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PART 4: Impact of volcanic processes

Chapter 2.4: Volcanic gas impacts

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Abstract

Volcanic gases can pose a long-term hazard as they may be released during eruptive and non-eruptive periods. Acidic plumes, diffuse degassing, limnic eruptions and release of gases into the troposphere and stratosphere can affect natural and human environments, scaled to eruption size. The components of volcanic emissions that cause the most impact are CO_2, SO_2, H_2S, ^{222}Rn, HCl, HF, and PM.

The consequences of volcanic gases for populations include deaths and impacts on physical and mental health. These depend on the duration of exposure and the concentration of the emissions. Socioeconomic impacts of gas emissions include evacuation of communities and abandonment of properties, damage to the built environment and disruption of tourism and agriculture even far from the degassing areas. Developing comprehensive risk management plans, including early warning systems, public education initiatives, and financial support mechanisms, may enhance community resilience and reduce the economic toll of volcanic gas emissions.

Keywords – Volcanic gases, health, gas hazard, acidic plumes, diffuse degassing, limnic eruptions

Introduction

Volcanic gases play a significant role in eruption dynamics and may have a considerable impact on people, the environment and the climate of the Earth. These gases are often overlooked but may constitute a permanent hazard in volcanic environments, as they can be released during and between eruptions. Volcanoes may actively release gases to the atmosphere through visible plumes and fumaroles as well as by invisible diffuse degassing through the surface [E1, E2]. While the specific composition of the volcanic gases depends on the type of volcano, state of activity and type of degassing, water vapor (H_2O) is the most abundant gas, usually followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2). Other volatiles include hydrogen (H_2), helium (He), hydrogen sulfide (H_2S), nitrogen (N_2), argon (Ar), carbon monoxide (CO), radon (^{222}Rn), methane (CH_4), hydrogen chloride (HCl) and hydrogen fluoride (HF). Volcanic plumes may also be rich in aerosol particulate matter (PM), formed from the conversion of gases to fine aerosol particles through interactions with water, oxygen and sunlight [E3, E4].

Acidic gases (mainly SO_2, H_2S, HCl, and HF) released into the lower troposphere may devastate local ecosystems (soils, vegetation, water bodies), affect downwind communities and be corrosive to buildings and infrastructure (Fig. 1). High CO_2 concentrations can also acidify soils with a significant impact on the local vegetation including forests and crops. Indirect effects, such as famine, may occur and be associated with crop and livestock failure. Beyond the impact on the proximal environment, volcanic eruptions may release large quantities of greenhouse gases into the troposphere or stratosphere, with important impacts on the regional and global climate [E5].

From a health perspective, the most relevant gases are CO_2, SO_2, H_2S, ^{222}Rn, HCl, and HF [1, 2, E6, E7]. These may deteriorate outdoor and indoor air quality and, depending on the type, concentrations and time of exposure, they may pose considerable hazard to the health of humans and animals.

While exposure to volcanic gases is responsible for only a small fraction (less than 1%) of the total fatalities from volcanic eruptions in the last five centuries, there have been major incidents during non-eruptive periods highlighting the insidious nature of this silent hazard. The CO_2 gas clouds released from lakes Monoun and Nyos in the 1980s, in the Cameroon Volcanic Line, dominate the number of fatalities and highlight the hazards related to undetectable diffuse degassing processes [3].

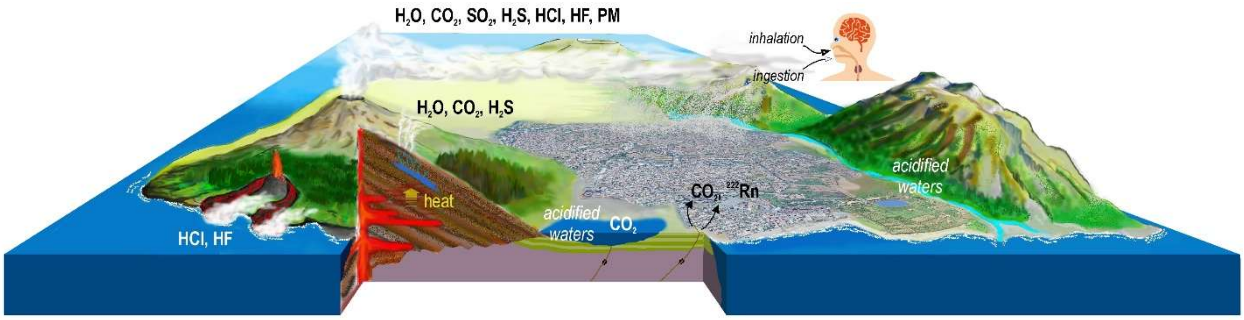

Figure 1 *- Volcanic emissions associated with eruptive and ocean entry plumes, lake overturn, soil and geothermal diffuse degassing, with exposed anthropogenic and natural environments. The scheme refers mainly to the proximal environments of a volcanic system.*

Characterization of hazardous volcanic gases

Sulfur dioxide has a characteristic acrid odor, like a struck match or fireworks, even at low concentrations, and it is a fast-acting respiratory irritant. Asthmatics are particularly sensitive to SO_2, and exposure can worsen symptoms. Close to eruptive vents, high SO_2 concentrations (> 100 ppm) may be extremely hazardous.

