NATURAL HAZARDS AND THE ENVIRONMENT

Bell F.G.
Blyth, Nottinghamshire, United Kingdom

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Summary

Natural geohazards are geological processes that become a hazard when they have an adverse impact on society and its environment, causing destruction of property, and worse, loss of life. The effects of a particular geohazard depend on its magnitude and duration, as well as the vulnerability of the community affected. These hazards may take effect rapidly, with disastrous consequences, or may unfold slowly or even imperceptibly. The latter are unlikely to cause loss of life, but they may be responsible for enormous damage if they affect large developed regions. Spectacular hazards include volcanic activity, especially when it is explosive, large earthquakes, landslides, floods, and marine inundations. Some glacial events, such as the sudden release of water from ice-dammed lakes, may be spectacular but seldom pose a hazard to humans since they usually occur in uninhabited areas.

The occurrence of one geohazard may trigger another: for example, landslides and tsunamis may be triggered by earthquakes. While some geohazards are easier to predict and deal with than others, it is essential to gather as much data as possible, cost permitting, on each if its effects are to be appreciated and counter-measures of some kind taken. Data is also of maximum importance when areas are to be developed or redeveloped, and here hazard zoning and maps play a vital role. Obviously humans cannot control volcanic eruptions or earthquakes, although contingency plans can be made with data gathered from monitoring and investigation, to be put into action when such events are likely to occur. By contrast, measures can be taken to attempt to control areas susceptible to landslides and flooding. Attempts also can be made to control

coastal hazards or to stabilize the movement of sand in arid regions. However, the best way of dealing with areas of potential hazard is to avoid them, and so planning and management are vitally important. Ideally, people should work in harmony with nature and not against it if planning is really to be successful.

Further natural geohazards are associated with the dissolution of rocks, which can lead to the formation of sinkholes, dry valleys, and underground chambers such as are found in limestone terrains. Gypsum and anhydrite are more soluble than limestone. Subsidence may be associated with such rocks. Lastly, gases such as radon and methane can present environmental problems. Radon can pose a health problem, and given concentrations of methane in the air can kill or be explosive.

1. Volcanic Activity

Volcanic eruptions and other manifestations of volcanic activity are variable in type, magnitude, and duration. Volcanic zones are associated with the boundaries of the crustal plates (Figure 1).

