the distribution of dental fluorosis is negatively skewed, with over half of the surveyed population in the highest categories of 'moderate' and 'severe'. Studies of populations with low drinking water fluoride concentrations produce positively-skewed distributions of fluorosis; any fluorosis present is in the milder forms. High drinking water fluoride concentrations, as seen in this current study, produce negatively-skewed distributions with more severe forms of fluorosis (as in Grimaldo *et al.*, 1995; Ibrahim *et al.*, 1995; Grobler *et* al., 2001; Griffin *et al.*, 2002). Calculations revealed that 36 out of the 37 West Ambrym communities in the survey had Fci values over the 0.6 threshold that Dean termed a 'public health concern'. These two measures, the category distribution and the Fci, both strongly suggest that dental fluorosis is at the severe end of the scale. What implications this may have for the people of Ambrym is discussed in Section 5.5.

It should be noted that while no skeletal deformities were seen, a few adults, upon learning that bones could be affected, complained of stiff or sore knees or joints. Further investigation would be required to ascertain if it was fluorosis related pain.

5.1.2 Geographical distribution

The Fci for surveyed West Ambrym villages (with sample size > 4) all exceed the threshold value that Dean termed a 'public health concern'. For this study the Fci values for each of these villages was plotted on a map of West Ambrym, but no strong trend in geographic distribution was evident. This is probably because West Ambrym is a relatively small, homogenous, geographic field area. However, three broad zones have been postulated which divides the area into high, intermediate, and low Fci zones radiating out from the caldera. These Fci zones *may* be a consequence of wind direction and plume fallout that was present at the time of tooth formation in the target population. Because the emergence of dental fluorosis is subject to many variables, these zones cannot necessarily be considered areas of future relative risk. Further detailed research would be required to validate or refute this zonal distribution.

While no strong pattern is evident in the distribution of dental fluorosis within West Ambrym, significant differences were seen when West Ambrym was compared to other surveyed areas that are in different geographic locations, yet still potentially affected by Ambrym's plume. These results clearly show a meteorological effect with the aberrant prevalence of dental fluorosis in the human populations downwind of active vents. West Ambrym is in close proximity, although not directly downwind of, degassing Marum and Benbow, and had a fluorosis prevalence of 96%, while the surveyed area on the adjacent island of Malakula (prevalence 85%) is directly southwest of the vents, but over 50 km away. North Ambrym (71%) and Southeast Ambrym (61%) are also in close proximity to the vents, but being upwind of the prevailing trade winds, they are less often exposed to the volcanic discharges.

Tongoa is nearly 100 km away from Ambrym and southeast of Ambrym, so the prevalence here of 36% was unexpected. However, serendipity provided the satellite image in Figure 5.1 which reveals non-prevailing winds carrying Ambrym's plume well beyond Tongoa. These findings, and given the prevalence levels in the "incidental islands" group, suggest that households harvesting rainwater on other islands in the archipelago within the plume's reach may also experience milder forms of dental fluorosis. Further investigation would need to confirm Ambrym's plume as the predominant fluoride source.

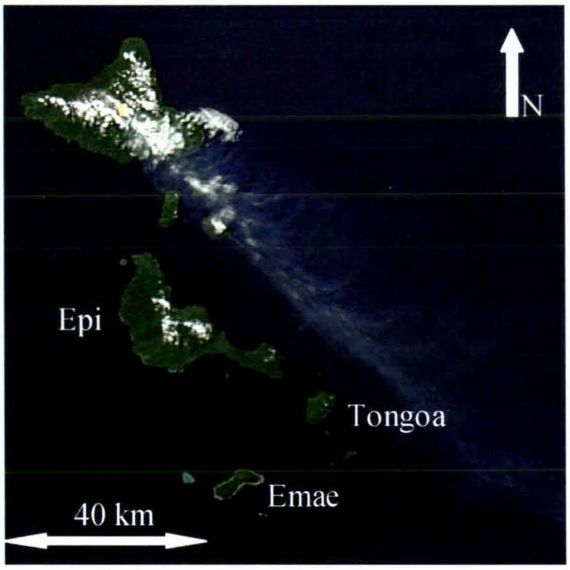


Figure 5.1: Satellite image shows Ambrym's plume over Southeast Ambrym, Paama, and Lopevi, and extending beyond the Shefa Province islands of Epi, Emae, and Tongoa. Harvesting rainwater on these islands may also lead to cases of dental fluorosis. (Source: NASA, 2004).

The high prevalence figure for Tanna (100%), and its distance from Ambrym, suggests a local source of fluoride. Although the survey on Tanna was small, the prevalence here was also somewhat of a surprise because Tanna's volcano, Yasur, has been found to be less fluoride-rich than the Ambrym volcanoes (Cronin and Sharp, 2002). However, the villages surveyed here were within 4 km of Yasur, whereas the closest villages to the vents on Ambrym were around 10 km away.

Looking at the distribution of the prevalence statistic amongst the classification categories for the different island locations, it was only in West Ambrym that more than half of the population were recorded as falling into the two most severe categories, although Tanna exhibited a similarly negatively skewed distribution. All the other locations, including Malakula and North Ambrym, are positively skewed, where most of the children who have dental fluorosis exhibit the milder, less conspicuous forms.

Twenty children suffered from 'severe' fluorosis. Nineteen of these came from West Ambrym, while only one came from the North. However, this child was seen during a survey in West Ambrym, and it is conceivable that he had initially lived in West Ambrym during the period of tooth formation, moved away, and at the time of the survey had returned to West Ambrym for schooling. No 'severe' cases were seen from the other island locations.

5.2 Water

Drinking water was targeted during the water sampling in West Ambrym because this is generally the main source of fluoride in the human diet. Most of the drinking water samples were harvested rainwater which was stored in household tanks, although a few were groundwater sources. For a broader understanding of the environmental situation, rain and surface water samples were also collected. As these samples were taken at a point in time rather than over a period of time, it must be remembered that they are merely a snapshot of the range of fluoride concentrations potentially available in drinking water supplies of West Ambrym.

5.2.1 Water fluoride concentrations

Of the 158 drinking water samples, all were high in fluoride and 99% were over the recommended 1 ppm F concentration for this tropical environment. The two exceptions came from rainwater tanks located distally to the degassing vents. Rainwater can collect fluoride from volcanic emissions, and anthropogenic sources, as well as from marine aerosols and continental dust or loess (Dissanayake and Chandrajith, 1999). When the average village fluoride concentrations were plotted on a map of West Ambrym, it was seen that the higher concentrations were found in those rainwater tanks that were closer, at greater elevation, and more directly west of the degassing vents. This geographical distribution of high-fluoride drinking waters in relation to prevailing plume direction is consistent with a volcanogenic source, and has been seen elsewhere (Bellomo *et al.* 2003). Further, there is no large-scale manufacturing industry on Ambrym or the surrounding islands producing atmospheric discharges that may otherwise be an alternative source of fluorides. Loess is unlikely to be a source of fluoride in these Southwest Pacific islands, and marine aerosols are likely to make a relatively minor contribution in West Ambrym, particularly when the prevailing wind direction is taken into account.

A range of fluoride concentrations were obtained and wide variation in stored rainwater was evident not only between villages (range 8.8 ppm), but perhaps somewhat surprisingly, within each village (up to 6.2 ppm). This spatial variation in fluoride concentration was also seen in the freshly collected rainwater samples (0.3 ppm F from Fali and 89 ppm F on the Ash Plain), along with a temporal effect (0.4 ppm F and 5.3 ppm F from Lalinda Presbyterian). This spatial and temporal variation was found also at Mt Etna and Stromboli, where freshly collected rainwater displayed an even wider range of fluoride concentrations from <0.1 to 495 ppm (Bellomo *et al.*, 2003). Fluoride in a volcanic plume is scavenged by rainfall, and its concentration and dispersion is influenced by factors such as rates of degassing and rainfall, wind direction and strength. Fluoride concentrations of rainwater stored in tanks will be subject to these natural variables, but also to anthropogenic factors such as water collection practices and storage methods.

The drinking water samples that came from groundwater, although still high in fluoride and exceeding the WHO 1.0 ppm guidelines, were lower than 79% of rainwater tank samples. The range of fluoride concentrations was also narrower (2.0 ppm cf. 8.8 ppm). Such groundwater samples are likely to have fairly constant fluoride concentrations and be subject to smaller seasonal variations (Grobler and Dreyer, 1988 in Grobler *et al.*, 2001). This suggests that groundwater as a potable water source may be preferable to the harvesting of roof rainwater when the volcanic plume is overhead and falling rain scavenges greater amounts of fluoride.

Samples of proximal stream waters, at 615 and 650 m asl, had much lower fluoride concentrations (8.6 and 7.7 ppm, respectively) than the rainfall collected on the ash plain or caldera flanks. A stream at Maranata, close to the coast and east of Lalinda in West Ambrym contained only 1.1 ppm F (Cronin and Sharp, 2002). This suggests the fluoride has become bound by volcanic soils into complexes which increases with distance (Zevenbergen *et* al., 1996; Loganathan *et al.*, 2005), and possibly is further diluted by lower, groundwater supplies. Conversely, in a contrasting environment, the arid regions of China, evaporation of stream water increases with distance and therefore leads to increasing fluoride enrichment further from source (Genxu and Guodong, 2001).

Most of the water samples were near-neutral pH although tending toward acidity. No correlation was found between fluoride concentration and pH, and therefore pH cannot be used as a proxy measure for fluoride concentration.

5.2.2 Catchment surfaces and tank materials

Data on catchment surfaces and tank materials were collected during the sampling because man-made materials utilised in the harvesting and storage of rainwater may influence water chemistry and quality. Although catchment and tank materials are not a main feature of this thesis, they are included as aspects that warrant further understanding and follow up. The small amount of data for tanks of different composition and the number of variables involved means no strong conclusions can be drawn here from these results, but tentative findings are as follows.

It appears that corroded/painted corrugated iron roofing may decrease the fluoride concentration in the resulting drinking water, but without affecting pH. A possible mechanism is that fluoride in rainwater may become bound to other elements that are not present or chemically available in newer iron roofing. It seems that corroded/painted corrugated iron roofing is beneficial in terms of fluoride-binding capacity, but the acid rain causing this corrosion may concurrently dissolve or leach potentially harmful elements such as heavy metals that could contaminate drinking water supplies, such as lead or zinc (Sutton and Elias, 1993; Calderon, 2000; SOPAC, 2004a). It has been noted that corrugated iron corrodes in a very short time (< 6 months) in environments of volcanic degassing (Delmelle *et al.*, 2002). Further research on the acid rain on metal catchment surfaces in volcanically active environments would be desirable.

One could expect that concrete tank material would provide a surface where fluoride would bind with calcium, thereby lowering the available fluoride in drinking water. Although this could not be confirmed in this study, it would be an advantage of concrete tanks over other materials. In a separate study, water in fibreglass tanks on Tanna and Ambrym were found to have a lower pH than concrete tanks, and it was proposed that this was due to the reaction of the acid rain with the cement carbonate (Cronin and Sharp, 2002). The pH results in this study support this hypothesis, as the pH of the concrete tanks was significantly higher than the fibreglass/aluminium tanks.

As well as tank composition, other variables which can affect fluoride concentration include:

- the age and condition of a tank (concrete surfaces may become fluoride-saturated over time),
- whether a tank is covered or uncovered (uncovered and unfiltered tanks are likely to receive more fluoride-coated tephra particles, which can later dissolve into the stored water),
- whether a tank is continually or intermittently connected to catchment surfaces (and whether this depends on the location of the volcanic plume and rainfall).

