The impact on air quality and associated health risks of the emissions of the Tavurvur volcano, Rabaul, Papua New Guinea

An interim final report based on a field visit in April 2008 for the World Health Organization

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Submitted to: WHO, Port Moresby, PNG
Date: 12 August 2008

Executive Summary

A field survey was undertaken in the Rabaul area in April 2008 to evaluate the health risks of the emissions of the Tavurvur volcano. The repeated ash falls were the main concern and common complaints were cough, chest tightness, sinus problems, and irritation of the skin and eyes. We estimated that exposures to PM_{10} in exceedance of WHO air quality guidelines (AQGs) will regularly occur over the six month period of the dry season each year. A comprehensive suite of tests was undertaken on ash samples to determine the toxic potential of the ash for human health. The overall hazard of the ash to the lungs was considered low and the crystalline silica content was 2-5%, mainly in the form of cristobalite. Nevertheless, the mean exposures to the fine, respirable component of the ash would be very high over prolonged periods in the dry season, and such repeated high exposures over 10-20 years could lead to the development of early radiological signs of mixed dust fibrosis in a small proportion of the population. The silica dust could also adversely affect the spread and severity of tuberculosis in the area.

Sulphur dioxide peaks and 24 hour averages were also in exceedance of WHO AQGs and the levels were capable of triggering asthma attacks in asthma sufferers. The condition of some patients in Nonga hospital suffering from acute and chronic respiratory ailments, such as pneumonia, TB, and chronic obstructive pulmonary disease (COPD), could also be adversely affected by the gas (and the high PM_{10} levels) in the ambient air. The exposure to elevated levels of both sulphur dioxide and fine ash on a six-monthly basis for many years could contribute to the development of COPD, especially in smokers. The susceptibility of children to the effects of this type of exposure on the lung is unknown, but it may well be increased in those growing up in the area compared to adults. The emissions lead to the contamination of rain water used for drinking with aluminium and zinc by accelerating the corrosion of galvanized roofs. Rapid corrosion of metal in the area is caused by the combined effects of ash and gas emissions, which also adversely impact on trees, crops and vegetation (WHO critical levels for sulphur dioxide are exceeded).

These preliminary findings show that the air pollution in the Rabaul area is severe by world standards and urgent action is needed to improve the monitoring of the ambient air and the volcano's emissions, as well as to develop mitigation measures. Various recommendations are included in the report, but the findings provide for the first time a basis for policy making and for developing specific preventive health measures.

Introduction

The aim of the WHO mission was to evaluate the health risks of the ash and gas emissions of the Tavurvur volcano, which has been erupting more or less continuously since the cataclysmic sub-plinian event involving both its Tavurvur and Vulcan craters in 1994. Rabaul town was hastily evacuated just before the eruption and many of the buildings were destroyed by the weight of the tephra on their roofs. Rabaul has not regained its original commercial and political position since and a new town was developed at Kokopo. Nevertheless, it continues to function as an important port and there are several major industries located there.

The main area under study is approximately a 180° sector north of Rabaul town, East New Britain, which extends northwards as far as the coast at Tavui point (the Bismarck Sea). The present population of Rabaul town is about 10,000 and the total population in the area affected by the volcanic emissions is about 40,000. The dry season is from May to October, when it may not rain for a month or more at a time; storage tanks run dry and drinking water is harder to obtain. The remainder of the year is the monsoon season when the wind blows the plume towards the south-east out to sea.

The prevailing winds blow the volcanic plume constantly toward the north-west in the dry season when the populated area is affected by ash and gases. On average, about 1-2 mm of ash can fall in Rabaul on many days during these months. For some years the impact of the emissions of volcano on the Rabaul area has caused concern, both for human health and for the fabric of buildings and infrastructure, which are subject to rapid and very destructive metal corrosion. A local government Air Quality Committee was established. In the 2007 dry season the emissions were considered to be particularly severe, when some schools suspended classes and health complaints increased, whilst the destructive effects on vegetation became very marked. In addition, a moderate-sized sub-plinian event occurred at Tavurvur in October 2006, leaving a 2-3 cm deposit of ash which also badly damaged vegetation, including bananas, palm and cocoa bean trees.

The volcanic activity is routinely monitored by the Rabaul Volcano Observatory. There are indications that the activity at Tavurvur may eventually start to decline, but at the time of writing the ash emissions appear to have resumed and vegetation is showing signs of damage as in 2007.

Scope of the report

This report is presented as an interim final report in order to provide WHO and other interested parties with the key results at the earliest opportunity. This is the first time that such a multi-disciplinary study has been undertaken at Rabaul and only the third time that a volcano has been studied with such a detailed analysis of its ash for public health actions (the other two are Mount St Helens, 1980, and Montserrat, West Indies, 1995 – present).

