THE HEALTH HAZARDS OF VOLCANOES AND GEOTHERMAL AREAS

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Volcanoes and their eruptions can result in a wide range of health impacts, arguably more varied than in any other kind of natural disaster. At least 500 million people worldwide live within potential exposure range of a volcano that has been active within recorded history. Many volcanic and geothermal regions are densely populated and several are close to major cities, threatening local populations (fig 1). Volcanic activity can also affect areas hundreds or thousands of kilometres away, as a result of airborne dispersion of gases and ash, or even on a hemispheric to global scale due to impacts on climate. Healthcare workers and physicians responding to the needs of volcanic risk management might therefore find themselves involved in scenarios as varied as disaster planning, epidemiological surveillance, treating the injured, or advising on the health hazards associated with long range transport of volcanic emissions.

The 1980 Mount St Helens eruption,[1] which resulted in fallout of ash across large areas of Washington and surrounding states, acted as a major stimulus to research into health hazards associated with volcanoes. This field, which had received little attention previously, now represents a mainstream in volcanological research, and is increasingly being addressed by multidisciplinary efforts with contributions from mineralogy, geochemistry, epidemiology, clinical medicine, toxicology, and healthcare planning, as well as volcanology. The aim of this article is to introduce the health hazards associated with volcanic phenomena and current approaches to risk management.

BASIC GEOLOGY OF VOLCANOES

Volcanoes are chiefly associated with tectonic plate margins.[2 3] The majority of destructive eruptions in history have occurred on continental margins or island arcs where the edge of one tectonic plate drops beneath another (a process known as subduction). Most are recognisably ''volcano-shaped''—tall cones with summit craters—and tend to erupt infrequently but violently. Examples include Mount St Helens (USA), Mount Fuji (Japan), and Pinatubo (Philippines), all belonging to the ''Ring of Fire'' around the Pacific (fig 2). European subduction zone volcanoes include Vesuvius (Italy), whose catastrophic eruption in AD 79 destroyed Pompeii and Herculaneum, and Santorini (Greece), whose massive eruption in the 17th century BC may have contributed to decline of the Minoan civilisation. Volcanoes are also found where tectonic plates are separating, for example, those in the African Rift Valley. Some volcanoes are not related to tectonic plates and instead to deeper seated convective processes occurring within the Earth's mantle. These so-called ''hot spots'' are found in both oceanic and continental regions, and include the volcanoes of Hawai'i and Yellowstone (USA).

Volcanic activity can be broadly defined as either effusive (predominantly quiet emission of lavas, for example, as routinely observed at Kīlauea, Hawai'i) or explosive (for example, the climactic eruption of Pinatubo in 1991).[2] Key influences on eruption style are the quantity and behaviour of the volatiles contained in magma. In very general terms, hotter, less viscous magmas (for example, basalt) allow gas to separate more efficiently, limiting explosivity of eruptions, while cooler, viscous magmas (for example, andesite, dacite, rhyolite) are liable to fragment violently on eruption.[2]

VOLCANIC PHENOMENA AND ASSOCIATED HEALTH HAZARDS

Volcanoes can pose health hazards between, as well as during, eruptions; the intensity or magnitude of an eruption is only loosely associated with the scale of its health impacts. While the history of a volcano's activity (recorded in sequences of lavas, pumice, and ash) gives an indication of potential future behaviour, the type of activity can vary from eruption to eruption. Inter-eruptive periods can be characterised by strong emissions of potentially harmful gases and particles; other hazardous phenomena including volcanic mudflows, debris avalanches, and volcanogenic tsunami can occur following, or unconnected with, eruptions. Table 1 presents a summary of health hazards associated with volcanic phenomena.

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Figure 1 Mount Etna dominating the skyline of Catania, Sicily. Note the plume from the volcano summit (photograph taken in 2001).

A comprehensive review by Witham[4] suggested that 490 volcanic events in the 20th century resulted in human impacts, with 4–6 million people evacuated, made homeless, or otherwise affected. Fatalities occurred in around half of the events, with an estimated total of 80 000–100 000 deaths. The risk of catastrophic human losses from future eruptions is significant given the possibility of much larger eruptions than witnessed in the historic period, the increase in human population, and proximity of major cities worldwide to active volcanoes, including Naples and the capitals of Mexico, Japan, the Philippines, Ecuador, Guatemala, and El Salvador.[2]

Post-eruption famine and epidemics, pyroclastic density currents, mudflows, and volcanogenic tsunamis account for the majority of recorded deaths arising from volcanism.[4] Few deaths have been associated with lava flows, which usually move sufficiently slowly to permit evacuation (though there are exceptions; see table 1). It seems likely that official statistics[4] greatly underestimate morbidity associated with volcanism, particularly from phenomena such as destruction of agricultural land, contamination of water supplies, sustained or sporadic small-scale eruptions, and community exposures to volcanic air pollution.[5]

This article focuses on volcanic phenomena for which recent research is providing new understanding of the specific health hazards involved. Readers are referred to other texts[6] for a discussion of important health impacts associated with diverse kinds of natural disasters that are not specific to volcanic phenomena—such as communicable diseases, exposure due to destruction of shelter, mental health disorders, and famine.