5.3 Food

Fluoride in food samples is reportedly very difficult to measure, and it is common to get a range of values for same-food samples (Davison, 1987; G. Wallace, pers. comm., 2006). Variation has been found due to the type of plant tissue analysed, its age, and geographic source (Ouwer, 1985).

The fluoride analyses of the food samples collected from Ambrym provide supplementary information about what is potentially available in the diet, although fluoride absorption decreases in the presence of food, and fluoride is less available when in solid form (Dean, 1936). While these items are high in fluoride, what is not known is the amount consumed, or perhaps more importantly, the bioavailability of the fluoride, which differs amongst food types (Cornelius *et al.*, 2000).

There was a wide range of fluoride concentrations in all the food samples analysed from < 6 ppm ("not detected") to over 100 ppm. This is not surprising as the samples came from different regions and from a variety of food types such as root crops, leafy vegetables, nuts, and fruit. Thus the environmental supply, plant uptake, and bioavailability of fluoride may differ markedly. Even within certain individual samples a range of fluoride concentrations were obtained. Out of the three regions of Ambrym, the highest concentration of fluoride in same-food samples came from West Ambrym, and this is probably a reflection of this region's greater exposure to volcanogenic fluoride. One sample of island cabbage from Southeast Ambrym had higher fluoride concentrations than island cabbage samples from an area exposed to Yasur's emissions on Tanna where fluoride content of island cabbage ranged from < 6 to 7 ppm F (Cronin and Sharp, 2002).

Research on food fluoride contents from other countries also shows them to exhibit a wide range of values. Differences in methods used in analysis may also contribute to the variability of results. Taro and coconut on Moorea in French Polynesia were found to contain 2 – 6 ppm F, whilst kumara and yam mainly < 1 ppm F (Baume and Meyer, 1966). Average fluoride contents in potato and cabbage in Tibet were 0.11 and 0.06 mg/kg, respectively. In a low water-fluoride area of Iran (<0.4 ppm), most of the 84 sampled foods including vegetables, bread, rice and fruit had less than 1 mg/kg F (Zohouri and Rugg-Gunn, 1999). Spinach, from the high groundwater-F countries of Tanzania and Burundi, was found to have 6.8 to 7.7 mg/kg fluoride, whilst sweet potato had only 1.0 mg/kg (Malde *et al.*, 1997).

It was beyond the scope of the current study to undertake a detailed dietary survey. However, UNICEF (2001) produced a report of 473 Ni-vanuatu school-attendees aged 12-17 years in the Malampa Province, of which Ambrym is included. Although these figures are not for Ambrym alone, they contain useful general information which would probably vary little from island to island. Fresh vegetables were found to be consumed by 70% of the youth at least once a day (UNICEF, 2001), and these are often boiled in coconut juice or water, or made into lap-lap which is a popular local vegetable dish (Speiser, 1923; personal observation). Cooking vegetables by these methods can increase fluoride levels because of the absorption of fluoride-rich cooking fluid (Zohouri and Rugg-Gunn, 2000). Taro was consumed by 39% of the population at least once a day, but yams are the primary root crop in Vanuatu (Speiser, 1923; UNICEF, 2001). On Ambrym bread is baked locally (personal observation). Mixing dry ingredients with local water would increase this product's fluoride concentration, a product which was consumed at least once a day by over half of the youth (UNICEF, 2001).

Perhaps more importantly is what drinks are consumed because fluoride is more easily absorbed from fluids. The UNICEF report showed that water, tea, and coconut juice were the most regularly consumed fluids (UNICEF, 2001). Interestingly, these fluids all have elevated fluoride levels. Coconut juice and water were found to be elevated locally in the current study, while tea, *Camellia sinensis,* is a known bioaccumulator of fluoride and releases fluoride on brewing. It has been documented as a fluoride-contributing factor in both dental and skeletal fluorosis (Hamdan, 2003; Whyte *et al.*, 2005).

That the coconut juice samples from the current study were considerably elevated in fluoride came as a surprise. The lowest concentration in coconut juice was 4.0 ppm F, higher than half of the drinking water samples; the highest concentration (10 ppm) was higher than all 158 drinking water samples. Further research may reveal that coconut may also be a bioaccumulator of fluoride. This is an important point because coconut has long been recognised as an important source of fluids in Vanuatu and at times may be relied on as the only source (Speiser, 1923). This may occur, for example, when there is a lack of fresh water due to cyclone damage. Remarkably, coconut juice has been used in the past in remote locations during times of conflict as an intravenous fluid replacement (Petroianu *et al.*, 2004). Should the need ever arise, the high fluoride content of Ambrym's coconut juice may render it unsuitable for this purpose.

In terms of dietary habits on a nationwide scale, two differences arise between the genders. Although water consumption was almost identical, boys were more regular coconut juice drinkers than girls (UNICEF, 2001). This may be a reflection of cultural and social customs where boys probably spend more time in the bush in physical activity and hunting, and relying on coconuts as a fluid source. Tekle-Haimanot *et al.* (1995) suggested manual labour as a contributing variable in fluorosis aetiology. Consumption of kava, a local intoxicating substance made from the root of the kava plant and reconstituted with water, was measured in the UNICEF survey in terms of "past ever use". 14% of the school children said they had tried it at least once (UNICEF, 2001). While it is not customarily drunk by youth, it is mostly restricted to men and would constitute part of the adult male population's fluoride intake.

5.4 Fci and water fluoride concentrations

A geographical distribution pattern was evident for fluoride concentration in drinking water. The highest concentrations were found in those villages closest and immediately west of the vents, reflecting wind-induced plume dispersal. In contrast, only broad zones could be proposed for the distribution of dental fluorosis based on the village Community Index of Fluorosis (Fci).

There were 16 villages that had both drinking water sampled, and children who participated in the dental survey. To ascertain if any dose-response type relationship existed, average village drinking water fluoride concentration and level of dental fluorosis (using Fci) were compared (Figure 5.2). No correlation was found between these variables (r = 0.03, p = 0.9).

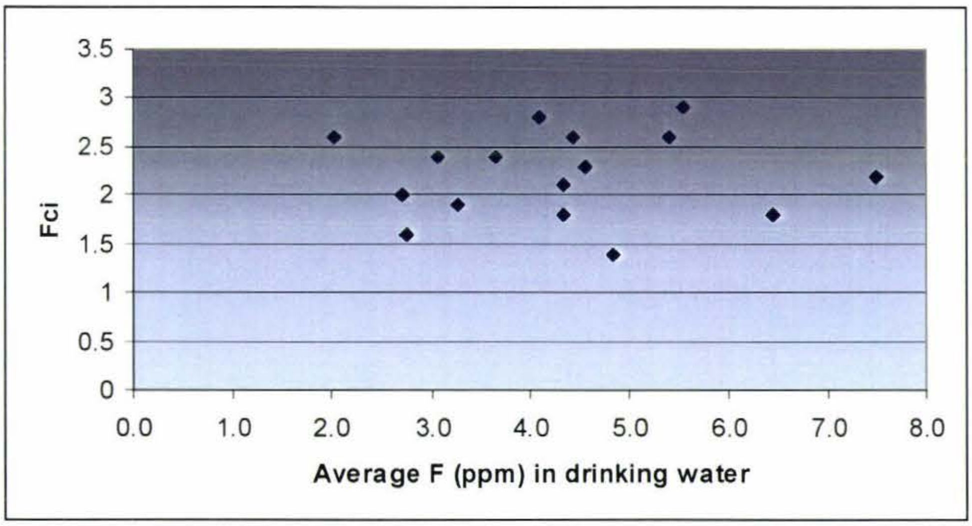


Figure 5.2: Community Index of Fluorosis (Fci) versus the average fluoride concentration in drinking water of 16 West Ambrym villages.

This result was not unexpected and a number of factors can account for this. Firstly, and most significantly, the water results from the current study are *recent* concentrations. Further, they are only a *snapshot* of concentrations which vary markedly from tank to tank, which would also vary 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). However, that the current study's fluorosis results 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 was at least over 2 ppm (Dean, 1942a).

A study by Dean (1942a) found a fluorosis prevalence of 88% where water had 2.9 ppm F; 98% with 4.4 ppm F, and 100% at over 5.7 ppm F. Although 4.2 ppm is only an *average* figure for the fluoride concentration in the current study, it resulted in a prevalence of 96%, which, peculiarly, is consistent with these results of Dean.

Individuals within an 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, 1942a; Krishnamachari, 1986). The measurement of confounders such as these was beyond the purpose and scope of this present 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 level of fluoride exposure is not feasible.

5.5 Societal impact

The impact of fluorotic teeth on a local population can be approached from two angles. The first is the biological changes that impact on physical health. In terms of long-term prognosis, little seems to be published other than general comment such as fluorotic teeth are weaker, fragile (at least surficially), and may be prone to premature loss (Black and McKay, 1916; McGill, 1995). Adults near Goma in the Democratic Republic of Congo (DRC) have been noted to have robust-*looking* fluorotic teeth (personal observation), but anecdotally it was reported that they tend to fall out. Although the general consensus is that fluorotic teeth have fewer caries (e.g. Ibrahim *et al.*, 1997; Stephen *et al.*, 2002), some research has found the opposite to be the case (e.g. Grobler *et al.*, 2001). Dental integrity is an essential component of general health, because poor oral health can result in compromised intake and nutritional deficiencies.

A South Pacific Commission health survey in 1964 commented that although no information was available on fluoride in drinking water, there were low figures for DMFT (decayed, missing, filled teeth) (Norman-Taylor and Rees, 1964). Reports from later dental health studies showed that low DMFT figures continued, and recommended the continuation of the existing fluoride mouth-rinsing programme, with it promotion being extended to other islands (Deong, 1991). Neither of these documents reported on dental fluorosis. In terms of general dental health, it is the issue of caries that is of greater concern.

The second angle is the psychosocial impact of fluorotic teeth, which was not investigated during the course of this study. Dean's term 'public health concern' was in relation to the aesthetics of fluorosis, and intimates at the unsightly nature of the disease. Without having seen fluorotic teeth, it is difficult to imagine their appearance, as well as the consequential poignant impression one is left with. As Black commented, "before I saw a case, dentists had endeavoured to describe the condition to me. The effort was a failure. I got no mental picture that was at all like what I saw when I visited ..." (Black and McKay, 1916). The photographs in the Results chapter were included partly for this reason. Clearly, the impact is greater in those who suffer from moderate dental fluorosis, which may be unsightly, and severe dental fluorosis which is always so.

Whilst undertaking the dental survey in North Ambrym, it was commented by a local clinic nurse, whose children had grown up in West Ambrym, that her children had 'West Ambrym teeth'. They were unaware of the cause. When asked about the discoloured teeth, one man I spoke to replied that the children did not like the discoloured teeth because they did not like to be different from others. A comment made to me by the headmistress of a school in Sake, DRC, was that the children did not mind having severely fluorosed teeth because they were like their peers, but it became an issue when they went outside their own village. They would become embarrassed and try to hide their teeth when talking and laughing. The issue of having teeth affected by fluorosis outside ones own community was noted in St David, Arizona, where "it was difficult...for girls to secure school teaching positions or other high types of work..." (Smith, 1942).

Social and self-esteem problems in children with dental fluorosis have been reported in Sri Lanka (Dissayanake, 1996), and Uganda (Robinson *et al.*, 2005). In Western Australia, the perception of mildly or moderately fluorosed teeth was that they indicated neglect, and it was agreed that having such teeth would cause embarrassment (Riordan, 1993). In India, the perception of suffering from skeletal fluorosis is that it is "a fate they are born with", and so do not seek help until problems are severe (Reddy, 1998). This belief may mean there are actually more cases than what is reported (McGill, 1995).