The scale of the analysis had to be extended when the first scanning electron microscope studies of the ash showed the presence of fibres in all the samples collected during the field visit. These fibres were also found in the ash samples from Manam and Langila volcanoes provided by the RVO. The possibility that the fibres had asbestos-like properties (with the potential to cause lung fibrosis, lung cancer and mesothelioma) had to be excluded. We are now confident that they are a fibrous-form of calcium sulphate and they do not have asbestiform properties. Although having the right size and aspect ratio as asbestos they do not show the structure or properties of a harmful fibre; in particular, they are likely to be readily soluble in the lung. More details can be found in the ash report.

Objectives of the work

The field study was undertaken by the writer in April 2008 when he was accompanied by a small team of PNG health professionals. We undertook our survey with the help of the Rabaul Volcano Observatory (RVO) and local government officials. The main aims of the field study were as follows:

1. To collect ash samples for subsequent analysis to measure the crystalline silica content of the ash, the proportion of respirable material present, its biological reactivity and other characteristics that might determine the risk of silicosis and other lung conditions in the exposed population. The work was greatly facilitated at the time by the occurrence of a moderate ash fall over the Rabaul area when fresh ash samples were collected and ambient PM_{10} levels were measured. The RVO also gave us some previous ash samples they had collected.

2. To derive an estimate of the sulphur dioxide concentrations in the ambient air using a passive diffusion tube network. The diffusion tubes were placed at 10 fixed sites representative of the area as a whole and were replaced every two weeks over a 10 week period, the results giving two week averages. These tubes are the same as the ones routinely used in EU countries for fulfilling air monitoring legislation and were pioneered for use on volcanoes by the writer.

3. To obtain a guide to the types of contamination that can occur to stored rain water used for drinking from the effects of the plume and ash. The rainwater is collected on roofs (mainly made of galvanized metal sheets) where contamination can occur from the corrosion caused by the action of ash and gases in the plume fumigating the area. The tanks are made of galvanised iron, Tuffa plastic or ferro-concrete. Stored water samples were collected, although these would give an incomplete picture of the extent of the contamination that would occur when the plume was regularly impacting the study area in the dry season.

Methods and results

Exposure to the volcanic plume was occurring intermittently as the seasonal winds were just beginning to change towards the Rabaul area. Indeed, the variable winds were leading to the disruption of flights from the airport at times and closure of schools in Kokopo. The total number exposed to ash from the volcano at different times of the year as the winds veer around may be as high as a quarter of a million people, when the nearby islands are also included.

1. Volcanic ash samples.

A full and comprehensive report of the analytical work on the ash by Le Blond et al. is attached. The provenance of the samples analysed is given in Table 1 of their report. The X-ray diffraction technique for measuring crystalline silica was developed at the Natural History Museum in London and is in our experience the most reliable method available. Attention is drawn to the ash analysis algorithm (page 6). This is the first time that volcanic ash has been submitted to such a comprehensive suite of tests in such a short length of time. As indicated, several laboratories in the UK and Italy were involved. Advice was also obtained from international experts in volcanology who were familiar with Rabaul volcano.

The main findings are as follows:

1.1. Crystalline silica.

The results of the analyses of 11 samples of Tavurvur and Vulcan ash collected at different times are shown in Table 10 of the report. The crystalline silica is present mainly in the form of cristobalite in the range 2 – 5 wt %. This concentration appears to have not changed since 1994, a conclusion substantiated by X-ray fluorescence analysis (Table 3) and the mineralogical findings of R. Cioni and M. Rosi whose study of Rabaul ash deposits from 1994-2002 showed no change in the magma composition over this period of time (Cioni, personal communication).

A result of 21 wt % obtained in 1999 at a UK laboratory on a single sample of ash dated 21 October 1998 was not confirmed: we now believe this was the result of a laboratory error.

1.2. Respirable fraction.

The dose of silica ash to the lungs depends upon the size, as well as the composition. of the particles. The proportion capable of being inhaled deep into the lungs (the *respirable* fraction with aerodynamic diameter < 4 microns) is about 4-6 wt %. The fraction with grain size < 10 microns (the equivalent of Particulate Matter with aerodynamic diameter of 10 µm or less - PM_{10} - which is the *inhalable* fraction) is around 10-11 wt %, which is comparable with other volcanoes around the world with a similar andecite/dacite magma composition. These results confirm that the ash may present a significant health hazard as it contains abundant numbers of respirable and inhalable particles .

1.3. Particle morphology and composition.

The work to exclude the presence of asbestiform fibres mentioned previously is shown in detail in the report. We are highly confident that the fibres are unaltered calcium sulphate and are likely to be soluble in the lungs and are not bio-persistent, as is the case with asbestos fibres. Concern was also raised that the chemical and physical state of the on-going eruption might modify the solubility of the calcium sulphate, such as by forming reactions with silica, but silicon mapping was undertaken to exclude this possibility. The blocky morphology of the larger particles is compatible with a hydro-magmatic eruption. The mixing of magma with sea-water in the hydrothermal system is probably a key feature of the on-going eruption.