TEPHRA AND ASH FALLS

Tephra is a general term for any fragmentary material originally emitted from volcanoes, while ash refers to tephra particles <2 mm across. Tephra presents several kinds of health hazard: through inhalation and abrasion of skin and conjunctiva, through building collapse from loading on roofs, and through impacts on terrestrial and aquatic environments. Heavy falls of tephra can damage vegetation, including agricultural crops. Tephra also typically carries volatiles scavenged from volcanic gases such as fluorine, emitted in

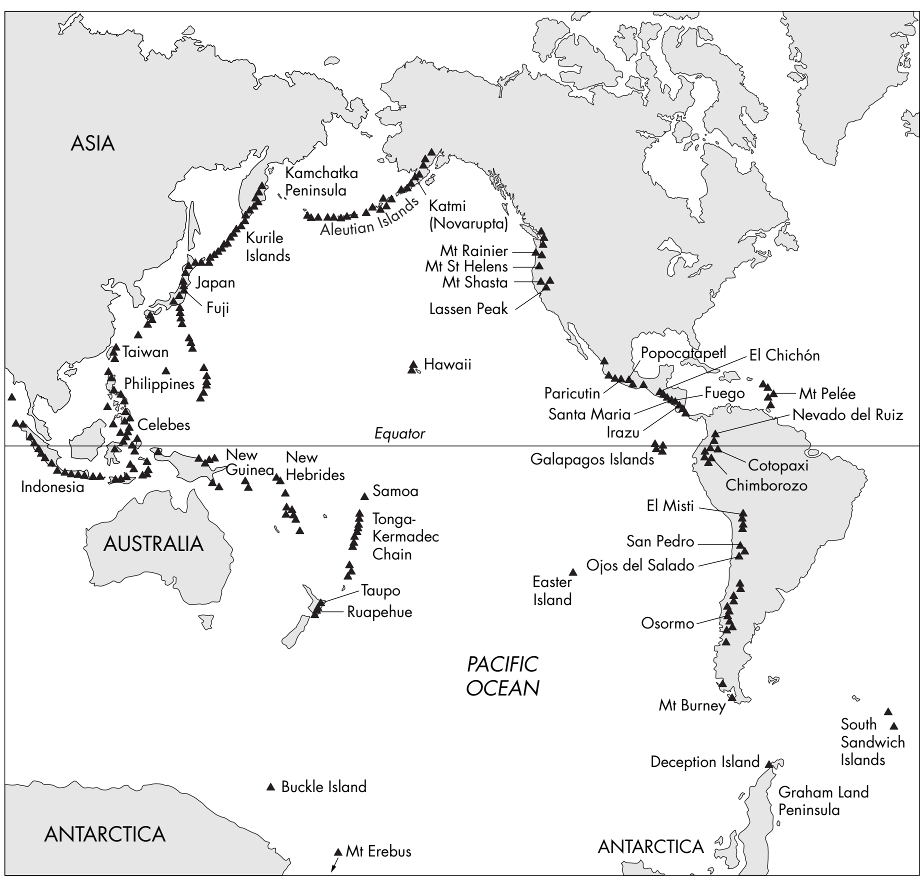

Figure 2 The ''Ring of Fire''; location of volcanoes on the Pacific rim. *Source*: Francis and Oppenheimer, p. 521.[2]

Table 1 Hazards associated with volcanic phenomena (in alphabetical order)