In Western societies, treatment for dental fluorosis has been developed using methods such as chemical bleaching and micro-abrasives (Akpata, 2001; Allen *et al.*, 2004; Bezerra *et al.*, 2005). However, this is not a new phenomenon, nor is it limited to the developed world. In some cultures, especially amongst girls, deliberate tooth abrasion or polishing occurs to remove the offending fluorotic staining (Fejerskov *et al.*, 1988). This may have occurred previously in Vanuatu. An anthropological study on skeletal remains found fluorotic-like staining on incisors, with a number of teeth exhibiting signs of polishing (Weets, 1996).

Only provincial figures are available in the UNICEF (2001) Vanuatu study on psychological wellbeing. Malampa youth reported the lowest figures for levels of unhappiness, severe sadness, and depression, but paradoxically, they reported the highest figures to have experienced bullying and deliberate injury. While it is not known if one island contributed more heavily than others to these figures, and that Malampa youth on the whole appear to be happier than those from other provinces, it is important to be aware that dental fluorosis, particularly in the more moderate to severe forms, can affect psychological wellbeing.

5.6 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, the establishment of an alternative low-fluoride water source.

- **Defluoridation**

There are four methods for the removal of excess fluoride from water: precipitation, adsorption, ion exchange, and reverse osmosis (Mariappan and Vasudevan, 2002). The first two are methods most often utilised for producing potable water supplies in rural and remote communities. Reverse osmosis appears to be an expensive technique for defluoridating industrial waste before its discharge to the environment (Ndiaye *et al.*, 2005), although it has been proposed as a treatment for high-fluoride groundwater (Arora *et al.*, 2004).

The most well known precipitation method is the Nalgonda technique (named after the village where it was pioneered in Andhra Pradesh, India) which flocculates fluoride ions using aluminium, lime, and bleach (Mariappan and Vasudevan, 2002; Pinon-Miramontes *et al.*, 2003).

Adsorption methods filter water through a column of adsorbent material. Suitability of locally-available materials have been found, experimentally at least, with ando (volcanic) soils in Kenya (Zevenbergen *et al.*, 1996), and clay water storage jars in India (Agarwal *et al.*, 2003). However, what works in one locality may not work in another. A study in South Africa revealed that some clays are more efficient defluoridators than others (Coetzee *et al.*, 2003). The possibility of utilising other materials such as hydrous ferric oxide (Dey *et al.*, 2004), brick, soil, fly ash (Chidambaram *et al.*, 2003), charcoal, bone, and coconut husks (Mariappan and Vasudevan, 2002) have also been explored.

Both these methods can be used at a community or household level. Major drawbacks are the maintenance requirements, and the careful disposal of the fluoride-rich waste to ensure no further contamination of water sources occurs (WHO, 2001; Mariappan and Vasudevan, 2002).

- **Alternative water sources**

Alternative water sources are the preferred method for long-term sustainability (WHO, 2001) and cost-effectiveness (Frencken and Smet, 1990, in Kloos and Tekle-Haimanot, 1999). Some communities where fluorosis was once endemic have been able to eliminate the disease by changing water supply (Dean, 1942b).

The groundwater samples analysed in this study, although lower in fluoride than many of the rainwater tank samples, were still high. Hydrogeochemical investigation would be required to establish if low-fluoride groundwater exists in West Ambrym. Theoretically, rainfall recharge reaching the water table may have lower fluoride levels due to the complexing of fluoride or adsorption by clays in the soil profile. However, if bedrock substrate is fluoride-rich, as it may well be, then residence time, leaching, and percolation would result in fluoride-rich aquifer water.

Suggestions and solutions for the West Ambrym situation may include:

- 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 coincident. Temporary tank disconnection advice from DGMWR in Port Vila has previously been broadcast over the radio during periods of increased degassing activity (C. Douglas, pers. comm., 2005).

- Ascertaining if a low-fluoride groundwater aquifer exists, which would involve hydrogeochemical investigation and ongoing monitoring.

- Consideration of employing locally suitable and acceptable defluoridation methods if water fluoride levels remain unfavourably high.

- Other possible considerations include prioritising low-fluoride water for drinking and cooking; and dilution of high-fluoride water with low-fluoride water.

Regardless of the method employed to provide low-fluoride potable water, either by defluoridation or establishment of an alternative water source, or any implementation of harvesting practices, of indisputable consensus is the need for community participation and decision-making at the outset (Kloos and Tekle-Haimanot, 1999) which will foster ownership and maintenance by the community, and, consequently, sustainability (Lian-Fang and Jian-Zhong, 1995).

Multidisciplinary collaboration, co-operation, and communication between the science disciplines is frequently brought up as an integral part to the success of any geomedical mitigation methods (Keller, 1979; Appleton *et al.*, 1996; Plant *et al.*, 1998; Cornelius *et al.*, 2000; Deckers and Steinnes, 2004). Williams (1971, in Hopps, 1975) delightfully expressed the grounds for this necessity, because "nature has never divided herself into the sharply defined areas of chemistry, biochemistry, physics, etc., but rather she has used all the advantages of each branch to design a unique, superbly produced, product".

For Vanuatu and the southwest Pacific, a number of documents are already in existence that promote participatory methods in areas such as health promotion and potable water resources (SPC, 1997; Crennan, 2004; Mosley *et* al, 2004; SOPAC, 2004a, 2004b). That foundations have already been laid in these areas is valuable, because collaboration must go beyond a purely scientific multi-disciplinary approach and embrace local, cultural, and community knowledge, methods, perspectives, and resources.

CHAPTER 6: CONCLUSIONS

Dental fluorosis has a high prevalence in West Ambrym, with 96% of surveyed children exhibiting signs of the disease. Over half suffered from moderate and severe forms of fluorosis, according to the Dean's Index of Fluorosis. At a community level, this degree of severity elevated the Fci such that it exceeded considerably the threshold designated by Dean as a "public health concern". Although it was not investigated, there was no noticeable evidence of malnutrition or overt signs of skeletal fluorosis in the population. The anecdotal reports of joint pain may, or may not be, indicative of bone involvement.

In contrast to most other environments in which fluorosis occurs where the pathway from parent rock to groundwater is well established, the fluoride donor in this scenario is the gas plume of Ambrym volcano. The airborne volcanogenic fluoride from the semi-continuously degassing vents becomes incorporated into rainwater which in turn the local people harvest for their potable water needs. This environmental pathway has not previously been recognised in fluorosis aetiology.

All harvested rainwater tank samples had elevated fluoride concentrations with 99% exceeding the WHO recommended concentration for drinking water of 1 ppm F. The wide range of fluoride concentrations from 0.7 to 9.5 ppm is seen not only between villages, but also from tanks within the same village. A trend of higher fluoride concentrations came from villages at greater elevation, in closer proximity to, and more west of the degassing vents. This variability reflects the inconsistency of fluoride concentrations in rainfall due to its dependency on volcanological factors such as plume chemistry and flux, and meteorological factors such as wind strength, direction, and rainfall. Fluoride concentration of freshly fallen rainwater samples confirmed this relationship both spatially and temporally.

Tank water chemistry may also be influenced by catchment surface and storage tank materials, but insufficient sample sizes in this study mean no statistically significant conclusions can be made. That painted and/or rusted corrugated iron roofing removes fluoride from rainwater before it is stored is a tentative finding only. The possible advantage of such roofing may be offset by the contribution of other potentially harmful elements to drinking water supplies such as lead.

Groundwater sources were also fluoride-rich, but contained less fluoride than most of the rainwater tank samples, and may be a consequence of adsorbent or complexing clay/soil properties. The narrower concentration range is also less likely to be subject to extreme fluctuation in fluoride concentration. Groundwater is used less frequently as a drinking water source, but is suggested as preferable to the harvesting of rainwater when the plume is overhead.

West Ambrym is a relatively small, homogenous field area. Geographic distribution into zones of fluorosis was postulated but these are not indicators of areas of future risk due to the high variability in water fluoride concentrations and confounding variables in dental fluorosis aetiology such as diet.

Current water fluoride levels cannot be correlated with the levels of fluorosis seen today because of the fluoride water concentrations may not have remained constant since the time of developing tooth formation. However, fluoride levels in current drinking water supplies are high enough to suggest dental fluorosis will continue to develop in upcoming generations.

Dental fluorosis in North Ambrym, Southeast Ambrym, Malakula, and possibly Tongoa and the incidental islands group also appear attributable to Ambrym's volcanic plume. Relative to these surveyed locations, West Ambrym can be considered as an area of higher risk due to its location and proximity to the vents and prevailing wind direction, hence the prevalence of fluorosis found there. Tanna's prevalence of 100% is doubtless due to its own degassing volcano, Yasur.

Areas of further research include investigation of food sources and bioavailability of fluoride, particularly from coconut juice; dietary practices; the possibility of skeletal involvement; and suitability of catchment surfaces and water storage materials.

Strategies to enhance harvested rain water supply include temporary tank disconnection when the volcanic plume is overhead, implementation of filtering devices, and covered water storage tanks. Defluoridation is an involved process to initiate and maintain, and accessing deeper groundwater sources as a supplementary (or primary) potable water supply is considered a more sustainable option.

APPENDIX 1: Dental survey data

(i) Dean's Index data for West Ambrym

Village	ID number	Age (yr)	M/F	Dean's Index
Baiap Presbyterian	BP-01	11	M	normal
Baiap Presbyterian	BP-02	14	M	normal
Baiap Presbyterian	BP-03	11	M	very mild
Baiap Presbyterian	BP-04	14	M	very mild
Baiap Presbyterian	BP-05	12	M	mild
Baiap Presbyterian	BP-06	10	F	moderate
Baiap Presbyterian	BP-07	10	M	moderate
Baiap Presbyterian	BP-08	12	M	moderate
Baiap Presbyterian	BP-09	13	M	moderate
Baiap Presbyterian	BP-10	14	M	moderate
Baiap Presbyterian	BP-11	9	F	moderate
Baiap Presbyterian	BP-12	10	M	moderate
Baiap SDA	BS-01	13	F	normal
Baiap SDA	BS-02	7	F	normal
Baiap SDA	BS-03	9	F	normal
Baiap SDA	BS-04	11	F	mild
Baiap SDA	BS-05	8	M	mild
Baiap SDA	BS-06	10	F	moderate
Baiap SDA	BS-07	10	M	moderate
Baiap SDA	BS-08	12	M	moderate
Baiap SDA	BS-09	13	F	moderate
Baiap SDA	BS-10	6	F	moderate
Baiap SDA	BS-11	7	F	moderate
Baiap SDA	BS-12	7	F	moderate
Baiap SDA	BS-13	7	M	moderate
Baiap SDA	BS-14	7	M	moderate
Baiap SDA	BS-15	9	M	moderate
Baiap SDA	BS-16	13	F	moderate
Baiap SDA	BS-17	14	F	moderate
Bakmir	BK-01	12	F	very mild
Bakmir	BK-02	11	F	mild
Bakmir	BK-03	10	F	moderate
Bakmir	BK-04	10	F	moderate
Bakmir	BK-05	10	F	moderate
Bakmir	BK-06	11	F	moderate
Bakmir	BK-07	11	F	moderate
Bakmir	BK-08	11	M	moderate
Bakmir	BK-09	12	F	moderate
Bakmir	BK-10	8	F	moderate
Bakmir	BK-11	9	M	moderate
Bakmir	BK-12	9	M	moderate
Bakmir	BK-13	11	M	severe
Boleanbal	BO-01	11	F	moderate
Boleanbal	BO-02	12	F	severe
Buliveao	BU-01	10	M	severe
Buliveao	BU-02	9	F	severe