1.4. Particle surface area and reactivity.

Ash with a high surface area and raised surface reactivity (e.g., due to the presence of abundant free radicles) would have greater potential to trigger pathological inflammation in the cells lining the airways and in the alveoli (small air sacs of the lungs). However, the Tavurvur ash did not show much evidence of surface reactivity and the surface area is not very different from that found in a standard suite of ash samples from other volcanoes

1.5. Particle oxidative capacity.

There are a number of tests that can measure oxidative capacity and are being used for research purposes in studies of particles found in the polluted air of cities. The measure reflects the potential of the ash to cause acute respiratory symptoms and involves testing the ash in a solution of artificial lung fluid. The result in the particular test system used was negative.

1.6. Leachate analysis.

This is a test of the soluble components of the ash which become liberated when the ash is in contact with water. They are mostly substances adsorbed on to the ash from gases in the plume. P. Delmelle's report (page 50) shows the expected concentrations of these substances in rain water. Calcium and sulphate concentrations were raised, as were the sodium and chloride levels. The concentrations of potentially toxic metals were not elevated. However, the leachable fluoride was found to be five times higher if the ash was mixed with hydrochloric acid. This indicates a possible risk of low level fluoride contamination of drinking water if it became mixed with large quantities of ash. More importantly for the environment and air pollution, the result means that low, but significant, amounts of hydrogen fluoride gas is present in the plume. The results are also relevant as far as the corrosion of metals is concerned (see discussion below).

1.7. Volcanic ash levels in the ambient air.

On 10 April the wind, which had been blowing in different directions away from Rabaul, began to blow in a north-west direction and the ash-laden plume went over the main commercial part of Rabaul town, including the market place. The ash fall started at around 1045 and the writer stood taking 15 min measurements of the particle concentrations (PM_{10}) in the ambient air in real time around the market and main shopping area as the ash fell and left a deposit of 1-2 mm. The ash fell in pin-point aggregates which broke up into fine particles. The mean levels were in the range 211 – 406 $\mu g/m^3$ with a maximum of 1.2 mg/m^3. Two days later, in dry conditions, the market and main shopping area was busy leading to obvious resuspension of ash by cars and human activity. The PM_{10} levels were elevated with means of 194 – 237 $\mu g/m^3$ and maximum 2 mg/m^3. In contrast, the readings in unpolluted air would be below 30 $\mu g/m^3$. These findings confirmed the fine nature of the ash and the hazard it posed to health from inhalation; they resembled ambient air PM_{10} in Montserrat under dry conditions after an ash fall. Additional DustTrak readings were obtained at other locations and these confirmed this general picture, with most readings between 9 – 14 April showing elevated background levels of PM_{10} in the air at different locations and various times of the day.

2. Ambient levels of sulphur dioxide: the diffusion tube network and air quality.

The results are given in the attached report from Harwell Scientifics which shows the results of readings using 50 tubes from 15 April to 27 June 2008. The tubes were changed every two weeks by the RVO and sent to the UK for analysis.

2.1. Background.

The volcanic plume is likely to contain a mixture of the main volcanic gases, water vapour, carbon dioxide, sulphur dioxide (SO_2), hydrogen chloride, hydrogen sulphide and lesser amounts of hydrogen fluoride. Abundant acid aerosols can be vented with these gases. The most important of the gases for public health at Rabaul is SO_2 as this gas is capable of triggering asthma attacks in susceptible people at even very low concentrations. Although we do not have an analysis of the composition of the gas plume available, by measuring SO_2 we can gain an important understanding of the main health impact of the gas pollution. However, only measuring SO_2 does mean that the additive irritant effects of the other gases and aerosols are ignored and so the total impact of the plume on respiratory health is underestimated, but probably by only a small margin for present purposes.

2.2. The network locations.

A network of 10 sites was established in key places in the path of the plume when it is being blown to the north-west. These comprised open spaces at five schools, a clinic, the Nonga hospital, the Roman Catholic Church in Matupit, and the Rabaul Volcano Observatory, as well as a site close to the volcano (Rapindik). The dense vegetation in the area is an excellent sink for SO_2 and other volcanic gases, but raised values were still found.

2.3. SO_2 network results.

For the first month of monitoring the levels of SO_2 were only slightly raised above background (mean 17 ppb), but for the remainder of the monitoring period the values rose over five fold, showing the difference as the prevailing winds became more constant. The mean value at all sites was 94 ppb, with the highest average values at the RVO (145 ppb), Nonga Hospital (164 ppb), Rabaul Clinic (162 ppb) and Tavui primary school (169 ppb). These sites appear to lie in a line along the main axis of the plume. These results are in excess of WHO guideline values for this gas (WHO, 2006) and being averages they conceal the peak and trough concentrations as the plume changes direction with the wind. The peaks are of special significance for SO_2 as attacks of asthma are triggered in asthma sufferers within minutes of brief exposures exceeding 400 ppb. Excursions of the SO_2 concentration above 400 ppm are likely to be occurring on a regular basis judging by the mean values. Those most at risk would be the more susceptible asthma sufferers and certain adults or children with pre-existing acute or chronic respiratory conditions. Adverse effects would also be of particular concern at the Nonga Hospital, where in-patients are treated for a wide variety of respiratory illnesses, including advanced tuberculosis and pneumonia in infants and children.