Hazard type	Brief description	Potential health effects	Example
Acid rain	Rain becomes acidic when falling through volcanic gas and acid particle emissions and may dissolve metal roofs	Irritant to eyes, skin. Secondary effects on vegetation, property and water quality. (Rainwater collected from metal roofs may be contaminated with metals such as lead.)	Masaya, Nicaragua, which has been degassing 1986 to present
Ash and tephra	Ash is a collective term for fine pyroclasts (solid fragments <2 mm diameter, ejected from volcanoes). Tehpra is the collective term for solid fragments such as ash or pumice ejected from volcanoes that have fallen to ground from eruption clouds	Airborne ash—respiratory and cardiovascular hazard (asthma, bronchitis, pneumoconiosis). Irritant to eyes and skin	Soufrière Hills, Montserrat 1995–present; Mount St Helens, USA, 1980
		Ash falls—can lead to property damage, contaminate water (e.g. with fluorine carried on ash or by causing turbidity), contaminate or bury agricultural land	Laki, Iceland, 1783–4. Famine
		Mesothelioma risk reported from weathered volcanic ash in certain areas	Biancavilla, Eastern Sicily
Ballistics (bombs, blocks)	Rocks or lava lumps ejected during major and minor eruptions	Impact injuries, burns. Secondary property damage	Galeras, Columbia, 1993
Global climate change	Massive eruptions cause release of acid aerosols and fine ash into the stratosphere, that block sunlight and are associated with global cooling and may accelerate ozone loss	Indirect impact via reduced crop yields	Laki fissure eruption, Iceland 1783; Krakatau eruption, Indonesia 1883
Earthquakes	Earthquakes can be associated with volcanic activity	Property damage resulting in impact injuries. May cause tsunami	El Chichón, Mexico, 1982
Gas and acid particle emissions	Emissions of SO_2, sulphuric acid aerosol, HCl, HF, CO_2, H_2S, radon and other gases may occur in association with eruptions or through degassing activity	Acid gases: bronchoconstriction, aggravation of respiratory disease; eye and skin irritation	Acid gas effects: occupational study of park rangers in Hawai'i Volcanoes National Park (reference Stephenson, 1991 on *OEM* website)
	Soil gas emissions of gases such as CO_2, H_2S, and radon are common in many volcanic areas (radon emissions are problematic only in houses with ground gas diffusion where CO_2 forms a carrier gas)	CO_2: asphyxiation; secondary effects on vegetation, e.g. areas of ''tree-kill''	CO_2: Sinila volcano, Dieng Plateau, Indonesia, 1979,139 deaths. Earthquake released large amounts of CO_2 held under pressure in a hydrothermal system
		H_2S: asphyxiation; low level long term population exposures potentially impacting on respiratory, cardiovascular, and nervous system	H_2S: death in a geothermal power plant worker (reference Kage, 1998 on *OEM* website); population exposures in Rotorua, New Zealand[5]
		Radon: lung cancer risk with long term exposure	No studies specifically in relation to volcanic exposures
Ground deformation	Subsidence and ground cracking	Secondary effects on property and roads	Mount Etna, Italy, 2001
Jökulhlaups	Meltwater flood resulting from a volcanic eruption under a glacier	Those of flooding: drowning and impact injuries. Secondary effects on property and agricultural land	Skeiðaràrsandur, Iceland, 1996
Landslides, debris avalanches and lahars	Debris avalanches are fast moving, gravity driven currents of partially or fully water saturated volcanic debris. If the debris flow consists of a significant fraction of clay sized particles it is called a lahar or mudflow. May be triggered by eruptions, gravity, earthquakes, or heavy rain	Drowning, impact injuries. Secondary damage to property and agricultural land	Nevado del Ruíz/Armero, Columbia 1985. Lahar caused by a small eruption melting snow and ice, resulted in 23 000 deaths
			Mount St Helens, USA, 1980
			Kelut, Java 1966. Hundreds of deaths from lahars caused by eruptive activity destroying a crater lake
Lava flows	Flows of molten rock. May emit acidic gases. Steam explosions may result from contact with groundwater	Usually relatively slow moving, therefore allowing evacuation. Thermal injuries. May cause forest and property fires. Methane explosions can occur as lava moves over vegetation	Nyiragongo, Congo 1977 and 2002 where fast flowing lava resulted in 700 and 170 deaths respectively
Laze	HCl gas clouds resulting from lava entering sea water	Chemical conjunctivitis and respiratory effects	Lava from Pu'u O'o vent, Hawai'i
Lightning in volcanic clouds	Common in volcanic ash clouds related to eruptions	Electrocutio	Paricutín, Mexico, 1943. Three killed
Pyroclastic density currents	Flows of hot ash, gas and rocks, resulting from the effects of gravity on a volcanic eruption cloud	Thermal injury and death. A high death: injuries ratio of 10:1 among exposed individuals	Vesuvius, Italy, AD 79: the major cause of death in Herculaneum and Pompeii; Mont Pelée, Martinique, 1902: 28 600 deaths
Tsunami	Tidal wave from volcanic debris avalanches into oceans or lakes or occasionally volcanogenic earthquakes	Drowning and injuries from property damage	Krakatau, Indonesia 1883: 36 000 deaths in Java and Sumatra

Source: Adapted from Table 18.1, Francis and Oppenheimer.[2]

large quantities in some eruptions. Grazing animals can ingest toxic quantities of fluorine when ash contaminated in this way lies on the ground.[7] Drinking water may also become contaminated by fluorine from tephra, although fluorine poisoning in human populations appears rare.

The eruption of Mount St Helens in 1980 motivated the first systematic epidemiological and toxicological research into health hazards of airborne volcanic ash. Mineralogical studies revealed that the ash contained crystalline silica,[1] raising for the first time the potential for long term risks of ash exposure, such as silicosis and chronic obstructive pulmonary disease (COPD), although risks were judged to be low. Epidemiological studies established that areas with high levels of airborne ash (daily average total suspended particulates (TSP) of 3000–33 000 $\mu g/m^3$) experienced a 2–3-fold increase in hospital admissions and 3–5-fold increase in emergency room visits for respiratory conditions.[8] Follow up of those with pre-existing lung conditions[9] and occupationally exposed loggers[1] reported short term increases in respiratory symptoms that persisted in some individuals for months, probably due to resuspension of loose ash deposits on the ground. A small, short term, reversible decline in lung function was seen in loggers working in the immediate vicinity of the blast zone.[1] Toxicological studies found that Mount St Helens ash acted as an irritant on the airways, leading to an increase in mucous and inflammation.