Buliveao	BU-03	9	M	severe
Elae	EL-01	10	F	mild
Elae	EL-02	10	F	moderate
Elae	EL-03	10	M	moderate
Elae	EL-04	11	F	moderate
Elae	EL-05	9	F	moderate
Elae	EL-06	9	M	moderate
Elae	EL-07	10	M	severe
Elae	EL-08	10	M	severe
Elae	EL-09	11	M	severe
Enmila	EN-01	14	M	questionable
Enmila	EN-02	18	F	very mild
Enmila	EN-03	14	M	mild
Enmila	EN-04	10	M	moderate
Enmila	EN-O5	12	M	moderate
Fali	FA-01	10	M	questionable
Fali	FA-02	11	F	very mild
Fali	FA-03	12	F	very mild
Fali	FA-04	12	F	very mild
Fali	FA-05	12	M	very mild
Fali	FA-06	10	F	mild
Fali	FA-07	14	F	moderate
Fali	FA-08	14	M	moderate
Fali	FA-09	16	F	moderate
Fali	FA-10	9	M	moderate
Fali	FA-11	9	M	moderate
Lalinda Presbyterian	LP-01	10	M	normal
Lalinda Presbyterian	LP-02	12	M	normal
Lalinda Presbyterian	LP-03	14	F	normal
Lalinda Presbyterian	LP-04	10	F	very mild
Lalinda Presbyterian	LP-05	10	M	very mild
Lalinda Presbyterian	LP-06	12	M	very mild
Lalinda Presbyterian	LP-07	13	F	very mild
Lalinda Presbyterian	LP-08	8	F	very mild
Lalinda Presbyterian	LP-09	8	M	very mild
Lalinda Presbyterian	LP-10	9	M	very mild
Lalinda Presbyterian	LP-11	8	F	mild
Lalinda Presbyterian	LP-12	10	F	moderate
Lalinda Presbyterian	LP-13	10	F	moderate
Lalinda Presbyterian	LP-14	10	M	moderate
Lalinda Presbyterian	LP-15	11	M	moderate
Lalinda Presbyterian	LP-16	9	F	moderate
Lalinda Presbyterian	LP-17	9	M	moderate
Lalinda SDA	LS-01	14	F	normal
Lalinda SDA	LS-02	14	F	normal
Lalinda SDA	LS-03	14	M	questionable
Lalinda SDA	LS-04	9	M	questionable
Lalinda SDA	LS-05	10	M	very mild
Lalinda SDA	LS-06	12	M	very mild
Lalinda SDA	LS-07	13	F	very mild
Lalinda SDA	LS-08	13	M	very mild
Lalinda SDA	LS-09	8	F	very mild

Lalinda SDA	LS-10	9	F	very mild
Lalinda SDA	LS-11	12	F	mild
Lalinda SDA	LS-12	10	F	moderate
Lalinda SDA	LS-13	10	F	moderate
Lalinda SDA	LS-14	10	M	moderate
Lalinda SDA	LS-15	10	M	moderate
Lalinda SDA	LS-16	11	M	moderate
Lalinda SDA	LS-17	12	M	moderate
Lalinda SDA	LS-18	13	M	moderate
Lalinda SDA	LS-19	7	M	moderate
Lalinda SDA	LS-20	9	M	moderate
Lalinda SDA	LS-21	9	M	moderate
Laobar	LA-01	10	M	moderate
Laonvea	LN-01	13	F	moderate
Lele	LL-01	12	F	very mild
Lele	LL-02	10	F	moderate
Lele	LL-03	13	F	moderate
Lolebulu	LB-01	11	F	very mild
Lolebulu	LB-02	10	M	mild
Lolebulu	LB-03	14	M	moderate
Lolebulu	LB-04	14	M	moderate
Lolira	LR-01	10	F	questionable
Lolira	LR-02	11	F	questionable
Lolira	LR-03	13	M	mild
Lolira	LR-04	12	F	moderate
Lolira	LR-05	12	F	moderate
Longmek	LK-01	10	M	moderate
Longmek	LK-02	12	F	moderate
Longmek	LK-03	14	M	moderate
Lontopol	LO-01	9	F	very mild
Lontopol	LO-02	11	M	mild
Lontopol	LO-03	8	M	mild
Lonvert	LV-01	11	F	moderate
Lonvert	LV-02	13	F	moderate
Lonvert	LV-03	13	F	moderate
Malvert	MV-01	13	F	questionable
Mapkinkin	MK-01	11	M	moderate
Melten	MN-01	12	F	moderate
Meltungan	ME-01	8	F	questionable
Meltungan	ME-02	10	F	very mild
Meltungan	ME-03	11	F	very mild
Meltungan	ME-04	7	M	very mild
Meltungan	ME-05	9	M	very mild
Meltungan	ME-06	11	F	mild
Meltungan	ME-07	8	M	mild
Meltungan	ME-08	11	F	moderate
Meltungan	ME-09	9	M	moderate
Meltungan	ME-10	13	F	moderate
Pelipetakever	PP-01	12	F	very mild
Pelipetakever	PP-02	12	F	very mild
Pelipetakever	PP-03	9	F	very mild
Pelipetakever	PP-04	9	M	very mild

Pelipetakever	PP-05	15	M	mild
Pelipetakever	PP-06	11	M	moderate
Pelipetakever	PP-07	13	F	moderate
Pelipetakever	PP-08	14	F	moderate
Pelipetakever	PP-09	15	M	moderate
Pelipetakever	PP-10	15	M	moderate
Pelipetakever	PP-11	8	M	moderate
Pemap	PM-01	11	F	very mild
Pemap	PM-02	10	M	moderate
Pemap	PM-03	11	F	moderate
Pemap	PM-04	11	M	moderate
Pemap	PM-05	9	F	moderate
Pemap	PM-06	10	F	severe
Pemap	PM-07	13	M	severe
Petan	PT-01	9	F	mild
Petan	PT-02	12	F	moderate
Petan	PT-03	12	F	moderate
Petan	PT-04	9	F	severe
Polimango	PO-01	14	M	mild
Polimango	PO-02	15	F	mild
Polimango	PO-03	13	F	moderate
Polimango	PO-04	13	F	moderate
Polimango	PO-05	14	F	moderate
Port Vato	PV-01	9	M	normal
Port Vato	PV-02	10	M	very mild
Port Vato	PV-03	11	F	very mild
Port Vato	PV-04	12	F	very mild
Port Vato	PV-05	13	M	very mild
Port Vato	PV-06	14	M	very mild
Port Vato	PV-07	9	F	very mild
Port Vato	PV-08	11	M	mild
Port Vato	PV-09	14	M	mild
Port Vato	PV-10	10	F	moderate
Port Vato	PV-11	9	M	moderate
Port Vato	PV-12	13	M	very mild
Sanbea	SB-01	9	Ftwin	moderate
Sanbea	SB-02	9	Ftwin	moderate
Sanesup	SA-01	11	F	very mild
Sanesup	SA-02	13	F	very mild
Sanesup	SA-03	10	F	moderate
Sanesup	SA-04	10	F	moderate
Sanesup	SA-05	10	M	moderate
Sanesup	SA-06	11	M	moderate
Sanesup	SA-07	13	M	moderate
Sanesup	SA-08	6	F	moderate
Sanesup	SA-09	7	M	moderate
Sanesup	SA-10	9	F	moderate
Sanesup	SA-11	9	F	moderate
Sanesup	SA-12	9	F	moderate
Sanesup	SA-13	9	M	moderate
Sanesup	SA-14	10	F	severe
Sanesup	SA-15	9	F	severe

Senter	SE-01	11	F	very mild
Sesivi	SV-01	13	M	very mild
Sesivi	SV-02	9	F	mild
Sesivi	SV-03	9	F	mild
Sesivi	SV-04	12	F	moderate
Sesivi	SV-05	12	M	moderate
Sesivi	SV-06	6	M	moderate
Sesivi	SV-07	7	F	moderate
Sesivi	SV-08	8	F	moderate
Sesivi	SV-09	9	F	moderate
Sulol	SU-01	9	M	questionable
Sulol	SU-02	13	M	moderate
Sulol	SU-03	7	M	moderate
Sulol	SU-04	9	M	moderate
Tow	TO-01	13	F	moderate
Vetap	VE-01	9	M	mild
Vetap	VE-02	10	F	moderate
Vetap	VE-03	11	M	moderate
Vetap	VE-04	11	M	moderate
Vetap	VE-05	9	F	moderate
Vetap	VE-06	10	F	severe
Vetap	VE-07	11	F	severe
Vetap	VE-08	11	M	severe
Vetap	VE-09	9	F	severe
Wakon	WA-01	14	F	moderate
Wuro	WU-01	10	F	very mild
Wuro	WU-02	15	F	very mild
Wuro	WU-03	15	F	very mild
Wuro	WU-04	15	F	very mild
Wuro	WU-05	11	F	mild
Wuro	WU-06	10	F	moderate
Wuro	WU-07	10	M	moderate
Wuro	WU-08	11	F	moderate
Wuro	WU-09	11	M	moderate
Wuro	WU-10	12	M	moderate
Wuro	WU-11	13	F	moderate
Wuro	WU-12	13	F	moderate
Wuro	WU-13	13	M	moderate
Wuro	WU-14	13	M	moderate
Wuro	WU-15	14	M	moderate
Wuro	WU-16	8	F	moderate
Wuro	WU-17	8	F	moderate
Wuro	WU-18	8	M	moderate
Wuro	WU-19	9	F	moderate
Wuro	WU-20	9	M	moderate
Wuro	WU-21	13	F	moderate
Yaou	YU-01	10	F	moderate
Yaou	YU-02	9	F	moderate
Yaou	YU-03	10	M	severe
Yaou	YU-04	11	F	severe
Yaou	YU-05	11	M	severe

(ii) Dean's Index data for North Ambrym

Village	ID number	Age (yr)	M/F	Dean's Index
Betlehem	NAM-001	15	M	normal
Bogor	NAM-002	13	F	questionable
Bogor	NAM-003	15	F	questionable
Bogor	NAM-004	14	M	very mild
Bogor	NAM-005	15	M	very mild
Fando	NAM-006	9	F	questionable
Fando	NAM-007	9	F	very mild
Fando	NAM-008	10	F	very mild
Fando	NAM-009	11	M	mild
Fanjever	NAM-010	11	F	normal
Fanjever	NAM-011	11	F	questionable
Fanjever	NAM-012	10	F	very mild
Fanjever	NAM-013	12	F	mild
Fanjever	NAM-014	13	M	very mild
Fanla	NAM-015	14	F	normal
Fanla	NAM-016	12	M	questionable
Fanla	NAM-017	13	F	questionable
Fanla	NAM-018	15	F	questionable
Fanla	NAM-019	13	F	very mild
Fanla	NAM-020	14	M	very mild
Fanla	NAM-021	14	F	very mild
Fanla	NAM-022	15	M	very mild
Fanla	NAM-023	15	F	very mild
Fanla	NAM-024	16	F	very mild
Fanomol	NAM-025	9	F	normal
Fanrereo	NAM-026	9	M	normal
Fanrereo	NAM-027	9	M	normal
Fanrereo	NAM-028	11	F	normal
Fanrereo	NAM-029	11	F	normal
Fanrereo	NAM-030	11	M	normal
Fanrereo	NAM-031	11	F	normal
Fanrereo	NAM-032	13	F	normal
Fanrereo	NAM-033	13	F	normal
Fanrereo	NAM-034	13	F	normal
Fanrereo	NAM-035	10	M	questionable
Fanrereo	NAM-036	11	M	very mild
Fanrereo	NAM-037	12	M	very mild
Fanrereo	NAM-038	13	F	very mild
Fanrereo	NAM-039	14	F	very mild
Fansfarl	NAM-040	10	M	mild
Fanto	NAM-041	13	F	very mild
Faramsu	NAM-042	9	M	normal
Faramsu	NAM-043	10	M	normal
Faramsu	NAM-044	11	F	normal
Faramsu	NAM-045	13	F	normal
Faramsu	NAM-046	13	M	normal
Faramsu	NAM-047	14	F	normal
Faramsu	NAM-048	11	M	very mild
Faramsu	NAM-049	13	F	very mild