2.4. Comparison with WHO Guidelines for short term exposures (WHO, 2006).

The diffusion tube measurements over two weeks are not directly comparable with WHO guideline values for 10-minute or 24 hour averages, but they are most likely to reflect the latter (20 µg/m³, 10 ppb). Clearly, this value is much lower than the above measured values. The WHO guideline value over 10 minutes is 500 µg/m³ (200 ppb), but as already mentioned the two–week averaging period will conceal many occasions when this WHO value will be exceeded. Thus, we conclude that the WHO short-term guideline values are, on a daily basis, being exceeded by a substantial margin in the study area.

3. Radon gas.

We have begun investigating the risk of radon emissions from Tavurvur. Previous studies by the isotope chemist Dr H. Scott Cunningham of MacQuarie University, Australia, have shown that Tavurvur could be a powerful emitter of radon gas. The analysis by Scott Cunningham of radioactivity on the ash in the form of 210polonium, a radon daughter, was sent to a radiation expert, Dr M. Bailey of the Health Protection Agency, UK, who estimated from this an annual dose to a person living in the Rabaul area. The *effective dose* was a few micro-Sieverts, which is too small to give any significant risk of lung cancer. Further work is needed to measure other radon daughters on the ash, as well as the contribution of the radon gas in the ambient air contaminated by the plume.

3. The impact of volcanic ash and gases on drinking water quality.

3.1. Water sample collection.

Twenty eight water samples were taken from storage tanks at the RVO, schools, houses, and two wells and two bore holes (the Rabaul town water supply, Nonga hospital and Volavolo school, both on the same supply). The analyses were undertaken by the Health and Safety Laboratories in the UK (see attachment), which has a pre-eminent occupational toxicology laboratory working under quality control schemes. A standard suite of toxic metals and other cations were analysed for, and the results were compared with the WHO Guidelines for drinking-water quality (WHO, 1996).

3.2. Main results.

The main abnormal findings relate, as expected, to the zinc and aluminium levels in the water, which would be raised if the galvanized metal roofs and tanks were being corroded by a combination of reactive ash and acid gases in rainwater and by dry deposition of gases. The water storage in the 23 houses was in 8 galvanized iron tanks, 7 made of ferro-concrete and 8 Tuffa (plastic). The WHO advisory level (not a health limit) for aluminium of 0.2 mg/L was exceeded in the water of 10 storage tanks. Only one of these was from a galvanized tank, showing that the aluminium was being dissolved from the galvanized roof sheets. For zinc, a WHO level of 3 mg/L based on appearance and taste was exceeded at 5 tanks; all were galvanized tanks except the one with the highest value of 6.6 mg/L, which was made of Tuffa plastic. Zinc levels over 4 mg/L will readily affect the taste of water, imparting an astringent taste, which is probably what people complain most about when drinking the stored rainwater (nausea and vomiting will occur on consumption of more than 500 mg of zinc sulphate). The levels for other toxic metals were within normal limits. The results for the two wells and two bore holes, including the supply to the Nonga hospital and Rabaul Town, were all within WHO acceptable limits.

It is important to emphasise that these results were obtained on water that had been collected before, as well as in some cases, after the light ash fall on 10 April. In other words they reflected corrosion processes which had mainly occurred at least 6 months previously when the plume was last regularly blowing over the study area. They are at least indicative of the contamination problem, and during the continuous ash fall period, higher values would clearly be expected.

4. Reports of ill-health in the affected community.

Since the 1980’s, western diseases like coronary heart disease and diabetes have become more common, but malaria, tuberculosis and pneumonia are still very prevalent in this part of PNG. There are 6-7 new cases of TB admitted every week to the main hospital at Nonga (250 beds). The availability of anti-tuberculosis drugs in the area was limited compared to other parts of PNG and drug compliance was said to be low. Tobacco is grown locally and the majority of adults and young people smoke.

Anecdotal reports on the health effects of the plume in the local population were all that was available in the absence of any surveys or reliable routine health statistics. Doctors were interviewed at Nonga and Kokopo hospitals, head teachers at schools in the Rabaul area and in Kokopo (those which had temporarily closed when they had received recent ash fall), local officials and residents, etc. Everyone we met in the Rabaul area complained bitterly about the nuisance of the ash and how it became intolerable at times, with chest, eye symptoms and skin irritation being commonplace during the dry season.