A review of respiratory health effects of volcanic ash involving one of the authors[10] found 35 studies relating to 11 volcanoes published since the Mount St Helens 1980 eruption, with the most well studied being Sakurajima, Japan, and Soufrière Hills, Montserrat. Comparisons were limited because of varying methodology, differences in ash size and composition, and poorly characterised and differing population exposures due to sheltering behaviour or rainfall inhibiting resuspension of ash. However, the following factors emerged as potentially important predictors of the scale and nature of respiratory effects:

- Concentration and size of the ash particles inhaled, particularly the percentage of finer particles (here <4 μm and <2.5 μm) able to penetrate deeply into the lung, and coarser particles (of 4–10 μm) chiefly impacting on the upper airways
- Mineralogic composition, particularly the free silica content
- Surface properties, especially Fe^{2+} content—higher iron resulting in more free radical generation in toxicological studies, with fresh ash generating more radicals than weathered samples.[11]

Sakurajima, Japan has been in eruption since 1955, affecting a large local population with frequent ash falls. However, the ash particles are mostly non-respirable in size; this is probably the reason that the 12 cross-sectional and ecological studies, mostly published in the 1980s and 1990s, have not shown conclusive impacts on respiratory morbidity or mortality.

Soufrière Hills volcano, Montserrat has been erupting since 1995. Health studies conducted in the last decade illustrate the increasing use of a multidisciplinary approach: detailed toxicological characterisation of ash related to eruption style, improved attempts to define individual exposures, individual level epidemiological studies, and formal risk assessment of long term health risks. Soufrière Hills ash typically contains 13–20% inhalable (<10 μm) particles, but crystalline silica (cristobalite, tridymite, and minor quartz) content of these particles has varied between 10–27 wt% and 4–6 wt%, depending on the style of associated volcanic activity[12] and size of the particles, with smallest particles having the highest concentrations.

Toxicological studies have found the Montserrat ash to be mildly toxic, but less harmful to the lungs than the cristobalite concentration might indicate, with disease causing potential more comparable to mixed coal dusts of moderate toxicity. A risk assessment conducted in 2003 for the UK Department for International Development suggested a risk of developing early radiological changes of silicosis of $>1\%$ for the population in the areas most frequently affected by ash falls given 20 years' exposure. However, gardeners and other outdoor workers were found to have higher ash exposures,[13] resulting in increased risks of 2–3% and up to 10% if their cumulative exposure over 20 years was at the extreme end of the likely range. The future silicosis risk in exposed children is unclear as there are no relevant epidemiological studies available. Two studies of health effects in adults have suggested increased respiratory symptoms, particularly in those with higher exposure to ash, but no clinical study has identified lung abnormalities by *x* ray examination following the first nine years of eruption. An epidemiological study of around 350 children aged under 12 years and still living on the island in 1998,[14] suggested fourfold increases in prevalence of wheeze in the preceding 12 months, and exercise induced bronchospasm (here indicated by a fall in peak flow of 10% or more) in children exposed to higher levels of ash.

Ash clouds are associated with explosive eruptions and can pose a risk to aviation through damage to jet engines and abrasion, for example, of cockpit windows. To date there have been no reported air crashes arising from encounters with volcanic clouds, but there have been several near misses. An International Airways Volcano Watch (IAVW) (http://www.icao.int/icao/en/anb/met/IAVW.htm; last accessed 8 October 2005) responsible for monitoring ash clouds and provision of warnings to the aviation community was established by the International Civil Aviation Organisation (ICAO) in the late 1980s.

PYROCLASTIC DENSITY CURRENTS

One of the major hazards to life associated with volcanic eruptions results from exposure to clouds of hot gas and tephra,[15] variously referred to as pyroclastic flows, pyroclastic surges, nuées ardentes, or grouped by some authors[2] under the term pyroclastic density currents (PDCs). A review by Baxter[15] of contemporary reports of eruptions showed that PDCs have very high dead:injured ratios of 10:1 or greater—much higher than in any other type of natural disaster.

PDCs typically form during collapse of an explosive eruption column (for example, Vesuvius in AD 79) or from gravitational failure of a lava dome (an extrusion of viscous lava at the vent of a volcano such as occurred on thousands of occasions during the eruption of Soufrière Hills volcano). They can be envisaged as hot avalanches of ash, rock, and gases, and can travel at speeds of 350 km/h or more, and reach temperatures of several hundred degrees Celsius. During an eruption of Mont Pelée on Martinique in 1902, PDCs swept into the town of St Pierre at an estimated speed of 160 km/h, resulting in the deaths of 29 000 individuals within minutes, including all but two of the city's population.