Sulfate aerosol is a type of particulate matter (PM) that forms when SO_2 and other volcanic gases react with oxygen, moisture, dust, and sunlight to form solid and liquid SO_4 particles, including sulfuric acid (H_2SO_4) droplets. Aerosol particles can be inhaled and PM exposure is known to be associated with increased risks of respiratory and cardiovascular disease and premature death in urban environments, but it is not currently known whether PM of volcanic origin has the same health effects as other PM.

Hydrogen sulfide emissions are frequently associated with geothermal and low-temperature steaming ground emissions in volcanic areas. H_2S has a distinctive odor like rotten eggs at low concentrations (0.008 to 30 ppm). However, at higher concentrations (> 100 ppm), the sense of smell to H_2S is lost, so odor is not a reliable warning sign. H_2S is a respiratory irritant, but is denser than air and can accumulate to life-threatening concentrations in confined spaces.

Carbon dioxide is an inert asphyxiant present in Earth's atmosphere at approximately 420 ppm (0.042%). As well as being emitted during explosive and effusive eruptions, it is passively emitted from the ground in volcanic and geothermal areas. CO_2 is a colorless and odorless gas denser than air and can accumulate in confined spaces and low-lying areas to life-threatening concentrations, as can H_2S.

Hydrogen chloride and hydrogen fluoride are acidic irritants and usually minor components of volcanic plumes but can cause severe irritation to the skin, eyes, nose, throat and lungs. They can also be generated when lava flows into the ocean, as it reacts with seawater to form acidic steam plumes containing HCl, HF, and volcanic glass particles. The term 'laze' (lava + haze) was coined in Hawaii to describe these plumes.

Radon is released from some volcanic and geothermal areas. It is a radioactive gas produced by the decay of uranium within the Earth. Outdoors it is rapidly diluted by air, but indoors, particularly in confined spaces, it can accumulate to hazardous concentrations.

Volcanic degassing and impacts

The impact of volcanic gas emissions on the environment, human health, and infrastructure varies significantly depending on the type and scale of the emissions. Different degassing regimes contribute to the spatial and temporal scales of the impacts. These regimes include acidic tropospheric plumes, soil diffuse degassing, sudden gas release from lakes, and eruptions releasing SO_2 into the stratosphere [4]. Each of these scenarios poses distinct challenges and hazards; however, all of them may cause health effects. Some components (SO_2 and PM) are common air pollutants, and thus ambient air quality guidelines to protect the most sensitive groups in the community are available. While some other gases such as H_2S, HF and HCl are not common air pollutants, many countries have established occupational guidelines for protecting workers (Table S1, Supplementary material).
Recurrent exposure to volcanic gases and the constant threat of eruptions can cause significant stress and anxiety among affected populations, contributing to mental health issues such as anxiety, depression, and other disorders. There nevertheless is a notable lack of long-term epidemiological studies on the health impacts of prolonged exposure to volcanic gases. While some research indicates potential risks of respiratory and cardiovascular diseases [1,2,5,6], more comprehensive studies are needed to fully understand the long-term health effects.

Acidic tropospheric plumes

Volcanic plumes can contain significant concentrations of acid gases and aerosol PM, impacting downwind communities and ecosystems. These plumes are emitted when magma is degassing at or near the Earth's surface, which can occur both during and between eruptions. Examples include lava effusion and/or other low-explosivity eruptions (e.g., Kīlauea (Hawaii), Reykjanes (Iceland), Tajogaite (La Palma, Spain)); the surface of lava lakes (e.g., Masaya (Nicaragua), Nyiragongo and Nyamulagira (DR Congo)); degassing lava domes (e.g., Soufriere Hills (Montserrat)) and high-temperature fumarole fields (e.g., Vulcano (Italy), Turrialba (Costa Rica).

Notable examples of volcanoes emitting acidic tropospheric plumes include Masaya volcano (Nicaragua), one of the longest-lived sources of an acidic volcanic plume. Its lava lake has been going through phases of on and off degassing at least as far back as written records exist (16th century CE). Its low-altitude summit (560 m a.s.l.) means that the plume is transported close to ground level and disrupts the local communities, with adverse effects for the general population and harmful impacts on cultivated vegetation [7].

The Laki 1783-1784 CE large fissure eruption in Iceland caused significant societal consequences. It is estimated that the impacts of Laki's plume led to the loss of ∼20% of Iceland's population (> 9,000 people) through environmental pollution and famine. Across large parts of the northern hemisphere, the eruption plume impacted visibility and damaged vegetation. It has been suggested that mortality in the UK and mainland Europe also increased [8]. The closest modern analog to the Laki eruption that has been well-studied is the 2014-2015 Holuhraun eruption [9].

Kīlauea (Hawaii, USA) erupts frequently from its summit and rift zones, and a particularly active period beginning in 1983 has significantly impacted local communities [10,11]. It is the best-monitored example of an acidic tropospheric plume and is explored further in **Case Study Box 1**.