4.1. Asthma.

All the schools we visited had a similar story of a small percentage of children and teachers becoming badly affected during periods of heavy ash fallout or resuspension, mainly complaining of chest problems, with the affected children being sent home and causing sufficient concern that the school would apply to be closed or to work only half days. The small number of children who were badly affected compared to the hundreds of pupils in each school was compatible with the low prevalence of asthma in PNG, with asthma sufferers being the most susceptible to the irritating effects of the fine ash and the gas on the airways.

4.2. Tuberculosis and other respiratory diseases.

Heavy exposure to dusts containing crystalline silica can reactivate primary tuberculosis (TB) or increase susceptibility to TB infection (Hnizdo and Murray, 1998). Hospital and health clinic statistics are not reliable. However, “discharge” figures for Nonga Hospital (which include clinic cases) do not show any increasing trend for TB, pneumonia (under 5 years and other), or other respiratory diseases during 2003 – 2007. A small number of children with chronic asthma had been permanently removed from the area by their parents to avoid the ash.

Ash continued to interfere with the running of the hospital and the treatment of patients in the monsoon season when it was still about in the environment. Staff and patients complained of breathing problems. One ward had been converted to keep out ash and was used to treat the most ill patients.

At St Mary’s Hospital, Kokopo, medical staff reported a small increase in admissions for acute pneumonia, chest infections and asthma-like conditions during the previous 6 weeks the ash had been blowing intermittently in the area. These doctors also commented that lung cancer was uncommon (despite the high prevalence of smoking).

Implications for health and the environment

As far as we are aware, this is the first health risk assessment of the volcanic emissions undertaken at Rabaul. We cannot exclude that there have been changes in the particle and gas composition of the plume since 1994, for example, through magma mixing, but we consider that the evidence, limited though it is, does not support any radical change that would seriously undermine our tentative conclusions. Clearly, more monitoring data over longer periods would be invaluable to confirm the findings reported here.

5. Implications of the study findings for human health.

5.1. Acute respiratory effects.

The increased levels of ash (PM_{10}) and SO_2 in the area will trigger asthma attacks in asthma sufferers and exacerbate respiratory symptoms in people with chronic lung problems. Pneumonia in sick infants and children would be exacerbated.

5.2. Chronic lung problems.

5.2.1. Mixed dust fibrosis. The crystalline silica content is low (2-5% cristobalite), but warrants concern because of the high exposure to respirable ash particles that occurs on a continual basis in the dry season. The inflammatory potential of the ash in the lungs appears low as far as surface reactivity and surface area is concerned and the state of the cristobalite appears to be in a low reacting form, judging by the negative erythrocyte haemolysis test (page 52) . The health risk, which is probably a low one, is the development of a mixed dust fibrosis, a disease usually seen in workers exposed to dusts containing low concentrations of crystalline silica whose action is modified by accompanying non-fibrogenic dusts. This condition has a better prognosis than silicosis and a lower complication rate of tuberculosis.

5.2.2. Chronic pulmonary disease. The combined irritant effects of SO_2 and the very high exposures to respirable ash particles on a 24 hour basis would potentially promote the development of chronic obstructive pulmonary disease (chronic bronchitis and emphysema), especially in smokers (Mannino and Buist, 2007). The harmful effects on lung growth in children leading to a small, but persistent, decrease in lung function also need to be considered (Gauderman, Avol and Gilliland, 2004).

5.2.3. Lung cancer.

The incidence of lung cancer in the Rabaul – Kokopo area was said to be low, despite the smoking of locally grown tobacco being common. Crystalline silica and radon daughters are recognized as human carcinogens and can cause lung cancer. The carcinogenic effect of exposure to dust containing crystalline silica is small unless associated with the development of silicosis. Radon may also make a small contribution to lung cancer risk at Tavurvur, but further research is needed.

5.3. Respiratory infections.

Susceptibility to TB is enhanced by heavy and prolonged exposure to dusts containing crystalline silica. The mechanism is not fully understood and may involve promoting the spread of infection or a reactivation/exacerbation of pre-existing TB infection. The effect is seen even in the absence of silicosis. Although the cristobalite concentration is low, the high dust concentrations during the dry season are a cause for concern, given that TB is a common and preventable cause of premature death in the area.

5.5. Water quality.

Rainwater collected from roofs readily becomes tainted by aluminium and zinc through the corrosion of the galvanized metal roofs and galvanized tanks. The levels found here are probably the least elevated that can be found and should become higher as the ash fall continues during the dry season. The raised zinc levels found are compatible with an adverse taste as reported by many people and higher levels in the dry season could cause nausea and malaise in children.

6. Implications for the environment.

Subsistence farming is widespread in an area noted for copra and cocoa beans; most people have a plot of land where they grow their own vegetables.