The main causes of death are heat induced fulminant shock, asphyxia due to plugs of ash in the airways, thermal lung injury, and deep thickness burns.[16 17] Skeletons of victims found in boat sheds at Herculaneum (killed during the eruption of Vesuvius in AD 79) suggest brief (a few minutes) exposure to temperatures of about 500℃;[16] skull markings suggested boiling of brain tissue. Lower temperature PDCs—around 200–300℃—can result in a characteristic ''pugilistic'' attitude of corpses (limbs flexed, spine extended).[15] This was observed in victims of PDCs from Soufrière Hills volcano 1997 and Vesuvius AD 79 (at Pompeii) but not in relation to the Mount St Helens eruption in 1980. Survivors from PDCs tend to have been exposed to more dilute parts of the current or sheltered in some way, but are at risk of respiratory burns resulting in fatal laryngeal or pulmonary oedema, secondary respiratory infections, and complications of deep thickness skin burns. The transient nature of the exposure to hot ash may result in serious burns to respiratory tract and skin while overlying clothing is undamaged.[15]

Prior evacuation from areas at risk from PDCs is the only recommended way to minimise fatalities, for example through the establishment of exclusion zones during the 1980 Mount St Helens eruption and Soufrière Hills volcano eruptions from 1995 onwards. Sheltering should only be used in an emergency—the few people that have survived PDCs have reported sheltering in closed rooms, followed by opening of windows as soon as the sensation of heat has passed because of choking sensations.[15] Some have survived out in the open, but only right at the margins of the currents.

VOLCANIC LANDSLIDES

Because of their slopes and construction from sometimes poorly consolidated materials (rubbly lavas, loose ash), and through the weakening action of acidic groundwaters, volcanoes are prone to gravitational collapses. These may be triggered by seismic events or heavy rainfalls. Even small volcanic landslides can be devastating in populated areas, and they can occur long after volcanic activity, for example, the landslide triggered by sustained and heavy rainfall at Casita volcano, Nicaragua, in 1998. In such cases, the landslides typically evolve into mudflows (see next section). The major health sequelae are physical injuries related to burial and property destruction. On volcanic islands, the landslides can initiate tsunami if the displaced material flows into the sea.

LAHARS (VOLCANIC MUDFLOWS)

Lahar is an Indonesian word for a flowing mixture of rock debris and water that originates on the slopes of a volcano. They form in a variety of ways, including the rapid melting of snow and ice by hot pyroclastic material, intense rainfall on loose volcanic deposits, breakout of crater lakes, and as a consequence of debris avalanches. They can travel at speeds of 50 km/h or more and run out many tens of kilometres. The lahar arising from the eruption of Nevado del Ruíz in 1985 travelled more than 60 km and resulted in the deaths of an estimated 22 800 people.[2] Of the 1000 or so hospitalised after this event, most had lacerations (69%), penetrating wounds (41%) and fractures (37%),[15] and minor eye lesions, with infections a frequent complication.

VOLATILES: GASES AND PARTICLES

The health effects of volcanic gases have been recently reviewed by two of the authors (CO and AH).[5] Emissions may occur in association with eruptions, but are also common between eruptions at many volcanoes and geothermal areas where they may be vented from the main crater, from fumarole fields, or diffusely through soil. Volatiles emitted include CO and CO_2, SO_2, HCl, HF, H_2S, and radon. Fluxes can be substantial—the annual emissions of SO_2 from Japanese volcanoes are comparable to those of anthropogenic activities in Japan. Volcanoes also emit particles with potential to impact human health, notably sulphate aerosol. Emissions of heavy metals, including lead and mercury, in both gas and particle phase, may also be important.

Components of volatile volcanic emissions have been extensively studied in industrial settings, laboratory human exposure studies, and population studies of anthropogenic air pollutants. However, the extent to which results from anthropogenic air pollutant studies can be directly extrapolated to volcanic emissions is not always clear. For example, some communities on Hawai'i are exposed to acid aerosol referred to as VOG on an ongoing basis—chiefly sulphate aerosol from the volcanic plume from Kilauea—in the absence of other major sources of air pollution. The effects of VOG on children with asthma are currently under study. It is unclear how comparable the scale of effects will be with those from anthropogenic sources—such as the acid summer haze on the eastern seaboard of the USA and Canada, which consists of a mixture of anthropogenic source pollutants including ozone and NO_x. Similar caveats apply to direct extrapolation from industrial studies to populations exposed to volcanic emissions, as populations include sensitive individuals (for example, those with pre-existing disease, the elderly, children) and may exhibit a different spectrum of health effects, or experience effects at much lower levels of exposure than tolerated in occupational settings. Few primary studies have been conducted into health effects of volcanic gases—those that exist are limited in terms of exposure assessment, so the full picture of health effects from volcanic gases is unclear.[5] Most research to date relates to exposures to CO_2, H_2S, and SO_2 from volcanic and geothermal sources.

CO_2 accumulates in topographical depressions, wells, trenches, basements, etc in some volcanic areas and can result in deaths due to asphyxiation. Such deaths have been reported from a range of countries: Furnas, Azores; Vulcano, Lazio and Alban Hills, Italy; Cosigüina, Nicaragua; and Mammoth Mountain, California.[5] Rarely, CO_2 accumulates in deep water in volcanic areas, such as lakes that are well stratified with little mixing or hydrothermal systems. If the water is saturated with CO_2 under pressure, sudden displacement of the water for whatever reason may cause a sudden release of the gas, like opening a bottle of champagne. The resultant cloud of CO_2 is able to flow under gravity, suffocating people and animals in its path with little warning. For example, release of a quarter of a million tonnes of CO_2 triggered by a landslide into Lake Nyos, Cameroon in 1986[18] resulted in 2000 deaths.