The duration and severity of impacts from acidic plumes can be local or regional, depending on the gas emission rate, the length of the activity, and the atmospheric conditions. After emission, the plumes are transported by the prevailing wind, and the gases and PM are gradually deposited through a combination of dry and wet deposition, and scrubbing by rain, snow or other precipitation. Atmospheric lifetimes vary greatly as they are controlled by a complex interaction of atmospheric conditions but the tropospheric lifetime of SO_2 gas is approximately a few days, while sulfate aerosol may last for 1-3 weeks.

The impacts from acidic tropospheric plumes can be subdivided into two interrelated areas, namely:

a) Air pollution and associated health impacts

Acidic tropospheric plumes contain an extremely wide variety of major and trace chemical components because their composition represents unmodified (or only slightly modified) magmatic degassing. Sulfur gas (in particular SO_2) and sulfate aerosol particulate matter (SO_4^{2-}) are the most important airborne hazards for population-scale, longer-term impacts. They have been shown to affect air quality locally as well as hundreds to thousands of kilometers from source [2]. SO_2 gas is a well-researched air pollutant that is monitored and regulated in many countries. Its short-term exposure impacts are well established, but the effects of long-term exposure to low levels are less well understood. SO_2 is particularly problematic for people with pre-existing asthma because it can induce asthma attacks at very low levels. Acidic tropospheric plumes can thus significantly disrupt air quality even very far from the source. For example, a small Icelandic fissure eruption in May 2024 raised SO_2 to >10.42 ppm hourly-mean in Edinburgh (Scotland) at >1,300 km distance, approximately 3 times over the recommended hourly concentration.

Acidic tropospheric plumes are also rich in aerosol PM. Volcanic PM can form a visible haze layer in the troposphere, significantly impacting visibility and diffusing sunlight. Epidemiological studies on PM air pollution have shown strong links between the increased concentration of PM and various health problems, with smaller PM causing stronger negative impacts. While volcanic PM is typically very fine (PM2.5 or PM1) and strongly acidic [2], it is currently unknown whether volcanic PM is as harmful as anthropogenic PM [2].

b) Impacts on terrestrial environments

Acidic tropospheric plumes can impact terrestrial environments (*e.g*. water bodies, soils, and plants) both through acute exposure with near-immediate effects, and chronic exposure over years or decades.

When volcanic plume components are scrubbed by snow or rain, or where PM liquid droplets (*i.e*. sulfuric acid droplets) rain out of the plume directly, the resulting precipitation can be highly acidic (*e.g.* pH 2.5 at Masaya and pH 1.9 at Kīlauea, Hawaii). Acid precipitation predominantly affects local environments but can also have far-reaching impacts, causing crop failures over regions, in particular during larger events like the Laki eruption 1783-1784 (Iceland). Flowering plants and trees typically do not thrive, but grasses tend to be more tolerant. For example, at Masaya volcano (Nicaragua), the vegetation is reduced from a tropical cloud forest to a yellowed scrubland for many kilometers in the prevalent plume direction [7] (Fig. 2). These impacts affect local and national economies, as coffee, an important export product, is very vulnerable to acid rain. Agricultural practices have been adapted: some of the techniques used at Masaya include growing more resistant crops (in particular pineapple and dragon fruit) or using resistant plants (*e.g.* yucca palms) to shield the acid-sensitive coffee plantations. Acid precipitation corrodes infrastructure, in particular metal surfaces. This leads to increased maintenance costs and a reduced lifespan. Adaptation techniques can include regular repainting of structures with corrosion-resistant paints and using more corrosion-resistant materials. Using examples from Masaya, residents report packing away small electrical items after each use; and avoiding using nails in construction by e.g. using ropes and rocks to hold down roofs.

Figure 2. *Masaya volcano (Nicaragua) acidic plume on the left side, and the vegetation altered zone due to the Masaya plume, on the right.*

In some regions, persistently degassing volcanoes can contaminate air, water, soil and vegetation with excess fluoride (F^-). Downwind communities may be exposed to this contaminant via several exposure routes (inhalation, ingestion of water and food, skin contact with soil and inadvertent soil ingestion) [12]. Fluoride concentrations in rain-fed drinking-water supplies are commonly used as a proxy for overall F exposure. Volcanogenic F contamination and increased prevalence of dental fluorosis has been recorded in communities living downwind of Ambrym and Tanna volcanoes, Vanuatu [13]. Fluorosis impacts on livestock have been observed in regions with persistent degassing. We refer readers to the chapters on volcanic ash hazards and impacts [E4, E5, E8] for more extensive coverage of fluorosis in livestock and wild animal populations from ingesting F-rich ash covering their feed.

203 **Case study box 1 - Gas Plumes**: - Kīlauea (USA)

Kīlauea on the Island of Hawaiʻi is one of the most active volcanoes in the world (Fig. 3), and a four-decade period of particularly persistent degassing beginning in 1983 has created a wide variety of impacts on the island.

Figure 3. *Left, the eruption plume from Halemaʻumaʻu crater at the summit of Kīlauea (Hawaii, USA) on 2 June, 2008. Right, acidic laze is formed as lava from Kīlauea lava enters the ocean. Photo credit: U.S. Geological Survey*

Volcanic air pollution, known locally as vog (volcanic smog), became a frequent problem on the Island of Hawaiʻi in 1986, when episodic eruptive activity transitioned to a constant effusion of lava and gas. People downwind of the volcano began reporting a wide range of problems for natural and human environments. The decade-long 2008-2018 summit eruption, and particularly the three-month long 2018 lower East Rift Zone eruption, increased the amount of vog on the island significantly.