6.1. Vegetation.

The levels of SO_2 exceed WHO critical levels for the impact of this gas on the growth of trees and natural vegetation (7 ppb), as well as agricultural crops (10 ppb); see WHO, 2000. Although these are annual and winter means, they are well below the levels we measured. In addition, the vegetation would be very susceptible to the dry deposition of acid aerosols, as well as the direct effect of hydrogen chloride and hydrogen fluoride gases in the plume. The reported browning of the vegetation in the Rabaul area in 2007, and again in 2008, could be explained by these impacts. Ash can strongly adhere to leaves even after very heavy rainfall, and a fine layer would reduce photosynthesis. The presence of sodium chloride and other chemicals in the leachate, e.g., calcium sulphate, act as cement between the ash particles when they become wetted.

6.2. Corrosion of metal.

One of the major concerns is the corrosion of metals, which is most obvious in the destruction of railings and metal posts supporting power transmission lines. The corrosion is due to the presence of SO_2, water and sodium chloride (and other salts) in the ash leachate, as well as direct fumigation by the acid aerosols and gases in the plume. The corrosion on structures was first remarked on after the 1994 eruption when Rabaul had been destroyed by the tephra fallout (Blong et al., 2003). It was noted then that acid solutions quickly dissolved the zinc/aluminium (Zincalume) coatings and exposed the steel of the galvanized sheets used for roofing. This might help to explain the raised aluminium, as well as zinc, in the drinking water collected from the roofs in our study. Householders commented on how difficult it was to remove all the ash when cleaning their roofs before collecting water from them and vigorous brushing was needed. The tenacity of the ash adhering to defects in the coating layer was observed by the writer after a heavy downpour.

At Nonga hospital, we were told that corrosion affected the air conditioning system, medical instruments, vehicles and the iron fence around the hospital perimeter. Ash had caused power failures and damaged computers.

7. Comparisons with other volcanoes.

Tavurvur is unique in the world in giving rise to elevated exposure in a large population to *both* volcanic ash and gases on a continuous basis for at least six months of the year.

7.1 Soufrière Hills volcano, Montserrat.

The closest comparison to the Rabaul crisis is the Soufrière Hills volcano (SHV), Montserrat, which has been erupting since 1995. The cristobalite concentration is 15 – 25 wt % in the respirable fraction of ash, compared to about 2-5 wt% in the Rabaul ash. . Toxicology studies of ash exposure have included laboratory animal studies and these have shown that the ability of the ash to cause inflammation in the lung is considerably less that the high concentration of cristobalite would normally imply because of the presence of other minerals which modify its toxicity (For a full discussion, see Horwell and Baxter, 2006). This has led experts to consider that the main chronic disease risk from the SHV ash is *mixed dust fibrosis*. Heavy exposure occurred for some months in 1997, but has been less since then, and the risk of mixed dust fibrosis has been formally estimated to be low, and even minimal, if the population and outdoor workers adopt sensible measures to control exposures after heavy ash falls which fortunately now occur infrequently. Unlike at Tavurvur, gases have not been a significant problem, the plume being blown out to sea by strong prevailing winds.

The cristobalite concentration of the Tavurvur ash is substantially lower than that found at SHV, but the exposure of the population to ash is unprecedented at Tavurvur compared to any other volcanic crisis in the world in recent times. The ash fall has been fairly constant in the last two months and there has been no rain. We can estimate from experience at SHV that the mean air concentrations in the commercial area during the daytime in these worst-case conditions would be double the spot readings we obtained last April, i.e., we would expect PM_{10} levels in the range of 0.5 – 1 mg/m³, depending upon wind speeds and human activity, which are the main factors in resuspending the fine ash in the air

7.2. Masaya volcano, Nicaragua

At Rabaul, the SO_2 concentrations are elevated on a daily basis as well, with peaks high enough to trigger acute respiratory attacks in asthma sufferers. A comparable exposure situation is at the Masaya volcano, Nicaragua, where similar levels of SO_2 have been occurring on a regular basis in the past with fumigation of the downwind area leading to the severe stunting of vegetation in a wide zone occupied by about 50,000 people. In 1999 we measured maximum average SO_2 values around 100 ppb in the worst affected populated area within 4 km of the emitting crater using the diffusion tube technique. In contrast to Tavurvur, this volcano has been going through quiet degassing periods over very many years and the plume does not contain large quantities of ash (Delmelle et al., 2002). The health consequences in the local population have not been studied.

7.3. Miyakejima, Japan.

An important degassing eruption has been occurring on Miyakejima, an island located south of Tokyo, since 2000. A large gas plume was produced following a big phreato-magmatic eruption and levels of SO_2 as high as 20 ppm at times were measured in residential areas. The island's population (3,800) was soon evacuated and did not return until 2005 when the gas emissions had fallen.