Accumulations of H_2S from volcanic and geothermal sources, including faulty geothermal heating systems, have also resulted in fatalities from asphyxiation.[5] Populations in a small number of geothermal areas experience long term exposures to H_2S. This has chiefly been studied in Rotorua in New Zealand,[19] suggesting impacts on the nervous system, and respiratory and cardiovascular disease, compatible with effects seen in acute industrial exposures. However, more work is needed to define exposure-response coefficients for these population exposures.[5]

Studies of health effects of SO_2 and acid aerosols from eruptions and degassing events related to six volcanoes included in a review by Hansell and Oppenheimer[5] provided evidence for increases in respiratory mortality and morbidity (for those with pre-existing disease), but not childhood asthma prevalence or lung function decrements. Some impacts were on a large scale affecting several countries (for example, Laki fissure eruption, 1783–84).[20]

SPECIFIC OCCUPATIONAL HEALTH HAZARDS

Groups of workers at particular risk from volcanological hazards due to the nature of their job include those working in geothermal power plants, geologists, and those involved in volcano tourism or documentary making. Additionally, workers in construction, quarrying, agriculture, and related industries may be exposed to new or ancient deposits of volcanic ash, potentially giving increased risk of silicosis (as described above in Monstserrat) or even asbestosis and mesothelioma (see table 1), depending on the composition of the ash.

Volcanologists and other geologists working in volcanic or geothermal areas may be exposed to any of the hazards mentioned in table 1. Working in the vicinity of fumarole gases (released in otherwise quiescent volcanic and geothermal areas) without wearing a gas mask may result in exposures to gases (for example, SO_2, HF, HCl, H_2S) and gaseous form metals (for example, Al, Hg, Rb, As) that are higher than in occupational settings. Exposure to acidic gases without wearing respiratory protection, especially if repeated frequently, may lead to irritant induced asthma including reactive airways dysfunction syndrome (RADS)—of which there are anecdotal reports. Geothermal steam from geothermal power plants also contains acid gases and heavy metals—a fatality from accumulation of H_2S within an enclosed space in a plant has been reported.[5]

The main problems specific to volcanoes experienced by volcano tourists and those working in volcano tourism are cuts and grazes from falls on sharp volcanic rocks, and respiratory and eye irritation when exposed to fumarole or crater gases. A small number of deaths of visitors to volcanic areas have been reported in different parts of the world following exposures to SO_2 (particularly in those with pre-existing respiratory disease such as asthma) and H_2S. These occur most commonly as a result of ignoring warning signs[5] or when hiking to active lava flows. Volcanic hazards are not always well appreciated—for example, the spectacular clouds produced when hot lava enters the sea (fig 3) are in fact a dense mist of hydrochloric acid. Additionally, second degree burns from waves of lava heated water have been reported in those viewing this spectacular sight from sea.

Figure 3 Tourists observing LAZE (hydrochloric acid mist), formed when lava from Kīlauea on Hawai'i island enters the sea.

OTHER POTENTIAL IMPACTS ON HUMAN HEALTH

Eruptions that discharge more than a few megatonnes of sulphur gases into the atmosphere, have the potential to cause regional to global scale climate change through complex mechanisms. A now well observed and understood phenomenon is the summer cooling and winter warming of Northern Hemisphere continental regions following large, sulphur-rich eruptions of volcanoes in the tropics. The 1815 eruption of Tambora, Sumbawa island, Indonesia, responsible for the greatest recorded fatalities due to volcanic activity,[4] also released sufficient sulphur into the upper atmosphere to result in widespread cooling during the Northern Hemisphere summer in 1816. This has been linked to epidemic disease in Ireland, the UK, and parts of continental Europe through a combination of socioeconomic factors and the effects of the climatological anomalies on crop yields.[21] In the immediately impacted region, an estimated 61 000 people died during and in the aftermath of the eruption, mostly as a result of famine and epidemic disease.

RISK MANAGEMENT

One of the main aims of research assessing and quantifying health risks of volcanoes is to formulate policy on preparations to deal with disasters and on land use planning. *Probabilistic* risk assessment for current and potential future volcanic hazards is a relatively new practice but it is increasingly being used to inform risk management and decision making.[22 23]

Summary

- Major mortality associated with volcanogenic phenomena in recorded history has resulted from pyroclastic density currents (avalanches of hot ash, gases, and rocks), tsunami, landslides, and debris flows.
- Exposure to volcanic ash may result in acute respiratory morbidity, especially in those with pre-existing respiratory disease, but the long term effects are unclear and may vary from volcano to volcano.
- Eruptions of ash and discharges of aerosols and acid gases may be transported long distances (hundreds of kilometres) and cause health effects remote from the volcano concerned.
- Large eruptions can cause global climate change through entrainment of gas and particles into the upper atmosphere.
- An increasingly multidisciplinary approach is being adopted in research into health hazards of volcanoes and improving management of health risks.