The acidic hazy mixture of SO_2 gas, sulfuric acid droplets, and other sulfate (SO_4) compounds that comprise vog, affects plants, agriculture, visibility, water quality, human health, and accelerates metal corrosion on the island. When lava flows into the Pacific Ocean, it reacts with seawater to create large steam plumes laden with hydrochloric acid (HCl), lesser amounts of hydrofluoric acid (HF), and volcanic glass particles. The HCl-rich ocean plumes pose a hazard for people in the immediate vicinity, while the sulfur-rich vog formed from the eruption plumes can impact environments hundreds to thousands of kilometers downwind. Emissions from Kīlauea have a regional impact on climate, influencing trade-wind cloud amounts and properties, and reducing rainfall far downwind of Hawaii. HF gas, a minor component of Kīlauea volcano's eruption plumes, caused symptoms of fluoride toxicity in livestock in downwind ranches during the 2008 summit eruption. Human health research shows that vog exposure is associated with an increase in upper respiratory symptoms (eye and throat irritation, cough, runny nose), headache, breathing problems, and difficulty in managing pre-existing asthma [18]. One extensive study [19] showed that the prevalence of asthma or bronchitis in children was not associated with vog exposure, although there was an increase in reported cough. In the late 1980's, elevated levels of lead, copper and zinc were found in drinking water from downwind water catchment systems due to acid rain leaching these metals from roofing and plumbing materials. Some residents of these homes had elevated blood lead levels, which prompted an island-wide effort to remove lead-bearing materials from rainwater catchment systems. While the long-term effects of vog exposure are still under study, acute exposures have resulted in 6 deaths between 1992 and 2002, with volcanic gases identified as a contributing factor. These included three heart-attack deaths with or without pre-existing cardiac or respiratory conditions; two deaths due to pulmonary edema at the ocean entry; and one death due to asthma in an area of sulfur-rich plume.

A variety of mitigation strategies have been employed in Hawaii to lessen the impact of vog. These include: a vog forecast model that calculates near-surface volcanic SO_2 and SO_4 concentrations and probabilities for the public; an Interagency Vog Dashboard that provides comprehensive information on vog data and research [20]; ranchers using alternative materials to minimize rapid corrosion of fencing and infrastructure, and relocating or feeding supplements to livestock to minimize effects of ingesting excess sulfur and fluoride; use of air purification systems at the Volcanoes National Park Visitor Centers and a nearby hospital and gymnasium; subsidized testing of catchment water for lead and copper; protection of sensitive school children by relocating to indoor areas with air handling systems during vog events.

Plumes can also contain high concentrations of metal pollutants (*e.g*. lead, zinc, arsenic, cadmium) and emission rates can reach levels comparable to anthropogenic fluxes from industrial emitters [11]. Near persistently degassing volcanoes, elevated levels of metals have been reported in air, soils, surface waters, and plants; there are common exposure sources for humans, especially in areas where communities consume catchment or surface water and locally grown crops. Furthermore, acidified rainfall can leach lead from plumbing fittings or roofing materials into roof catchment rainwater tanks. It has not been conclusively established whether volcanic metal air pollutants lead to health impacts through chronic exposures, and more studies would be needed for conclusive determinations.

Diffuse degassing

Diffuse degassing refers to the permanent and less perceptible degassing that occurs at the surface of volcanoes and preferentially through faults and fractures. These emissions are dominated by CO_2 that may persist for long periods between and during eruptions, and that can be released from extinct volcanoes even after tens of thousands of years. Radon is also commonly detected in diffuse degassing areas, and H_2S is sometimes released associated with fractures and vents. Denser than air at atmospheric conditions, these gases may accumulate in hazardous concentrations in underground structures (such as basements) or topographic lows (*e.g.* depressions, pits). CO_2 acts as an inert asphyxiant and can lead to sudden unconsciousness and death from acute hypoxia, severe acidosis, and respiratory paralysis. Lethal indoor and outdoor CO_2 concentrations have been measured mainly associated with quiescent volcanic areas, such as Colli Alban (Italy), La Fossa caldera (Aeolian Islands, Italy), Furnas and Fogo (Azores, Portugal), Methana (Greece), Massif Central (France), Mammoth Mountain (USA), and Cumbre Vieja (Canary Islands, Spain) (**Case Study Box 2**). Thus, diffuse CO_2 emissions are a permanent and silent hazard even during non-erupting periods. Diffuse degassing may be highly affected by meteorological factors, such as barometric pressure, wind speed, rainfall, and air temperature [14]. Both indoor and outdoor volcanic gases may reach lethal concentrations solely due to changes in the weather conditions, as has occurred in the Azores and Canary Islands, Mammoth Mountain or Colli Albani. High indoor CO_2 concentrations have been responsible for the forced evacuation of residents from several buildings in villages in the Azores, Aeolian and Canary Islands and at Colli Albani [5,14]. The hazardous indoor levels make the buildings non-habitable, and residents need to be relocated with the consequent impact on the community. High indoor ^{222}Rn concentrations can result not only from the soil gases entering buildings through piping systems and/or fractures/cracks in the pavement or walls, but also released by the building materials and/or by tap water. Anomalous ^{222}Rn and CO_2 are often associated, for example at Colli Albani, Cumbre Vieja or Furnas volcanoes.