Faramsu	NAM-050	9	F	mild
Faramsu	NAM-051	15	F	mild
Fatima	NAM-052	15	M	very mild
Fona	NAM-053	12	M	normal
Fona	NAM-054	13	F	normal
Fonmur	NAM-055	15	M	very mild
Fonteng	NAM056	13	F	normal
Harimal	NAM-057	14	M	questionable
Harimal	NAM-058	13	F	very mild
Harimal	NAM-059	14	F	very mild
Harimal	NAM-060	15	M	moderate
Likon	NAM-061	11	M	normal
Linpul	NAM-062	12	M	normal
Linpul	NAM-063	14	F	normal
Linpul	NAM-064	13	F	very mild
Linpul	NAM-065	13	F	very mild
Linpul	NAM-066	13	M	very mild
Linpul	NAM-067	15	F	very mild
Linpul	NAM-068	13	M	mild
Lonbe	NAM-069	12	F	very mild
Lonbokor	NAM-070	10	F	normal
Longbwe	NAM-071	12	M	very mild
Longbwe	NAM-072	11	M	moderate
Magam	NAM-073	11	M	normal
Magam	NAM-074	13	F	normal
Magam	NAM-075	15	M	normal
Magam	NAM-076	12	M	questionable
Magam	NAM-077	12	M	questionable
Magam	NAM-078	10	F	mild
Magam	NAM-079	11	F	very mild
Magam	NAM-080	12	M	very mild
Magam	NAM-081	12	F	very mild
Magam	NAM-082	12	M	very mild
Magam	NAM-083	13	F	very mild
Magam	NAM-084	14	F	very mild
Magam	NAM-085	10	M	mild
Magam	NAM-086	11	F	mild
Magam	NAM-087	10	F	moderate
Melvat	NAM-088	13	F	normal
Melvir	NAM-089	10	F	questionable
Melvir	NAM-090	12	F	very mild
Metamly	NAM-091	11	M	normal
Metamly	NAM-092	13	M	normal
Metamly	NAM-093	14	F	normal
Metamly	NAM-094	11	F	very mild
Nazareth	NAM-095	15	M	normal
Nazareth	NAM-096	14	F	very mild
ND Mont Carmel	NAM-097	15	M	very mild
Nehartling	NAM-098	14	M	normal
Nehartling	NAM-099	15	M	normal
Nehartling	NAM-100	11	M	questionable
Nehartling	NAM-101	10	F	very mild

Nehartling	NAM-102	11	M	very mild
Nehartling	NAM-103	12	M	very mild
Newha	NAM-104	13	M	very mild
Newha	NAM-105	15	F	very mild
Newha	NAM-106	15	M	very mild
Newha	NAM-107	13	M	mild
Norbul	NAM-108	14	M	very mild
Norbul	NAM-109	13	F	moderate
Olal	NAM-110	12	F	normal
Olal	NAM-111	13	M	questionable
Ranbe	NAM-112	8	F	very mild
Ranbe	NAM-113	10	F	very mild
Ranbe	NAM-114	11	M	very mild
Ranbe	NAM-115	11	F	very mild
Ranbe	NAM-116	9	F	mild
Ranmuhu	NAM-117	11	F	normal
Ranmuhu	NAM-118	12	M	questionable
Ranon	NAM-119	9	F	normal
Ranon	NAM-120	13	F	normal
Ranon	NAM-121	10	M	questionable
Ranon	NAM-122	13	F	questionable
Ranon	NAM-123	9	F	very mild
Ranon	NAM-124	10	F	very mild
Ranon	NAM-125	10	F	very mild
Ranon	NAM-126	11	F	very mild
Ranon	NAM-127	12	M	very mild
Ranon	NAM-128	13	F	very mild
Ranon	NAM-129	13	M	very mild
Ranon	NAM-130	13	F	very mild
Ranon	NAM-131	9	M	mild
Ranon	NAM-132	11	M	mild
Ranon	NAM-133	12	M	moderate
Ranon	NAM-134	13	M	moderate
Ranon	NAM-135	14	M	moderate
Ranon JSS	NAM-136	10	F	very mild
Ranou	NAM-137	8	M	questionable
Ranou	NAM-138	10	M	very mild
Ranvetkere	NAM-139	12	M	normal
Ranvetkere	NAM-140	11	M	very mild
Ranvetkere	NAM-141	12	F	very mild
Ranvetkere	NAM-142	15	F	mild
Ranvetlam	NAM-143	10	M	normal
Ranvetlam	NAM-144	11	M	normal
Ranvetlam	NAM-145	9	M	very mild
Ranvetlam	NAM-146	9	F	very mild
Ranvetlam	NAM-147	11	F	very mild
Ranvetlam	NAM-148	13	M	very mild
Ranvetlam	NAM-149	12	M	moderate
Ranvetrere	NAM-150	10	M	normal
Ranvetrere	NAM-151	11	M	questionable
Ranvetrere	NAM-152	10	F	very mild
Ranvetrere	NAM-153	11	F	very mild

S Albert	NAM-154	12	F	moderate
St Jeanne D'arc Harimal	NAM-155	12	F	normal
St Marie Viane	NAM-156	13	M	normal
St Marie Viane	NAM-157	13	F	normal
St Michel	NAM-158	10yr	F	moderate
St Michel	NAM-159	10yr	M	moderate
St Michel	NAM-160	11yr	M	severe
St Pierre Chanel	NAM-161	12	M	normal
St Pierre Chanel	NAM-162	13	M	normal
St Pierre Chanel	NAM-163	15	M	normal
St Pierre Chanel	NAM-164	13	M	questionable
St Pierre Chanel	NAM-165	15	M	very mild
St Therese	NAM-166	15	M	very mild
St Therese Fonmur	NAM-167	15	F	very mild
Tonbang	NAM-168	10	F	questionable
Tonbang	NAM-169	11	F	questionable
Tonbang	NAM-170	15	M	very mild
Tonbang	NAM-171	16	M	very mild
Willit	NAM-172	14	F	mild

(iii) Dean's Index data for Southeast Ambrym

Village	ID number	Age (yr)	M/F	Dean's Index
Asse	SEA-001	10	M	normal
Asse	SEA-002	12	F	normal
Asse	SEA-003	12	F	normal
Asse	SEA-004	10	M	questionable
Asse	SEA-005	10	M	questionable
Asse	SEA-006	12	F	questionable
Asse	SEA-007	10	M	very mild
Asse	SEA-008	12	M	very mild
Bareas	SEA-009	12	F	normal
Bethel SDA	SEA-010	12	F	normal
Bethel SDA	SEA-011	13	M	normal
Bethel SDA	SEA-012	13	M	normal
Bethel SDA	SEA-013	13	F	normal
Bethel SDA	SEA-014	13	M	questionable
Bethel SDA	SEA-015	12	F	very mild
Endu	SEA-016	12	M	mild
Endu	SEA-017	9	M	moderate
Endu	SEA-018	12	F	moderate
Endu	SEA-019	8	F	normal
Endu	SEA-020	9	M	normal
Endu	SEA-021	9	M	normal
Endu	SEA-022	9	F	normal
Endu	SEA-023	9	M	normal
Endu	SEA-024	9	M	normal
Endu	SEA-025	11	F	normal
Endu	SEA-026	11	M	normal
Endu	SEA-027	12	F	normal
Endu	SEA-028	12	M	normal

Endu	SEA-029	7	M	questionable
Endu	SEA-030	9	F	questionable
Endu	SEA-031	9	M	questionable
Endu	SEA-032	9	F	questionable
Endu	SEA-033	12	F	questionable
Endu	SEA-034	13	M	questionable
Endu	SEA-035	9	F	very mild
Endu	SEA-036	9	M	very mild
Endu	SEA-037	11	F	very mild
Endu	SEA-038	12	M	very mild
Lulap	SEA-039	11	M	very mild
Maat	SEA-040	10	F	questionable
Moru	SEA-041	9	M	very mild
Moru	SEA-042	13	M	normal
Moru Presbyterian	SEA-043	12	F	mild
Moru Presbyterian	SEA-044	12	F	normal
Moru Presbyterian	SEA-045	13	F	normal
Not recorded	SEA-046	13	F	normal
Paamal	SEA-047	9	F	normal
Paamal	SEA-048	9	F	normal
Paamal	SEA-049	9	M	normal
Paamal	SEA-050	9	F	normal
Paamal	SEA-051	12	M	normal
Paamal	SEA-052	12	F	normal
Paamal	SEA-053	12	F	normal
Paamal	SEA-054	12	M	normal
Paamal	SEA-055	12	F	normal
Paamal	SEA-056	12	F	normal
Paamal	SEA-057	13	M	normal
Paamal	SEA-058	9	F	questionable
Paamal	SEA-059	13	M	questionable
Paamal	SEA-060	10	M	very mild
Paamal	SEA-061	10	F	very mild
Paamal	SEA-062	12	M	very mild
Penapo Presbyterian	SEA-063	11	M	normal
Penapo Presbyterian	SEA-064	11	M	normal
Penapo Presbyterian	SEA-065	12	M	normal
Penapo Presbyterian	SEA-066	13	F	normal
Penapo Presbyterian	SEA-067	9	M	questionable
Penapo Presbyterian	SEA-068	10	F	questionable
Penapo Presbyterian	SEA-069	11	F	questionable
Penapo Presbyterian	SEA-070	12	M	questionable
Penapo Presbyterian	SEA-071	11	M	very mild
Penapo Presbyterian	SEA-072	12	F	very mild
Penapo Presbyterian	SEA-073	12	M	very mild
Penapo Presbyterian	SEA-074	13	F	very mild
Sahuot	SEA-075	11	M	normal
Sahuot	SEA-076	12	M	normal
Sahuot	SEA-077	14	F	normal
Sahuot Presbyterian	SEA-078	13	M	questionable
Sai	SEA-079	10	M	very mild
Sai Presbyterian	SEA-080	11	F	normal