A very comprehensive scheme of SO_2 monitoring is in place, with 14 stations around the island: a speaker and "traffic light" warning system has been erected along the main road around the island which keeps the population alerted to sudden rises in the ambient gas concentrations as the plume behaviour and direction alters with the wind and weather conditions. The advice triggers actions at increasing levels of SO_2 and in theory people are expected to carry gas masks around with them all day. At 200 ppb (measured over 5 minutes) susceptible people are told to put on masks, and at 400 ppb they are advised to escape from the area. At this level schools in affected areas also close for the half day. Healthy people are advised to wear masks at 2 ppm (2000 ppb) and leave the area at a level of 4 ppm (4000 ppb), though this level has not been measured since the population returned to the island. There are also many public buildings and homes fitted with special filtered ventilation systems. Hydrogen chloride and hydrogen sulphide are also present in the gas plume, especially the former, as at Tavurvur. According to our data, the highest peak (5 minute) exposures to people in the Rabaul area are probably in the 200 – 1000 ppb range (affecting mainly susceptible people only, according to the Japanese scale).

8. Comparison with the health effects of urban air pollution.

The vast amount of literature available on this topic has been well summarised in the Air Quality Guidelines Global Update 2005. WHO, 2006). The effects of increases of PM_{10} in cities on daily cardio-respiratory mortality are well established, but the effects of air pollution by volcanic ash particles and other natural mineral particles (NMP) with a minimal contribution from traffic emissions has not been adequately studied. The conventional approach has been to regard NMP as a major contributor to the coarse fraction of PM_{10} which is regarded as having a lower toxicity than the fine fraction. Using occupational exposure standards for so-called nuisance dusts as the basis for setting an ambient air quality standard for NMP would not incorporate the finding that the volcanic NMP at Rabaul does have a fine and even ultra-fine NMP fraction and occupational standards would also not take into account the people in the community who are most susceptible to air pollution, namely the sick and aged (and children). On the other hand, our studies show that the *bulk* ash samples show little biological reactivity (separation of the PM_{10} fraction is not a routine procedure) and so the potential for the Tavurvur ash to cause inflammation in the lung appears low. With the above caveats, we would recommend using the WHO AQGs for particles, at least as a benchmark.

The WHO air quality guideline (AQG) value for PM_{10} (24 hour mean) is 50µg/m³. WHO interim target levels for developing countries are 150, 100 and 75 µg/m³, which represent approximate increases in mortality over the AQG of 5%, 2,5% and 1.2%, respectively (WHO, 2006). We have no firm evidence that these mortality figures would apply to Rabaul, however.

Both PM_{10} and SO_2, as well as other gases such as ozone and nitrogen oxides, are primary air pollutants in cities. Beijing, China, is one of the most populous and polluted cities in the world: annual averages (2000-2005) were PM_{10} 100 µg/m³ and SO_2 25 ppb. In the Rabaul area, during the half year when the volcano is polluting the air, the mean concentrations are likely to be significantly higher than these values.

9. Indoor solid fuel (biomass) burning.

Cooking using biomass is now recognized as a major contributor to lung disease where it is done indoors and heavily pollutes the indoor air. Fortunately, traditional methods of cooking in houses in the Rabaul area usually include an outside kitchen building either separate or attached to the house, and so such very high exposures do not generally arise. There may be some small fires inside houses at night to keep mosquitoes away.

Conclusions

1. Health impact of volcanic ash.

1.1. Acute effects.

The ash will cause eye, skin and respiratory tract irritation, all of which will be common in the population, manifesting as cough, sore throat, exacerbation of sinus problems, itchy eyes and skin, etc. Single large ash particles may cause corneal abrasions.

In the small percentage of adults and children with asthma, and adults with chronic respiratory problems such as TB or chronic bronchitis, their conditions will be aggravated.

1.2. Chronic effects.

The bulk ash does contain cristobalite at a concentration of 2-5 wt %, which may be slightly higher in the respirable fraction (Baxter and Horwell, 2006). Although the ash does not appear to be very biologically active in our tests, the very high exposures during the dry season are nevertheless cause for concern if they recur on an annual basis for up to 10 - 20 years or more. Early radiological changes of mixed dust fibrosis might become manifest at least in a small percentage of the population. The susceptibility of children growing up in the area is not known, but on a precautionary basis we should regard them as at increased risk. The condition could progress to cause symptoms (e.g., breathing difficulties) in a small proportion of affected individuals.

The crystalline silica in the ash could increase the susceptibility to TB infection and adversely affect the severity of illness due to TB. Since TB is very common in the area and many cases do not receive adequate treatment, the ash could have a small but significant effect on TB mortality.

The ash in combination with other irritants in the plume (the main one being sulphur dioxide) could be a factor in the development of chronic obstructive pulmonary disease (COPD), especially in smokers. In children, there might be a measurable effect on lung growth as shown by lung function testing in an epidemiological survey.

2. Health impact of gases in the plume.

2.1. Acute effects.

A proportion of asthma sufferers (adults and children) will develop asthma attacks during short peaks of exposure to sulphur dioxide, the levels and their frequency depending on the wind direction whilst the plume is over the area. Healthy people are not likely to be affected. Some ill patients at Nonga hospital could also be affected.