Case study box 2 - Diffuse degassing: Cumbre Vieja (La Palma, Canary Islands, Spain)

Post-eruptive soil CO_2 anomalies associated with the 2021 Tajogaite eruption of the Cumbre Vieja volcano (La Palma, Canary Islands) disrupted the inhabited areas of Puerto Naos and La Bombilla, from late 2021 to mid-2024, the date on which most of the 1,500 inhabitants of Puerto Naos were allowed to return home. These areas are also some of the most heavily visited tourist sites on the island, and hotels and other facilities were closed.

Lethal indoor and outdoor CO_2 concentrations were measured at human breathing height in these areas located about 5 km from the erupting vents. Hazardous indoor CO_2 concentrations have been measured not only in basements and subterraneous structures but also on higher floors.

Anomalous concentrations of volcanic-hydrothermal CO_2 have appeared in inhabited and cultivated areas. Approximately 70% CO_2 was measured in the outdoor environment (CO_2 IDLH - Immediately Dangerous to Life or Health - is 4%) during the post-eruption period from June 2022 to June 2024 in a banana plantation of approximately 4,200 m^2. The banana plants withered and terrestrial and aerial fauna (including cats, mice, birds, lizards, insects) constantly appeared dead due to CO_2 inhalation (Fig. 4).

Figure 4. *Fauna found dead on a banana plantation affected by the high CO_2 emissions in La Palma (Spain). On the left, three dead birds, and on the right, a decomposing cat and bird.*

No visible emanations or thermal anomalies have been recognized in La Bombilla and Puerto Naos areas. Nevertheless, high ^{222}Rn emissions have also been detected. The carbon isotopic composition of the released CO_2 confirmed its volcanic origin and association with the Tajogaite eruption. Air $\delta^{13}C\text{-}CO_2$ values in the outdoor ambient air ranged from -9.0 to -3.2 ‰ vs. VPDB in surveys carried out between 2022 and 2023. Due to the high CO_2 concentrations, the community was relocated, but scientists and authorities faced difficulties in making the population accept evacuation orders, which was potentiated by the actions of some individuals that contradicted official information.

Mitigation strategies have been implemented including a real-time monitoring and early-warning system with the

The temporary evacuation of the population of Vulcano Island during the 2021-2023 unrest that increased diffuse degassing in the inhabited area, showed how these silent gas emissions may impact the population. In this case, the population could access buildings only if accompanied by authorized personnel equipped with CO_2 detectors. The impact on tourism, which is the main economic support of the island, was also significant. It could, however, have been worse if the unrest occurred during the high season.

Structural effects associated with CO_2 degassing in buildings are very few and comprise essentially swelling of floors due to the pressure of soil gases, as reported in Virunga area (DR Congo) and Colli Albani (Italy). For the areas where H_2S is also emitted, in addition to being a health hazard, hydrogen sulfide may cause rapid and unusual deterioration of building materials and metal infrastructure components, for instance at Rotorua (New Zealand) (Fig. 5), Furnas (Portugal), Colli Albani, and Vulcano (Italy).

Figure 5. *Corrosion in geothermal gas environments in Rotorua (New Zealand). The panels on the left are mild steel, whose corrosion rate is fundamental to estimating the service life of steel structures. The panels on the right are copper, widely used in power distribution systems.*

Human fatalities associated with diffuse degassing areas have been reported in Colli Albani, Vulcano, Mammoth Mountain, Hakkoda (Japan) and Rotorua. Cold CO_2 emissions, referred to as *Mazuku* by the local population in the Democratic Republic of the Congo, are implicated in several fatalities reported on the flanks of the active Nyiragongo and Nyamulagira volcanoes [15] (**Case Study Box 3**).

Few epidemiological studies have focused on the health impacts resulting from long-term exposure to CO_2 in volcanic areas. Research carried out in the Azores (Furnas Volcano) reports respiratory restrictions and chronic obstructive pulmonary disease (COPD) in exposed individuals. At Colli Albani (Italy) recent studies discuss increased risk of mortality associated with cardiovascular diseases and increased emergency room visits for central nervous system diseases [5]. Cohort studies are needed to better explore health effects over time. By contrast, epidemiological studies in Rotorua City, which has the world's largest population exposed to ambient H_2S, have found no association between long-term exposure to this gas and lung function, chronic obstructive pulmonary disease or asthma.

Animals are commonly found dead in diffuse degassing areas, usually in topographic lows or poorly ventilated zones. These vary from insects and rodents to birds and pets, such as cats and dogs. Even large animals such as boars, cows, elephants, lions, hippos, and buffalos have been reported.