Such assessment makes use of information from a variety of sources, for example, studies of the rock record associated with past volcanism, data from volcano monitoring equipment, results of theoretical models, and data on population distribution and building stock. In a few cases, health outcomes have been modelled in terms of probability exceedence curves for morbidity and mortality.[23]

Science based evaluation of risks alone is not enough, as painfully underscored by the Nevado del Ruíz tragedy in 1985 (when the town of Armero that was inundated by lahars had already been identified as at risk, but no concrete action was taken to protect the population). It is now widely acknowledged that systematic development and application of policies, strategies, and practices is essential, and that social and economic policies designed to reduce vulnerability are crucial.[2] Communities, and the officials responsible for their protection, need to appreciate not only the nature of risks, but also the uncertainties in the science underpinning the forecasting of volcanic activity and the effectiveness of actions that may be taken to prevent or mitigate the risks. Practicalities of risk management plans also need to be thought through in advance—for example, for successful evacuation, plans need to encompass communications, transport, lodging, medical care, and protection of assets. As a consequence, public awareness programmes, education, and training are increasingly being undertaken as part of volcanic risk management, for example in the communities threatened by Vesuvius.[2]

Volcanology and volcano monitoring techniques have advanced tremendously in the last 20 years. Volcanologists now have a much clearer understanding of the physics controlling eruptions and the reasons for dramatic switches in volcanic behaviour. There is now tremendous scope for increasing the involvement of health professionals in volcanic risk assessment (for example, in estimating expected health outcomes from different eruption scenarios) and risk reduction, in addition to the more obvious areas of post-disaster medical response.

FURTHER RESOURCES

References to key papers additional to those in this review, books, videos, and websites are provided on the OEM website (http://www.occenvmed.com/supplemental). However, we particularly highlight the International Volcanic Health Hazard Network (IVHHN), which was launched in February 2003 with the aims of facilitating research and disseminating information on the health effects of volcanic emissions. The website (www.ivhhn.org) contains guidelines and information on a number of health topics for both the general public and professionals.

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Additional references are available on the *OEM* website (http://www.occenvmed.com/supplemental)

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REFERENCES

1 **Buist S**, Bernstein R, eds. Health effects of volcanoes: an approach to evaluating the health effects of an environmental hazard. *Am J Public Health (Supplement)* 1986;**76**.

► **The entire supplement is devoted to the Mount St Helens eruption in 1980 and includes sections on disaster planning, mental health effects, as well as a detailed description of the health impacts of the eruption.**

2 **Francis P**, Oppenheimer C. *Volcanoes*, 2nd edn. Oxford: Oxford University Press, 2004.

► **An approachable undergraduate geology textbook, which demystifies the terminology and provides detailed descriptions of the volcanic eruptions referred to in this article. Chapter 18, Reducing volcanic risks, is particularly relevant to a reader from a health background.**

3 **Sigurdsson H**, ed. *Encyclopedia of volcanoes*. San Diego, CA: Academic Press, 2000:1035–43.

► **This book is a comprehensive reference source on volcanoes for the general and scientific reader. There is a chapter on health impacts of eruptions by the leading world expert on health hazards of volcanoes, Dr Peter Baxter, on pages 1035–43.**

4 **Witham CS**. Volcanic disasters and incidents: a new database. *Journal of Volcanology and Geothermal Research* 2005;**148**:191–233.

► **An assessment of human impacts of volcanic phenomena in the 20th century, with arguably more complete and accurate information than might be obtained from the existing CRED EM-DAT disaster database.**

5 **Hansell A**, Oppenheimer C. Health hazards from volcanic gases: a systematic literature review. *Arch Environ Health*. In press.

► **Critical review of all health studies of volcanic gases, including published scientific papers identified from three biomedical and two geological databases, and unpublished reports.**

6 **Noji EK**. *The public health consequences of disasters*. Oxford: Oxford University Press, 1997.

► **The handbook of natural disasters produced by the Centers for Disease Control and Prevention. Chapter 9 on volcanoes is written by Dr Peter Baxter. Other chapters deal with tsunami, earthquakes and weather related events, and features relevant to all disasters including epidemiology and surveillance, environmental health (water, sewage, shelter), communicable disease, mental health, and handling the media.**

7 **Witham CS**, Oppenheimer C, Horwell CJ. Volcanic ash-leachates: a review and recommendations for sampling methods. *Journal of Volcanology and Geothermal Research* 2005;**141**:299–326.

8 **Baxter PJ**, Ing R, Falk H, *et al*. Mount St Helens eruptions, May 18 to June 12, 1980. An overview of the acute health impact. *JAMA* 1981;**246**:2585–9.

9 **Baxter PJ**, Ing R, Falk H, *et al*. Mount St. Helens eruptions: the acute respiratory effects of volcanic ash in a North American community. *Arch Environ Health* 1983;**38**:138–43.

10 **Horwell CJ**, Baxter PJ. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bulletin of Volcanology*. In press.

11 **Horwell CJ**, Fenoglio I, Ragnarsdottir KV, *et al*. Surface reactivity of volcanic ash from the eruption of Soufrière Hills volcano, Montserrat, West Indies with implications for health hazards. *Environ Res* 2003;**93**:202–15.