2.2. Chronic effects.

As already mentioned, the chronic irritation from the plume over the dry season could be a factor in the development of COPD.

3. Impact of the volcanic plume on drinking water and health.

Corrosion of galvanized sheet roofs by the acids in the plume and the ash will lead to increased levels of zinc and aluminium in the rain water collected from the roofs and stored in tanks. In the dry season the levels may become high enough to affect the taste and colour of the water; the zinc content may even cause nausea if sufficient quantities of the water are consumed.

4. Impact of the plume on the environment.

4.1. Vegetation.

The acid gases and aerosols and the ash (when mixed with rainwater or dew) will damage all types of vegetation in the affected area, including the production of coconuts, cocoa beans and vegetables of all kinds. These may rapidly regrow in the wet season and there may be some resistant species of plant able to flourish in the gas even during the dry season.

4.2. Corrosion.

Metal corrosion will be common and severe due to the combined gaseous and ash components of the plume. This will affect buildings and all manner of articles and equipment.

Recommendations

1. Data needs

The following steps need to be undertaken before the end of the dry season when the plume changes direction:

- Obtain more measurements of exposure to ash: static measures over 12-24 hours using DustTrak instruments and some representative personal measures of exposure using air samplers
- Continue the SO2 diffusion tube network to obtain a more complete picture of the concentrations of gas in the ambient air
- Estimate levels of radon gas and its daughters in the ambient air using alpha track badges left for at least 2 months in key locations.

Additional data requirements in the longer term include:

- Continue monitoring the composition of the erupted ash in case it changes over time
- Provide more effective air monitoring of ash and gases as changes in the emissions may occur over time, including having equipment to monitor SO_2 flux from the volcano
- Consider installing a station with real time SO_2 and PM_{10} monitors in Rabaul
- The incidence of TB and the number of deaths from this condition should be carefully monitored at the hospitals and local clinics.

2. Mitigation actions.

2.1. Infrastructure.

- Consideration has already been given to moving the hospital and schools from the worst affected area; the latter would lead to a significant reduction in the exposure of children to the emissions
- A wide range of measures to combat corrosion, or its effects, should be attempted. Special coatings to reduce the corrosion of galvanized sheets on roofs need further consideration and old galvanized iron water tanks should be replaced with Tuffa tanks.

2.2. Human health.

- Ideally, lightweight high efficiency masks (e.g., FFP2, FFP3, N95 or equivalent) should be available for the population to use during periods of high exposure to ash
- People with chronic lung and heart problems should obtain medical advice on relocating from the area during the dry season
- Water from local bore holes or wells should be made more widely available for drinking during the dry season: more bore holes may be needed
- Guidelines for the treatment of asthma and tuberculosis should be introduced and effective medications made more available
- Information on controlling exposure to ash and other useful advice is available on the International Volcano Health Hazard Network (IVHHN) website and the information should be widely disseminated to the population.

2.3. Future research.

- The effect of the ash on the spread of tuberculosis in the Rabaul area could be studied by a survey of 100-200 schoolchildren heavily exposed to ash and a similar number of control schoolchildren living in Kokopo. A symptom questionnaire, chest X-ray and a blood test for TB infection (T-cell based diagnostic test – ELISPOT) performed for each child would be the minimum requirements for such a survey.

- A chest X-ray-based study of a cohort of children born and brought up in the Rabaul area compared to a control group in Kokopo should be considered. There is very little information on the susceptibility of children to silica dust; its effect on lung growth and the risk of fibrosis.

Acknowledgements

I am immensely grateful for the effort that has gone into the analysis of the Rabaul ash by Jen Le Blond, guided by Claire Horwell. Jen worked full-time for 6 weeks to ensure the analysis was completed. Their collaborators are listed as coauthors to their report, and other contributors in the acknowledgments, and I thank them all for their invaluable work, including Pierre Delmelle for his advice on the ash leachate analysis. Special thanks are also due to Gordon Cressey, Catherine Skinner and Bice Fubini for their advice on the characterization of fibres. Heather Cunningham Scott and Mike Bailey were both generous in giving their time to this project at very short notice: Heather worked on the radioactivity of fresh ash samples and Mike expertly advised on the radiation dose.

I also thank Ken Donaldson, Paul Cullinan, Debbie Jarvis and Ajit Lalvani for helpful discussions on health aspects.

Volcanological advice was gratefully received from Wally Johnson, John Pallister, and Raffaello Cioni; Raffaello also kindly provided us with his unpublished data set on ash deposits at Rabaul.

In Rabaul, my co-workers and field companions were Joel Kolam, Peter Johnson and Patrick Malamut, without whom this study would not have been possible. I also gratefully acknowledge the assistance of the Rabaul Volcano Observatory, in particular Herman Patia, Steve Saunders and Kila Mulina. Local doctors, teachers, health workers, officials, and many residents all willingly assisted in this project. I am indebted to them all.

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