High CO_2 concentrations acidify the soils, usually resulting in bare soils. Even if some plants are mofettophilic [16], i.e., well adapted to the presence of anomalously high CO_2 levels in the soil, most of the species do not develop well, or even die. The most studied case occurred in Mammoth

Mountain (USA), where about 50 ha of vegetated area was destroyed in the 1980s-1990s due to increased CO_2 fluxes in the area, probably associated with a magmatic intrusion [17]. Lack of vegetation or even reduction in its diversity, is being now used as an indicator of unrest and contributes to remotely monitor volcanoes. CO_2 also affects microbial diversity, which is usually reduced and dominated by anaerobic and acidophilic microorganisms. Diffuse CO_2 degassing can also lead to biased radiocarbon dating of volcanic deposits since plants assimilate soil CO_2 free of ^{14}C, the plant's $^{14}C/^{12}C$ may be lower than the concurrent atmospheric ratio. This can be interpreted as an apparent older age compared to the plant's actual age, as has been observed in the Furnas (Azores) and Campi Flegrei (Italy) volcanic areas.

Case study box 3 - Diffuse degassing: *Mazuku* sites (DR Congo)

Mazuku, from the Kinyabwisha dialect in the Eastern DR Congo, are CO_2-rich and oxygen-depleted sites in the Virunga Volcanic Province (VVP) where people and animals die from asphyxiation [18]. The effects of high CO_2 concentrations on people (Table S1) are traditionally attributed to evil forces, and thus why these locations are referred to as "devilish wind" or "evil places". *Mazuku* are one of the permanent hazards in the VVP and typically correspond to dry gas vents, usually in depressions or along the lava flow front. As the specific density of CO_2 gas is ~1.5 times greater than that of air, when CO_2 reaches the surface it can accumulate to lethal levels in poorly-ventilated depressions. In most *Mazuku*, CO_2 concentrations are low during the day, especially days with high insolation, and increase to lethal levels during the night, increasing by up to 80% next to the ground. Due to lower ambient temperatures and wind speeds, *Mazuku* are more dangerous at night, in the early morning or evening hours, or after rainfall. *Mazuku* are easily recognized through the presence of black lichen on rocks, vegetation such as reeds and grasses, and dead animals, such as insects, birds, lizards, rats or snakes. Larger dead animals (elephants, lions, hippos, buffalo, and hyenas) have also been found in *Mazuku* of the Virunga National Park. Operating as a natural trap, children have been attracted to these sites by the naturally captured animals. Children are the most vulnerable because of their short stature, and because they frequent the scrublands for firewood collection or livestock grazing. Apart from their high CO_2 concentration, *Mazuku* also provide a false impression of warmer temperatures making them preferential shelter for refugees. Between 1994 and 1996, many Rwandan refugees died sheltering in *Mazuku* not knowing their toxicity.

Goma city and the neighboring villages (~2 million inhabitants) are built on Nyiragongo and Nyamulagira, highly active volcanoes with most of the *Mazuku* being located to the west of Goma, where the city has been extending during the last decade. Over the last three decades, ongoing political unrest in the region has led people seeking greater security and move from their home villages to Goma city. This exodus has dramatically increased the population in and around Goma, thereby increasing exposure to *Mazuku*. Goma is bordered to the south by Lake Kivu, to the north by Nyiragongo volcano and the Virunga National Park, and to the east by the Rwandan border; hence, the west part containing *Mazuku* remains the only place where the city can extend and where newly arriving inhabitants can settle. Presently an estimated 1 million war displaced persons and refugees live in camps located in areas with *Mazuku*, where human deaths due to these gas hazards have been regularly reported.

Mitigation measures consist of regular evaluation of the CO_2 concentrations in known *Mazuku*, and the mapping and delimitation of all new and existing *Mazuku* located near urban zones, especially the refugee and displaced camps.

Limnic eruptions

The sudden release of gases from lakes, also known as limnic eruptions or lake overturns, occur when dissolved gases, primarily CO_2, accumulate in the deep water, and enhanced by water stratification, form a stable layer of gas-rich water. Stratification results from the differences in temperature between the surface and the deep layers, especially during warm periods. Sudden escape of gas from these deep lake waters forms a dense gas cloud that can flow down valleys and into low-lying areas, suffocating humans and animals. These sudden gas bursts were first recognized in the mid-1980s, with the eruptions of Lakes Monoun and Nyos in northwest Cameroon. The first known limnic eruption occurred at Lake Monoun on August 15, 1984. This lake, with a depth of ~ 99 meters and located in the Oku Volcanic Field, underwent the sudden release of CO_2 that resulted in 37 fatalities and deaths of numerous livestock. On August 21, 1986, a large amount of CO_2 suddenly escaped from Lake Nyos, a ~ 200 m deep crater lake, killing approximately 1,700 people and more than 3,000 cattle within a radius of up to 25 kilometers from the lake [3]. Besides the fatalities, survivors reported numerous respiratory symptoms and cutaneous erythema and bullae. Practically no damage was done to plants, crops or inanimate property. Although CO_2 was recognized as the main released gas, the presence of other gases such as H_2S, in minor amounts, cannot be excluded.

The trigger mechanisms for these gas burst releases are still uncertain but include seismic activity, landslides, or meteorological changes (pressure, air temperature) that lead to the mixing of water layers and the release of accumulated gases. Mitigation actions, including piping systems to vent the gas, have been set up in these lakes to prevent the buildup of hazardous CO_2 levels.