Sai Presbyterian	SEA-081	12	F	questionable
Sai Presbyterian	SEA-082	11	M	very mild
Sameou	SEA-083	10	M	mild
Sameou	SEA-084	9	M	moderate
Sameou	SEA-085	10	F	normal
Sameou	SEA-086	10	M	normal
Sameou	SEA-087	10	M	normal
Sameou	SEA-088	11	M	normal
Sameou	SEA-089	12	M	normal
Sameou	SEA-090	8	F	questionable
Sameou	SEA-091	9	M	questionable
Sameou	SEA-092	12	M	questionable
Sameou	SEA-093	13	M	questionable
Sameou	SEA-094	14	M	questionable
Sameou	SEA-095	9	F	very mild
Sameou	SEA-096	11	F	very mild
Sameou	SEA-097	11	M	very mild
Senai Presbyterian	SEA-098	13	M	questionable
Taviak	SEA-099	11	M	normal
Taviak	SEA-100	12	M	normal
Taviak Presbyterian	SEA-101	14	F	mild
Taviak Presbyterian	SEA-102	11	M	normal
Taviak Presbyterian	SEA-103	13	F	normal
Taviak Presbyterian	SEA-104	13	F	questionable
Taviak Presbyterian	SEA-105	11	M	very mild
Taviak Presbyterian	SEA-106	12	M	very mild
Taviak Presbyterian	SEA-107	12	F	very mild
Toac	SEA-108	15	M	mild
Toac	SEA-109	9	M	moderate
Toac	SEA-110	12	F	moderate
Toac	SEA-111	12	M	moderate
Toac	SEA-112	8	F	normal
Toac	SEA-113	8	M	normal
Toac	SEA-114	9	M	normal
Toac	SEA-115	9	F	normal
Toac	SEA-116	10	M	normal
Toac	SEA-117	11	F	normal
Toac	SEA-118	12	F	normal
Toac	SEA-119	12	F	normal
Toac	SEA-120	13	F	normal
Toac	SEA-121	8	F	questionable
Toac	SEA-122	8	M	questionable
Toac	SEA-123	8	M	questionable
Toac	SEA-124	9	F	questionable
Toac	SEA-125	9	M	questionable
Toac	SEA-126	9	M	questionable
Toac	SEA-127	9	M	questionable
Toac	SEA-128	10	M	questionable
Toac	SEA-129	10	F	questionable
Toac	SEA-130	10	F	questionable
Toac	SEA-131	10	M	questionable
Toac	SEA-132	10	F	questionable

Toac	SEA-133	11	M	questionable
Toac	SEA-134	11	F	questionable
Toac	SEA-135	12	M	questionable
Toac	SEA-136	8	F	very mild
Toac	SEA-137	9	M	very mild
Toac	SEA-138	9	F	very mild
Toac	SEA-139	9	M	very mild
Toac	SEA-140	10	F	very mild
Toac	SEA-141	10	F	very mild
Toac	SEA-142	11	M	very mild
Toac	SEA-143	13	M	very mild
Toac	SEA-144	14	M	very mild
Toac	SEA-145	15	M	questionable
Toac	SEA-146	16	M	very mild
Ulei	SEA-147	8	M	mild
Ulei	SEA-148	14	M	mild
Ulei	SEA-149	14	M	mild
Ulei	SEA-150	11yr	M	mild
Ulei	SEA-151	12	F	moderate
Ulei	SEA-152	12	M	moderate
Ulei	SEA-153	14	F	moderate
Ulei	SEA-154	8	M	normal
Ulei	SEA-155	8	M	normal
Ulei	SEA-156	10	M	normal
Ulei	SEA-157	11	M	normal
Ulei	SEA-158	12	F	normal
Ulei	SEA-159	12	M	normal
Ulei	SEA-160	8	M	questionable
Ulei	SEA-161	9	F	questionable
Ulei	SEA-162	10	M	questionable
Ulei	SEA-163	10	F	questionable
Ulei	SEA-164	11	M	questionable
Ulei	SEA-165	9	M	very mild
Ulei	SEA-166	9	F	very mild
Ulei	SEA-167	11	M	very mild
Ulei	SEA-168	12	M	very mild
Ulei	SEA-169	12	F	very mild
Utas Presbyterian	SEA-170	10	M	normal
Utas Presbyterian	SEA-171	11	M	normal
Utas Presbyterian	SEA-172	10	F	very mild
Vanan SDA	SEA-173	11	M	mild
Vanan SDA	SEA-174	13	F	mild
Vanan SDA	SEA-175	12	F	normal
Vemagog	SEA-176	13	F	normal
Venan	SEA-177	13	F	questionable

(iv) Dean's Index data for Malakula

Village	ID number	Age (yr)	M/F	Dean's Index
Aichin	MAL-01	11	F	very mild
Aichin	MAL-02	13	F	moderate
Amelsanwir	MAL-03	10	F	mild
Amelvet	MAL-04	13	F	mild
Barik	MAL-05	10	M	questionable
Benut	MAL-06	12	F	moderate
Bosliw	MAL-07	11	F	questionable
Botko	MAL-08	9	F	questionable
Calvary	MAL-09	10	F	normal
Chibare	MAL-10	12	F	very mild
Chibirbir	MAL-11	11	F	moderate
Chibirbir	MAL-12	11	M	moderate
Chinamtenwo	MAL-13	9	F	very mild
Chinartsets	MAL-14	10	F	questionable
Chinawo	MAL-15	8	F	questionable
Chinemtenwo	MAL-16	10	M	very mild
Chinetra	MAL-17	9	M	very mild
Chinowan	MAL-18	9	M	normal
Chinowan	MAL-19	12	F	questionable
Chinowan	MAL-20	10	F	very mild
Chiptir	MAL-21	11	M	normal
Chiptir	MAL-22	10	M	questionable
Chiptir	MAL-23	13	F	mild
Dixon	MAL-24	13	M	very mild
Epivalet	MAL-25	9	M	moderate
Fatima	MAL-26	10	F	normal
Fenua	MAL-27	9	F	questionable
Galili	MAL-28	10	F	mild
Galili	MAL-29	12	M	mild
Ille	MAL-30	12	F	very mild
Kanegai	MAL-31	12	M	questionable
Lakatoro	MAL-32	14	M	questionable
Lamap	MAL-33	9	F	very mild
Lepeten Wala	MAL-34	11	M	moderate
Lepinmas	MAL-35	9	F	normal
Lepinmas	MAL-36	11	F	very mild
Lepitan	MAL-37	11	M	questionable
Lopo	MAL-38	12	F	mild
Malprew	MAL-39	9	F	normal
Melnator	MAL-40	10	M	very mild
Merew	MAL-41	9	F	moderate
Oonwa	MAL-42	10	F	normal
Orap	MAL-43	11	F	normal
Orap	MAL-44	9	F	questionable
Orap	MAL-45	11	F	questionable
Orap	MAL-46	11	F	questionable
Orap	MAL-47	12	F	questionable
Orap	MAL-48	9	M	very mild
Orap	MAL-49	10	F	very mild

Orap	MAL-50	10	M	very mild
Orap	MAL-51	11	F	very mild
Orap	MAL-51	11	M	very mild
Orap	MAL-53	11	M	mild
Orap	MAL-54	9	F	moderate
Orap	MAL-55	11	M	moderate
Orap	MAL-56	11	M	moderate
Orap	MAL-57	12	M	moderate
Paita	MAL-58	12	M	moderate
Paradis	MAL-59	9	F	questionable
Paradis	MAL-60	10	M	mild
Paradis	MAL-61	11	M	moderate
Peterlep	MAL-62	12	F	normal
Peterlep	MAL-63	13	M	normal
Peterlep	MAL-64	13	F	normal
Peterlep	MAL-65	9	M	very mild
Potouare	MAL-66	12	M	very mild
Potouare	MAL-67	14	F	very mild
Poura	MAL-68	9	M	questionable
Rori	MAL-69	10	F	questionable
Rose Bay	MAL-70	9	M	very mild
Saha	MAL-71	9	M	moderate
Sanwir	MAL-72	10	F	normal
Sanwir	MAL-73	10	M	very mild
Sanwir	MAL-74	10	F	very mild
Sanwir	MAL-75	9	M	moderate
Senal	MAL-76	12	M	questionable
Senal	MAL-77	16	M	mild
Senal	MAL-78	9	M	moderate
Sleslenabe	MAL-79	9	F	mild
Sowole	MAL-80	14	M	questionable
Sowole	MAL-81	13	M	very mild
St Joseph	MAL-82	9	M	very mild
St Louis	MAL-83	9	F	normal
Tepew	MAL-84	9	M	questionable
Tepew	MAL-85	10	F	very mild
Unu	MAL-86	14	F	moderate
Vetan	MAL-87	9	F	normal
Vetan	MAL-88	11	M	very mild
Wala	MAL-89	13	F	very mild
Watacha	MAL-90	9	F	mild
Watindir	MAL-91	12	M	normal
Woranari	MAL-92	12	M	questionable
Worlep	MAL-93	13	M	questionable
Worlep	MAL-94	12	M	very mild
Wormalaki	MAL-95	8	F	moderate
Wornari	MAL-96	13	F	questionable
Worprew	MAL-97	10	F	questionable
Wowot	MAL-98	10	F	moderate

(v) Dean's Index data for Tongoa

Village	ID number	Age (yr)	M/F	Dean's Index
Erata, Tongariki	TON-01	13	F	normal
Erata, Tongariki	TON-02	13	M	normal
Euta	TON-03	15	F	very mild
Euta	TON-04	11	F	mild
Euta	TON-05	15	F	moderate
Kuramabe	TON-06	8	M	normal
Kuramabe	TON-07	9	M	normal
Kuramabe	TON-08	10	M	normal
Kuramabe	TON-09	10	F	normal
Kuramabe	TON-10	11	F	normal
Kuramabe	TON-11	12	F	normal
Kuramabe	TON-12	12	F	normal
Kuramabe	TON-13	12	F	normal
Kuramabe	TON-14	12	F	normal
Kuramabe	TON-15	12	M	normal
Kuramabe	TON-16	13	F	normal
Leiwaima, Tongariki	TON-17	14	F	very mild
Lupalea	TON-18	16	F	questionable
Lumbukuti	TON-19	9	F	normal
Lumbukuti	TON-20	9	F	normal
Lumbukuti	TON-21	10	M	normal
Lumbukuti	TON-22	11	F	normal
Lumbukuti	TON-23	12	M	normal
Lumbukuti	TON-24	13	F	normal
Lumbukuti	TON-25	14	M	normal
Lumbukuti	TON-26	16	M	normal
Lumbukuti	TON-27	11	F	questionable
Lumbukuti	TON-28	16	F	questionable
Lumbukuti	TON-29	16	F	questionable
Lumbukuti	TON-30	9	M	very mild
Lumbukuti	TON-31	11	M	very mild
Lumbukuti	TON-32	12	F	very mild
Lumbukuti	TON-33	15	M	very mild
Lumbukuti	TON-34	8	M	mild
Lumbukuti	TON-35	12	F	mild
Lumbukuti	TON-36	12	F	mild
Lumbukuti	TON-37	11	F	moderate
Lupalea	TON-38	9	F	normal
Lupalea	TON-39	10	F	normal
Lupalea	TON-40	10	F	normal
Lupalea	TON-41	10	M	normal
Lupalea	TON-42	11	M	normal
Lupalea	TON-43	12	F	normal
Lupalea	TON-44	13	F	normal
Lupalea	TON-45	14	M	normal
Lupalea	TON-46	9	F	questionable
Lupalea	TON-47	10	M	questionable
Lupalea	TON-48	9	F	very mild
Lupalea	TON-49	13	F	very mild