► **The first paper to consider the importance of surface reactivity and in particular, iron content, of volcanic ash.**

12 **Baxter PJ**, Bonadonna C, Dupree R, *et al*. Cristobalite in volcanic ash of the Soufriere Hills Volcano, Montserrat, British West Indies. *Science* 1999;**283**:1142–5.

13 **Searl A**, Nicholl A, Baxter PJ. Assessment of the exposure of islanders to ash from the Soufrière Hills volcano, Montserrat, British West Indies. *Occup Environ Med* 2002;**59**:523–31.

14 **Forbes L**, Jarvis D, Potts J, *et al*. Volcanic ash and respiratory symptoms in children in the island of Montserrat, British West Indies. *Occup Environ Med* 2003;**60**:207–11.

15 **Baxter PJ**. Medical effects of volcanic eruptions. *Bulletin of Volcanology* 1990;**52**:532–44.

► **One of the first articles to review health impacts of a number of volcanoes from a health perspective.**

16 **Mastrolorenzo G**, Petrone PP, Pagano M, *et al*. Herculaneum victims of Vesuvius in AD79. *Nature* 2001;**410**:769–70.

17 **Weinstein P**, Cook A. Volcanic emissions and health. In: Komatina MM, ed. *Medical geology: effects of geological environments on human health*. Developments in Earth and Environmental Sciences Series. Elsevier Science, 2004.

► **A comprehensive review with a toxicological focus.**

18 **Baxter PJ**, Kapila M, Mfonfu D. Lake Nyos disaster, Cameroon, 1986: the medical effects of large scale emission of carbon dioxide? *BMJ* 1989;**298**:1437–41.
► **An example of how good descriptive epidemiology can be carried out under difficult circumstances in remote and undeveloped areas.**
19 **Bates MN**, Garrett N, Shoemack P. Investigation of health effects of hydrogen sulfide from a geothermal source. *Arch Environ Health* 2002;**57**:405–11.
20 **Witham CS**, Oppenheimer C. Mortality in England during the 1783–4 Laki Craters eruption. *Bulletin of Volcanology* 2004;**67**:15–26.
► **The first attempt to scientifically quantify European impacts of the 18th century Icelandic eruption by the imaginative use of historical mortality and temperature datasets. This illustrates the potential for substantial continental health impacts of large eruptions.**
21 **Oppenheimer C**. Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography* 2003;**27**:230–59.
22 **Newhall CG**, Hoblitt RP. Constructing event trees for volcanic crises. *Bulletin of Volcanology* 2002;**64**:3–20.
23 **Aspinall WP**, Loughlin SC, Michael FV, *et al*. The Montserrat Volcano Observatory: its evolution, organization, role and activities. In: Druitt TH, Kokelaar BP, eds. *The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. London: Geological Society Memoirs, 2002:71–91.

QUESTIONS (SEE ANSWERS ON P 125)

Please indicate whether each statement is true or false.

(1) Terminology and geology
- (a) Jökulhlaups are tsunami resulting from a volcanic eruption
- (b) Tephra refers to fragmentary material emitted from a volcano including volcanic ash
- (c) Volcanic ash refers to particles <10 mm diameter
- (d) Hotter, more fluid magmas like basalt tend to erupt more violently than cooler, less fluid lavas

(2) Volcanogenic hazards
- (a) Lava flows are not one of the major causes of mortality associated with volcanism
- (b) Approximately 10 000 deaths worldwide have been attributed to volcanic activity in the 20th century
- (c) Fatalities occurred in around 50% of recorded volcanic events with human impact in the 20th century
- (d) The capitals of the following Central and Latin American countries are in close proximity to active volcanoes: Belize, Honduras, Columbia

(3) Pyroclastic density currents
- (a) The ratio of dead:injured in those exposed to pyroclastic density currents is usually 1:1
- (b) Survivors of pyroclastic density currents may have serious skin burns under clothing that has no sign of heat damage
- (c) Pyroclastic density currents can generally be outrun
- (d) Sheltering in a closed room with a moist towel over the face is the recommended procedure to minimise fatalities or injuries from a pyroclastic density current

(4) Volcanic ash
- (a) Epidemiological studies of health effects of volcanic ash exposure relating to various volcanoes have suggested increases in asthma prevalence
- (b) Toxicological studies of ash from Soufrière Hills, Montserrat eruptions since 1995 suggest a toxicity comparable to mixed coal dusts of moderate toxicity
- (c) Toxicological studies of ash from Soufrière Hills, Montserrat eruptions can be readily applied to other volcanoes
- (d) The silica content of volcanic ash is unlikely to produce long term health problems

(5) Occupational and other hazards in relation to volcanoes
- (a) Workers at specific risk from volcanic hazards include geothermal power plant workers, geologists, and those involved in volcano tourism
- (b) Death due to accumulation of HF has been reported from a geothermal power plant
- (c) Volcanologists may be at increased risk of irritant induced asthma
- (d) To date there have been two reported air crashes arising from encounters with volcanic clouds