Together with the reported incidents, several other volcanic lakes are candidates for the occurrence of limnic eruptions. Lake Kivu, located in the Nyiragongo and Nyamulagira volcanic fields (DR Congo), has a maximum depth of 485 m, and its anoxic (oxygen-poor) deep waters contain ~300 km^3 of CO_2 and 60 km^3 of CH_4. Due to the high hydrostatic pressure, the dissolved gases have accumulated at depth and reached high concentrations that could lead to a limnic eruption, potentially affecting about 5 million people living on the shores of Lake Kivu. Mitigation actions consist of CH_4 extraction for electricity production, reducing gas pressure by removing CO_2 via pipes, monitoring gas accumulation levels, as well as seismicity and ground deformation of the Lake Kivu basin.

Large explosive eruptions releasing SO_2 into the stratosphere

Large explosive eruptions can inject significant amounts of sulfur dioxide (SO_2) into the stratosphere, leading to widespread climatic effects. Notable examples include the 1991 eruption of Mount Pinatubo in the Philippines and the 1982 eruption of El Chichón in Mexico; however, this topic is further discussed in the chapter related to the impact on climate [E5].

Economic consequences

Volcanic gas emissions can lead to substantial economic losses. The evacuation of communities and abandonment of properties impose a significant financial burden on affected regions. The costs associated with mitigation measures, such as remediation strategies (e.g., impermeable membranes, ventilation systems), fire brigade operations, monitoring and alarm systems (**How to box 1**), further exacerbate this burden. These efforts, essential for ensuring public safety, require considerable investment and ongoing maintenance, potentially straining local and national budgets.

➢ "How to" box 1

Setting up monitoring, early warning, and response systems for areas with volcanic emissions

The installation of monitoring networks and alarm systems help manage the access to, or the evacuation from, hazardous zones.

In diffuse degassing areas, where hazardous gases are not visible, monitoring systems are crucial for human safety and are usually the only tools available to reduce the evacuations of the population to a minimum number. Systems installed both indoors and outdoors in the Azores and La Palma islands accomplish this with robust CO_2 detectors coupled with visual and acoustic alarms.

In acidic plume areas, such as Aso volcano (Island of Kyūshū, Japan), tourist-accessible areas may be suddenly restricted by the Aso Volcano Disaster Prevention Council through real-time automated warning lights and announcements in multiple languages. The warnings are issued to protect visitors from increases in volcanic gas concentrations due to changes in wind conditions.

An effective real-time Early Warning System for gas hazard (GH-EWS) should consist of a network of integrated sensors aimed at detecting and automatically providing timely alerts when increased dangerous concentrations of gas occur in indoor or outdoor environments.

Monitoring and early warning systems should be customized based on the type of degassing environment; however, the following is a list of desirable requirements for a robust and reliable GH-EWS.

Before and during the installation:

- Recognize areas of gas exposure with an appropriate level of spatial resolution to account for local gas anomalies. Develop **gas susceptibility/hazard maps** (E3, E4, E8), or identify the hazardous gases and approximate concentrations using monitors, existing measured and modeled data.
- Become familiar with **regulatory and health standards and threshold values** to assess potential risks. Take into consideration that these thresholds usually do not account for the permanent and long-term effects of exposure to low- to mid-concentrations of volcanic gases. Further studies would be welcome for more conclusive determinations.
- Select appropriate **real-time monitoring sensors** for species, range, precision, and robustness based on the environment. It is highly recommended to include sensors for key meteorological parameters, which may influence gas emission and accumulation.
- Select **monitoring locations** based on the measured/modelled data. If indoors, confirm adequate coverage of rooms and floors based on size and usage.
- Select a proper **alarm system and define the alert levels.** This will include the visual and audible alarm equipment (*i.e*. lights and sirens and centralized system management software capable of i) triggering forced air ventilation equipment for confined spaces, ii) automatically detecting system malfunctions, and iii) triggering an emergency power supply in case of power outage.
- Install appropriate **telemetry systems** to send the sensor information to the system management software/data acquisition center.
- **Prepare an emergency plan** and establish roles and responsibilities among all-level authorities (including civil protection) and the scientific community.
- Identify **temporary safety zones** near the areas at risk with the capacity to accommodate individuals if gas hazard escalates. These sites also need to be monitored for air gas concentration.

Follow-up after installation:

- **Quality assurance/quality control** include maintaining a stringent sensor calibration program and testing the alarms and system malfunction warning regularly.
- Perform **alarm drills** and develop a robust **education and awareness program** to ensure that the community, tourists, and authorities follow the action plan if an alarm is triggered.
- Check and **update the emergency plan**, if needed.
- Complement the system with the availability of **first-aid tools** and adequately train personnel for medical emergencies.
- Install **surveillance cameras** when GH-EWS are in public places to ensure equipment security.