Lupalea	TON-50	11	F	mild
Mangarisu	TON-51	9	M	normal
Mangarisu	TON-52	10	F	normal
Meriu	TON-53	8	F	normal
Meriu	TON-54	9	F	normal
Meriu	TON-55	9	M	normal
Meriu	TON-56	11	M	normal
Meriu	TON-57	12	F	normal
Meriu	TON-58	12	F	normal
Meriu	TON-59	13	F	normal
Meriu	TON-60	13	M	normal
Meriu	TON-61	14	M	normal
Meriu	TON-62	18	M	normal
Meriu	TON-63	9	F	questionable
Meriu	TON-64	9	M	questionable
Meriu	TON-65	9	M	questionable
Meriu	TON-66	10	M	questionable
Meriu	TON-67	9	M	mild
Morua	TON-68	10	M	normal
Paneta	TON-69	9	M	normal
Paneta	TON-70	10	F	normal
Paneta	TON-71	10	M	normal
Paneta	TON-72	11	M	normal
Paneta	TON-73	11	M	normal
Paneta	TON-74	9	M	mild
Pele	TON-75	10	M	normal
Pele	TON-76	10	M	normal
Pele	TON-77	10	M	normal
Pele	TON-78	12	M	normal
Pele	TON-79	18	F	normal
Pele	TON-80	9	F	questionable
Pele	TON-81	12	M	questionable
Pele	TON-82	9	M	very mild
Ravenga	TON-83	10	F	mild
Senekae	TON-84	10	M	normal
Senekae	TON-85	12	F	normal
Senekae	TON-86	17	F	normal

(vi) Dean's Index data for the "Incidental Islands" group

Village	**ID number**	**Age (yr)**	**M/F**	**Dean's Index**
Efate	IEF-01	9	F	normal
Efate	IEF-02	12	F	normal
Efate	IEF-03	13	F	normal
Efate	IEF-04	15	M	normal
Efate	IEF-05	17	M	questionable
Efate	IEF-05	19	F	questionable
Efate	IEF-06	13	F	very mild
Efate	IEF-07	12	M	mild
Emae	IEM-01	15	F	mild
Futuna	IFU-01	16	M	normal

Nguna	ING-01	12	F	normal
Nguna	ING-02	12	F	normal
Nguna	ING-03	12	M	normal
Nguna	ING-04	12	F	questionable
Nguna	ING-05	12	F	questionable
Nguna	ING-06	13	F	questionable
Nguna	ING-07	14	F	very mild
Pentecost	IPE-01	13	F	normal
Pentecost	IPE-02	14	F	normal
Pentecost	IPE-03	14	F	normal
Pentecost	IPE-04	13	F	questionable
Santo	IES-01	9	F	normal
Santo	IES-02	12	M	normal

(vii) Dean's Index data for Tanna

Village	ID number	Age (yr)	M/F	Dean's Index
Loono	TAN-01	7	F	very mild
Loono	TAN-02	9	F	moderate
Lounasunan	TAN-03	7	M	questionable
Lounasunan	TAN-04	8	M	questionable
Lounasunan	TAN-05	8	F	very mild
Lounasunan	TAN-06	8	M	very mild
Lounasunan	TAN-07	7	F	mild
Lounasunan	TAN-08	8	F	mild
Lounasunan	TAN-09	8	M	mild
Lounasunan	TAN-10	10	M	moderate
Lounasunan	TAN-11	10	M	moderate
Lounasunan	TAN-12	15	F	moderate
Lounasunan	TAN-13	8	M	moderate
Lounasunan	TAN-14	8	M	moderate
Sulphur Bay	TAN-15	12	F	questionable
Sulphur Bay	TAN-16	15	F	questionable
Sulphur Bay	TAN-17	7	n/r	questionable
Sulphur Bay	TAN-18	10	F	very mild
Sulphur Bay	TAN-19	7	F	very mild
Sulphur Bay	TAN-20	8	F	very mild
Sulphur Bay	TAN-21	10	F	mild
Sulphur Bay	TAN-22	10	M	moderate
Sulphur Bay	TAN-23	12	F	moderate
Sulphur Bay	TAN-24	7	F	moderate
Sulphur Bay	TAN-25	8	F	moderate
Sulphur Bay	TAN-26	9	F	moderate

n/r = not recorded

APPENDIX 2: Water analyses

Village	Sample number	Water type	Tank material	Catchment material	F (ppm)	pH	GPS ref	GRID	EASTING	NORTHING	Elevation (m asl)
Lalinda Presbyterian	R05-7	HRW	concrete	ci, p	5.0	4.96	84	59K	185224	8191276	56
Lalinda Presbyterian	R05-8	pipe	n/a	n/a	2.2	7.19	85	59K	185244	8191309	57
Lalinda Presbyterian	R05-9	spring	n/a	n/a	2.0	7.15	86	59K	185253	8191310	54
Craig Cove	R05-10	HRW	concrete	ci, p	3.6	6.33	n/r	59K	n/r	n/r	n/r
Meltungan	R05-11	HRW	concrete	ci	6.4	5.64	89&90	58K	819182	8199889	235
Meltungan	R05-12	HRW	concrete	n/r	6.3	6.62	91	58K	819259	8199847	233
Meltungan	R05-13	HRW	concrete	ci, r	7.7	6.34	92	58K	819279	8199837	231
Meltungan	R05-14	HRW	concrete	ci, r, p	6.4	6.61	93	58K	819302	8199805	227
Meltungan	R05-15	HRW	concrete	ci	5.5	6.87	94	58K	819277	8199791	227
Meltungan	R05-16	HRW	concrete	ci	5.3	6.41	95	58K	819239	8199805	226
Meltungan	R05-17	HRW	concrete	ci	6.1	6.35	96	58K	819239	8199807	225
Meltungan	R05-18	HRW	concrete	n/r	5.8	6.64	97	58K	819241	8199822	225
Meltungan	R05-19	HRW	concrete	n/r	4.7	7.04	98	58K	819254	8199827	226
Meltungan	R05-20	HRW	concrete	other (bamboo)	8.4	6.73	99	58K	819208	8199845	223
Meltungan	R05-21	HRW	concrete	ci	6.1	6.26	100	58K	819197	8199818	221
Meltungan	R05-22	HRW	concrete	ci	7.1	6.35	101	58K	819173	8199789	217
Meltungan	R05-23	HRW	concrete	ci, p	5.4	6.21	102	58K	819177	8199762	216
Meltungan	R05-24	HRW	concrete	ci	9.0	6.88	103	58K	819116	8199758	215
Fali	R05-25	HRW	concrete	ci	2.4	6.14	105&106	58K	812181	8200252	17
Fali	R05-26	HRW	concrete	ci, r	4.1	6.54	107	58K	812184	8200301	17
Fali	R05-27	HRW	aluminium	ci, p	5.4	4.55	108	58K	812192	8200307	17
Fali	R05-28	HRW	concrete	ci, r	3.5	6.53	109	58K	812222	8200314	18

Fali	R05-29	HRW	concrete	other (steel)	2.6	6.42	110	58K	812276	8200286	19
Fali	R05-30	HRW	concrete	ci, p	2.6	6.82	111	58K	812280	8200279	19
Fali	R05-31	HRW	fibreglass	ci, p	0.7	5.67	112	58K	812284	8200317	21
Fali	R05-32	HRW	concrete	ci, r	2.9	6.96	113	58K	812252	8200330	20
Fali	R05-33	HRW	concrete	ci	2.8	7.19	114	58K	812255	8200355	20
Fali	R05-35	HRW	concrete	ci	4.5	6.77	116	58K	812267	8200397	15
Fali	R05-36	HRW	fibreglass	ci, r	1.7	4.37	117	58K	812291	8200331	19
Fali	R05-37	HRW	concrete	ci, r	1.8	7.03	118	58K	812330	8200369	18
Fali	R05-38	HRW	concrete	ci	2.8	6.88	119	58K	812337	8200358	20
Fali	R05-39	HRW	concrete	other (concrete)	2.4	7.13	120	58K	812342	8200393	19
Fali	R05-40	HRW	concrete	ci, r	2.1	n/r	121	58K	812345	8200428	18
Fali	R05-41	HRW	concrete	ci	1.3	7.28	122	58K	812347	8200445	16
Fali	R05-42	HRW	concrete	ci	2.8	6.97	123	58K	812524	8200236	28
Wuro	R05-43	HRW	concrete	ci	2.1	6.1	124	58K	812149	8199967	23
Wuro	R05-44	HRW	concrete	ci, p	2.5	6.55	125	58K	812199	8200002	4
Wuro	R05-45	HRW	concrete	ci, r	2.0	6.65	126	58K	812228	8200025	5
Wuro	R05-46	HRW	concrete	ci, p	1.8	6.12	127	58K	812236	8200068	5
Wuro	R05-47	HRW	concrete	ci, p	1.0	6.66	128	58K	812261	8200070	7
Wuro	R05-48	HRW	concrete	ci	1.3	6.64	129	58K	812282	8200110	10
Wuro	R05-49	HRW	concrete	ci	1.6	6.58	130	58K	812318	8200086	13
Wuro	R05-50	HRW	concrete	ci, p	2.3	6.64	131	58K	812309	8200055	12
Wuro	R05-51	HRW	concrete	ci, p	2.7	6.86	132	58K	812315	8200021	14
Wuro	R05-52	HRW	concrete	other (steel)	2.6	7.22	133&134	58K	812316	8200022	14
Wuro	R05-53	HRW	concrete	ci	3.4	7.03	135	58K	812335	8200010	15
Wuro	R05-54	HRW	concrete	ci, p	1.5	6.84	136	58K	812273	8199998	13
Wuro	R05-55	HRW	concrete	ci, p	1.3	5.88	137	58K	812241	8200010	19

Wuro	R05-56	HRW	concrete	ci	1.9	6.29	138	58K	812713	8200080	22
Wuro	R05-57	HRW	concrete	ci	2.9	5.74	139	58K	812479	8200169	22
Baiap SDA	R05-63	HRW	concrete	ci, r	3.2	5.87	141	58K	816644	8197320	42
Baiap SDA	R05-64	HRW	concrete	ci	3.4	6.65	142	58K	816669	8197335	48
Baiap SDA	R05-65	HRW	concrete	ci, r	1.9	5.48	143	58K	816704	8197335	49
Baiap SDA	R05-66	HRW	concrete	ci, r	3.6	6.09	144	58K	816732	8197357	50
Baiap SDA	R05-67	HRW	concrete	ci, r	3.2	6.76	145	58K	816766	8197360	52
Baiap SDA	R05-68	HRW	concrete	ci, r	3.1	6.55	146	58K	816774	8197328	52
Baiap SDA	R05-69	HRW	concrete	ci, r	3.3	6.55	147	58K	816755	8197320	51
Baiap SDA	R05-70	HRW	concrete	ci, r, p	2.3	5.45	148	58K	816760	8197271	49
Baiap SDA	R05-71	HRW	concrete	ci, r	2.1	6.12	149	58K	816771	8197274	49
Baiap SDA	R05-72	HRW	concrete	ci, r	1.9	6.43	150	58K	816807	8197267	52
Baiap SDA	R05-73	HRW	concrete	ci, r	2.7	5.37	151	58K	816795	8197237	52
Baiap SDA	R05-74	HRW	concrete	ci, r	2.0	6.42	152	58K	816755	8197236	51
Baiap SDA	R05-75	HRW	concrete	ci, r	4.3	6.89	153	58K	816746	8197224	51
Baiap SDA	R05-76	HRW	concrete	ci, r	4.4	6.48	154	58K	816728	8197228	50
Baiap SDA	R05-77	HRW	concrete	ci, p	4.2	5.91	155	58K	816765	8197168	52
Baiap SDA	R05-78	HRW	concrete	ci, r	3.0	6.71	156	58K	816766	8197169	52
Baiap SDA	R05-79	HRW	concrete	ci	2.8	6.92	157	58K	816783	8197202	53
Baiap SDA	R05-80	HRW	concrete	ci	3.6	7.32	158	58K	816791	8197173	55
Baiap SDA	R05-81	HRW	concrete	ci, r, p	4.4	6.61	159	58K	816761	8197148	51
Baiap SDA	R05-82	HRW	concrete	ci, p	3.1	7.03	160	58K	816701	8197126	45
Baiap SDA	R05-83	HRW	concrete	ci, p	2.7	7.4	161	58K	816694	8197147	47
Baiap SDA	R05-84	HRW	concrete	ci, p	2.1	7.24	162	58K	816644	8197209	46
Sesivi	R05-85	HRW	concrete	ci, p	4.1	6.95	163	58K	819010	8194838	34
Sesivi	R05-86	HRW	concrete	ci, r	3.9	5.32	164	58K	819012	8194817	34