Additionally, the disruption of tourism and agricultural activities, which are often vital to local economies, can result in considerable economic downturns. Tourist destinations near active volcanoes where eruptions can be safely observed (*i.e*. Hawaii and Iceland) may actually increase their visitation. However, if visitors perceive safety risks, tourism can experience a sharp decline, leading to losses for businesses reliant on tourism. Agriculture can suffer from reduced productivity due to acid rain damage to crops and farm infrastructure, livestock morbidity and mortality, and soil degradation caused by volcanic emissions. The long-term effects on soil and water quality can impede recovery and reduce agricultural output for years, compounding economic hardships.

The lack of insurance coverage for volcanic gas-related damages is another significant economic impact. Many insurance policies do not cover volcanic gas damage, which can delay recovery efforts and force affected individuals and businesses into financial distress.

- **Mitigation strategies box**

Persistent degassing is frequently overlooked in terms of disaster preparedness, consequently, mitigation strategies are essential to reduce the gas risk and require a comprehensive approach that includes among others monitoring and early-warning systems, policies and legislations, land-use planning, protective measures and infrastructures, health preparedness, and public education and awareness. Regulations and implementation of public policies are essential to reduce the risk and should be implemented in any volcanic area prone to being affected by degassing.

This chapter details several mitigation and adaptation strategies that include measures to protect livestock, crops, water systems, infrastructure and health. For example, the selection of more resistant crops or using corrosion-resistant materials are strategies used to reduce the impacts of volcanic emissions. Systems installed in some lakes to avoid accumulation of gases on the bottom are crucial to allowing communities to live safely in the surroundings. Further strategies include:

- **Real-time monitoring coupled with early warning systems**. These effective systems can be applied to all degassing areas, both indoor and outdoor. This requires the implementation of air quality monitoring networks that provide real-time data. When installed indoors and/or in underground structures, these systems may be coupled to forced automatic ventilation that is activated when gases reach hazardous concentrations.

  These ventilation strategies are within the **protective measures for infrastructures** that we can refer to as "gas-resistant" regulatory codes. Some of these strategies include prohibiting basements or any other subterraneous structure, implementing gas-proof membranes, installing positive-pressure air conditioning, filling potential cracks in the foundations, or using gas-impermeable paints to "gas-proof" the floors and walls of the basements of buildings. These strategies are particularly useful for indoor environments in diffuse degassing areas.

  When gas concentrations are too high and can be harmful to the population, **relocation of residents** from the exposed buildings and/or closing access to hazard zones are the only acceptable strategies to mitigate the risk.

- **Volcanic gas and particle pollution forecasts**. These can alert communities to potential impacts by airborne volcanic emissions. These forecasts use gas emission rate, atmospheric dispersion models and detailed weather prediction systems to forecast near-surface air quality from volcanic gas emissions. Static maps or animations provide real-time information *(continuing Mitigation strategies box)* on the location and possible health risks of volcanic pollutants and can help sensitive individuals plan their activities to minimize risk.

- **Land-use planning**. Development of buildings in high degassing risk zones is likely to result in greater damage. Hazard and risk maps are tools that can be used by the authorities to reduce risk. These maps can be used in considering specific **legislation** for regulating land-use planning as well as the construction codes. Informed land-use planning will significantly reduce the possibility of building in hazardous gas zones and the consequences (economic, health, disruption of the community) of any anomalous gas exposure.
- Providing **Personal Protective Equipment (PPE**) for workers. Authorities, scientists or any other individual involved in crisis management who may be exposed to hazardous gas concentrations should have PPE available, such as gas masks or breathing apparatus to comply with local health and safety regulations. Whenever IDLH (Immediately Dangerous to Life or Health) concentrations are reached, supplied-air breathing equipment generally must be used, however individuals should be trained in their use outside of the hazardous zone. N95-type face masks are recommended for airborne ash but do not protect the wearer from gases. Carrying out **drills** in the anomalous degassing areas is also important, especially to test the response to the warning that may be produced by the alert systems, as well as to train the use of PPE, when applicable. Emergency kits are also important and may include, for example, compressed oxygen cylinders, gas masks, respirators, bottled water, and pharmacological support.
- **Educational and awareness campaigns** are the basis of any mitigation strategy. Educating communities about "good practices" on how to face gas hazards is crucial and ideally starts with young students at schools. Educational campaigns using diverse dissemination channels (*e.g*. booklet, newspapers, social media, TV shows) contribute to increased preparedness and knowledge about volcanic gas risks. Any volcanic area prone to being negatively affected by degassing phenomena should have mitigation actions in place, and these can be augmented by **public policies** and education.
- **Inform the public**. Installing **visible, clear and schematic warning signs** can inform the community about potential hazards and safe practices. This signage should be easily understood since most of the degassing areas are highly frequented by tourists. We suggest that an international icon for volcanic gas hazard could be created that would include all types of gas effects (e.g. toxic, asphyxiant).

Summary

Volcanic gases released both during eruptive and quiet periods may constitute short- or long-term hazards not only locally but also at regional and global scales. The most hazardous emissions (CO_2, SO_2, H_2S, ^{222}Rn, HCl, HF, and PM) may affect not only humans and animals, but also entire ecosystem. Impacts to the human environment include disruption of communities and economic consequences. The combined health and economic impacts underscore the need for more thorough research and robust mitigation strategies to address the multifaceted consequences of volcanic gas emissions on the population and environment.

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