Sesivi	R05-87	HRW	concrete	ci, r, p	3.2	6.15	165	58K	818989	8194803	35
Sesivi	R05-88	HRW	concrete	ci, r	3.8	6.74	166	58K	818945	8194775	33
Sesivi	R05-89	HRW	concrete	ci, r	4.7	6.75	167	58K	818939	8194741	34
Sesivi	R05-90	HRW	concrete	ci, p	3.6	6.95	168	58K	819009	8194645	38
Sesivi	R05-91	HRW	concrete	ci	5.1	5.84	169	58K	818981	8194619	38
Sesivi	R05-92	HRW	concrete	ci, r, p	3.2	6.71	170	58K	819028	8194572	34
Sesivi	R05-93	HRW	concrete	ci	3.8	6.85	171	58K	819047	8194572	36
Sesivi	R05-94	HRW	concrete	ci	4.5	7.36	172	58K	819090	8194522	36
Sesivi	R05-95	HRW	concrete	other (aluminium)	3.8	6.49	172	58K	819090	8194522	36
Sesivi	R05-96	HRW	concrete	ci	4.3	7.07	172	58K	819090	8194522	36
Sesivi	R05-97	HRW	concrete	ci	5.0	7.13	173	58K	819112	8194464	33
Sesivi	R05-98	HRW	plastic	n/s	4.0	7.28	174	58K	819103	8194389	30
Sesivi	R05-99	HRW	concrete	ci	3.1	7.36	172	58K	819090	8194522	36
Sesivi	R05-100	HRW	n/r	ci	9.2	5.04	175	58K	818846	8194721	35
Sesivi	R05-101	HRW	concrete	ci	6.4	5.96	176	58K	818862	8194769	33
Sesivi	R05-102	HRW	concrete	ci	4.4	6.69	177	58K	818853	8194774	33
Sesivi	R05-103	HRW	concrete	ci	4.2	6.91	178	58K	818875	8194778	35
Bakmir	R05-105	HRW	concrete	ci, r, p	4.0	6.59	180	58K	819920	8194757	45
Bakmir	R05-106	HRW	concrete	ci, r	3.9	6.63	181&182	58K	819948	8194729	43
Bakmir	R05-107	HRW	concrete	ci, r	4.1	6.6	183	58K	819932	8194789	45
Bakmir	R05-108	HRW	concrete	ci	4.2	6.97	184	58K	819844	8194453	40
Bakmir	R05-109	HRW	concrete	ci	4.4	7.07	184	58K	819844	8194453	40
Lalinda Presbyterian	R05-113	pipe	n/a	n/a	1.8	6.98	184	58K	819844	8194453	40
Lalinda SDA	R05-114	HRW	concrete	ci	5.6	6.18	185	59K	185431	8191052	24
Lalinda SDA	R05-115	pipe	n/a	n/a	2.1	7.16	186	59K	185515	8191042	26
Lalinda SDA	R05-116	HRW	concrete	ci	2.1	7.25	187	59K	185545	8191014	26

Port Vato	R05-117	HRW	concrete	ci, p	5.6	4.71	188	59K	183680	8191768	25
Port Vato	R05-118	HRW	concrete	ci	5.6	7.38	189	59K	183679	8191748	23
Port Vato	R05-119	HRW	concrete	ci	5.6	5.06	190	59K	183750	8191785	23
Port Vato	R05-120	spring	n/a	n/a	2.4	7.15	191	59K	183699	8191592	14
Port Vato	R05-121	HRW	concrete	ci	5.9	4.91	193	59K	183720	8191842	26
Port Vato	R05-122	HRW	concrete	ci, r	5.4	5.26	194	59K	183682	8191861	24
Port Vato	R05-123	HRW	concrete	ci, r	5.7	5.87	195	59K	183718	8191883	24
Port Vato	R05-124	HRW	concrete	ci, r	6.3	5.88	196&197	59K	183665	8191911	23
Port Vato	R05-125	spring	n/a	n/a	2.8	7.16	198	59K	183537	8191874	10
Port Vato	R05-126	HRW	concrete	ci, p	6.4	5.15	199	59K	183621	8192027	22
Port Vato	R05-127	HRW	fibreglass	ci	3.4	3.62	200	59K	183425	8192420	21
Port Vato	R05-128	HRW	concrete	ci	3.2	6.27	201	59K	183497	8192438	25
Baiap Presbyterian	R05-129	HRW	concrete	ci	4.3	5.27	202	58K	816698	8196778	25
Baiap Presbyterian	R05-130	HRW	concrete	ci	3.8	5.6	203	58K	816657	8196882	26
Baiap Presbyterian	R05-131	HRW	concrete	ci	4.8	6.23	204	58K	816614	8196874	24
Baiap Presbyterian	R05-132	HRW	concrete	ci	3.9	6.09	205	58K	816577	8196932	21
Baiap Presbyterian	R05-133	HRW	concrete	ci	3.7	6.05	206	58K	816559	8196888	22
Baiap Presbyterian	R05-134	HRW	concrete	ci	3.8	5.01	207	58K	816637	8196921	31
Baiap Presbyterian	R05-135	HRW	fibreglass	ci	5.1	3.64	208	58K	816635	8196921	35
Baiap Presbyterian	R05-136	HRW	concrete	ci	3.8	4.75	209	58K	816666	8196903	37
Baiap Presbyterian	R05-137	HRW	concrete	ci	4.1	5.78	210	58K	816689	8196889	35
Baiap Presbyterian	R05-138	HRW	concrete	ci	3.9	5.89	211	58K	816735	8196956	43
Baiap Presbyterian	R05-139	HRW	fibreglass	ci	4.2	3.9	212	58K	816728	8196964	44
Baiap Presbyterian	R05-140	HRW	fibreglass	ci	5.7	3.61	213	58K	816744	8196940	44
Baiap Presbyterian	R05-141	HRW	concrete	ci	4.9	8.58	214	58K	816844	8196975	54
Baiap Presbyterian	R05-142	HRW	concrete	ci	4.9	5.69	215	58K	817224	8196819	69

Lolira	R05-143	HRW	concrete	ci	4.2	6.32	216	58K	815307	8200847	152
Lolira	R05-144	HRW	concrete	ci	4.9	7.25	217	58K	815315	8200852	153
Lolira	R05-145	HRW	concrete	ci	3.9	6.69	218	58K	815341	8200863	100
Lolebulu	R05-146	HRW	concrete	other (tarpaulin)	5.1	6.62	219	58K	815541	8201592	162
Lolebulu	R05-147	HRW	concrete	ci	6.1	7.36	220	58K	815614	8201582	161
Lolebulu	R05-148	HRW	concrete	ci	4.1	6.84	221	58K	815631	8201520	162
Lolebulu	R05-149	HRW	concrete	ci, p	4.0	6.44	222	58K	815594	8201545	160
Lolebulu	R05-150	HRW	concrete	ci, r	4.6	5.75	223	58K	815697	8201588	162
Lolebulu	R05-151	HRW	fibreglass	ci, r	3.6	3.62	224	58K	815705	8201589	163
Lolebulu	R05-152	HRW	concrete	ci, p	4.5	5.33	225	58K	815698	8201565	163
Sanesup SDA	R05-153	HRW	concrete	ci, r	7.8	4.94	226	59K	180698	8192767	18
Sanesup SDA	R05-154	HRW	concrete	ci, r	7.0	6.72	227	59K	180654	8192691	17
Sanesup SDA	R05-155	HRW	concrete	ci	5.7	5.75	228	59K	180748	8192674	18
Sanesup SDA	R05-156	HRW	concrete	ci, r	5.7	6.47	229	59K	180705	8192886	19
Sanesup SDA	R05-158	HRW	concrete	ci, p	1.6	6.9	231	59K	181070	8193034	23
Pelipetakever	R05-159	HRW	concrete	ci, r	6.1	6.99	232	58K	818571	8201875	208
Pelipetakever	R05-160	HRW	concrete	ci	6.1	6.4	233	58K	818605	8201929	209
Pelipetakever	R05-161	HRW	concrete	ci	7.4	6.59	234	58K	818565	8201871	208
Pelipetakever	R05-162	HRW	concrete	ci	8.4	6.34	n/r	58K	n/r	n/r	n/r
Pelipetakever	R05-163	HRW	concrete	ci	9.5	6.88	235	58K	818589	8201847	208
Polimango	R05-165	HRW	concrete	ci, p	6.4	6.71	236	58K	816979	8202040	191
Polimango	R05-166	HRW	concrete	ci, p	4.7	6.5	237	58K	816981	8202041	163
Polimango	R05-168	HRW	concrete	ci	5.0	6.58	238	58K	816664	8202100	150
Polimango	R05-169	HRW	n/r	ci, r	5.2	5.81	239	58K	816582	8202180	149
Polimango	R05-170	HRW	concrete	ci, p	5.8	6.93	240	58K	816401	8202208	151
Valemalemal	R05-173	HRW	n/r	n/r	6.0	6.93	241	58K	816449	8202011	155

Sulol	R05-174	HRW	concrete	ci	4.3	6.56	242	58K	812441	8201011	29
Sulol	R05-175	HRW	concrete	ci	3.4	6.89	243	58K	812395	8201014	23
Sulol	R05-176	HRW	concrete	ci	4.3	n/r	244	58K	812558	8200892	22
Sulol	R05-177	HRW	concrete	ci, p	3.2	6.2	245	58K	812446	8200812	20
Sulol	R05-178	HRW	concrete	ci	3.1	6.45	246	58K	812460	8200819	20
Sulol	R05-179	HRW	concrete	ci	3.5	6.65	247	58K	812431	8200773	12
Non-drinking samples											
Caldera flanks	R05-1	stream			8.6	4.84	31	59K	190440	8196438	615
Ash Plain	R05-2	rainwater			89	2.55	66&67	59K	191370	8197090	744
Caldera flanks	R05-3	rainwater (with ash)			104	2.36	68	59K	191109	8196629	681
Caldera flanks	R05-4	rainwater			100	2.53	69	59K	191054	8196618	681
Caldera flanks	R05-5	rainwater			72	2.51	71	59K	190716	8196596	658
Caldera flanks	R05-6	stream			7.7	4.24	72	59K	190671	8196593	650
Fali	R05-34	rainwater			0.3	6.89	115	58K	812252	8200358	19
Craig Cove	R05-62	rainwater			6.1	3.19	n/r	58K	812479	8200169	n/r
Lalinda Presbyterian	R05-110	rainwater			0.4	6.12	184	58K	819844	8194453	40
Lalinda Presbyterian	R05-112	rainwater			5.3	3.38	184	58K	819844	8194453	40

HRW = harvested rain water
ci = corrugated iron
p = painted
r = rusted

n/r = not recorded
n/a = not applicable

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