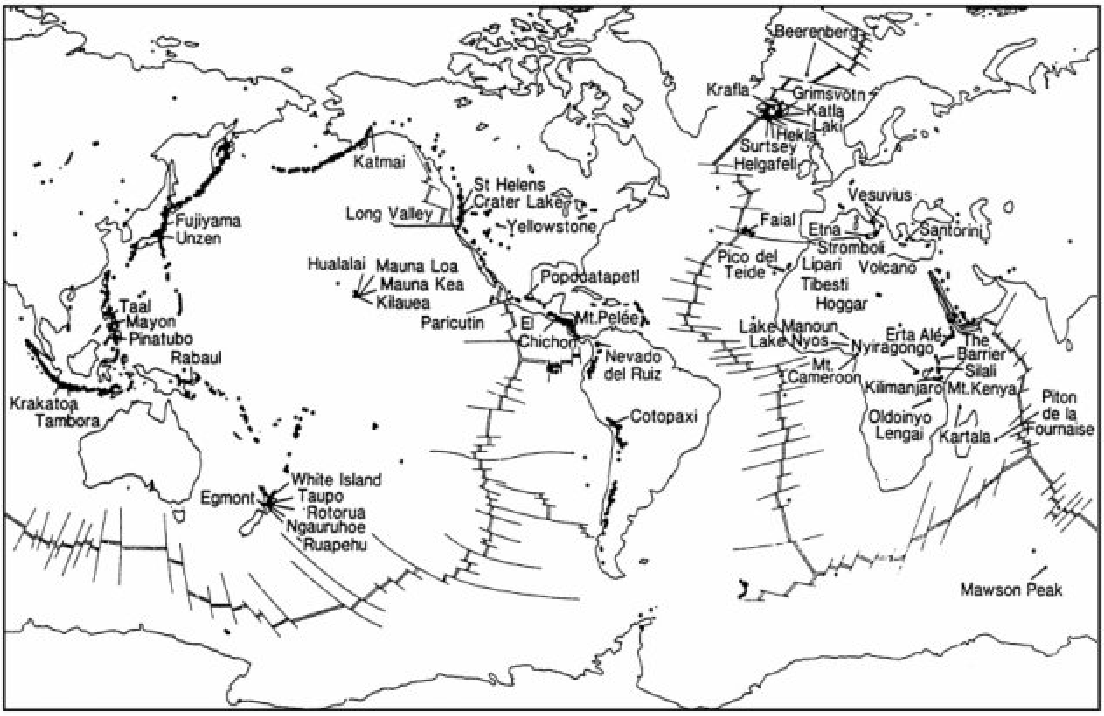

Figure 1. Active volcanoes of the world, showing the plate boundaries

The type of each plate boundary offers some indication of the type of volcano that is likely to develop there. Plates can be largely continental, oceanic, or both oceanic and continental. Oceanic crust is composed of basaltic material whereas continental crust varies from granitic to basaltic in composition. At destructive plate margins, oceanic plates are overridden by continental plates. The descent of the oceanic plate, together with any associated sediments, into zones of higher temperature leads to melting and the formation of magmas. Such magmas vary in composition but some may be comparatively rich in silica. The latter form andesitic magmas and are often responsible for violent eruptions. By contrast, at constructive plate margins, where plates are diverging, the associated volcanic activity is a consequence of magma formation in the upper mantle. This magma is of basaltic composition, which is less viscous than andesitic magma. Hence, there is relatively little explosive activity and associated lava flows are more mobile. However certain volcanoes, for example those of the Hawaiian Islands, are located in the centers of plates. Obviously, these volcanoes are totally unrelated to plate boundaries. They owe their origins to hot spots in the mantle that have "burnt" holes through the overlying plates as they moved over them.

When volcanic activity occurs in areas of high population density, it poses various kinds of hazard to the people living in the vicinity. It is impossible to restrict people from all hazardous areas around volcanoes, especially those that are active only intermittently. Hence, it is important to recognize the various types of hazard that may occur in order to prevent or militate against disasters. Ten percent of the population of the world live on or near potentially active volcanoes, at least 91 of which are in high-risk areas (42 in Southeast Asia and the western Pacific, 42 in the Americas, and 7 in Europe and Africa). An eruption, or the precarious conditions that it creates, may continue for months, and therefore volcanic emergencies are often long-lasting in comparison with other sudden-impact natural disasters. Nonetheless, most dangerous volcanic phenomena happen very quickly. For instance, the time interval between the beginning of an eruption and the appearance of the first nuées ardentes may be only a matter of hours.

In any assessment of risk due to volcanic activity the number of lives at stake, the capital value of property threatened, and the productive capacity of the area concerned all have to be taken into account. Evacuation from danger areas is possible if enough time is available, but the vulnerability of property is often close to 100% in the case of the most violent volcanic eruptions. Hazard must also be taken into account in such an assessment. This is a complex function of the probability of eruptions of various intensities at a given volcano, and of the location of the site in question with respect to the volcano. Hazard is the most difficult of factors to estimate, mainly because violent eruptions are rare events about which there are insufficient observational data for effective analysis. For example, in the case of many volcanoes, large eruptions occur at intervals of hundreds or thousands of years. Thorough stratigraphic study and dating of volcanic deposits will help to provide the evidence needed to calculate the risk factors of such volcanoes. Because in the foreseeable future humans are unlikely to influence the degree of hazard, the reduction of risk can only be achieved by reducing the exposure of life and property to volcanic hazards. This can be assessed by balancing the loss of income resulting from nonexploitation of a particular area against the risk of loss in the event of an eruption.

There are several categories of hazard, namely premonitory earthquakes, pyroclast falls, lateral blasts, pyroclast flows and surges, lava flows, structural collapse, and associated hazards. Each type represents a specific phase of activity during a major eruptive cycle of a polygenetic volcano, and may occur singly or in combination with other types. Damage resulting from volcano-seismic activity is rare, but intensities on the Mercalli scale varying from 6 to 9 have been recorded over limited areas.

Pyroclastic fall deposits may consist of bombs, scoria, lapilli, pumice, dense lithic material, crystals, or any combination of these. There are, on average, about 60 pyroclast or tephra falls per century that are of social importance. In violent eruptions, intense falls of ash interrupt human activities and cause serious damage. The size of the area affected by pyroclastic falls depends on the amount of material ejected and the height to which it is thrown, as well as the wind speed and direction. They can affect areas several tens of kilometers from a volcano within a few hours of the commencement of an eruption. For example, the ash cloud associated with the Mount St Helens eruption in 1980 traveled 400 km downwind in the first six hours after the eruption. During the eruption darkness occurred within 390 km of the volcano. Ash-fall during and after the eruption contained 3–7% free silica, which may cause silicosis of the lungs if inhaled over long periods. The principal hazards to property resulting from pyroclastic falls are burial, impact damage, and fire if the material has a high temperature. The latter hazard is most dangerous within a few kilometers of the vent. The weight of the material collected on roofs may cause them to collapse.

Laterally directed blasts are among the most destructive volcanic phenomena (Figure 2).

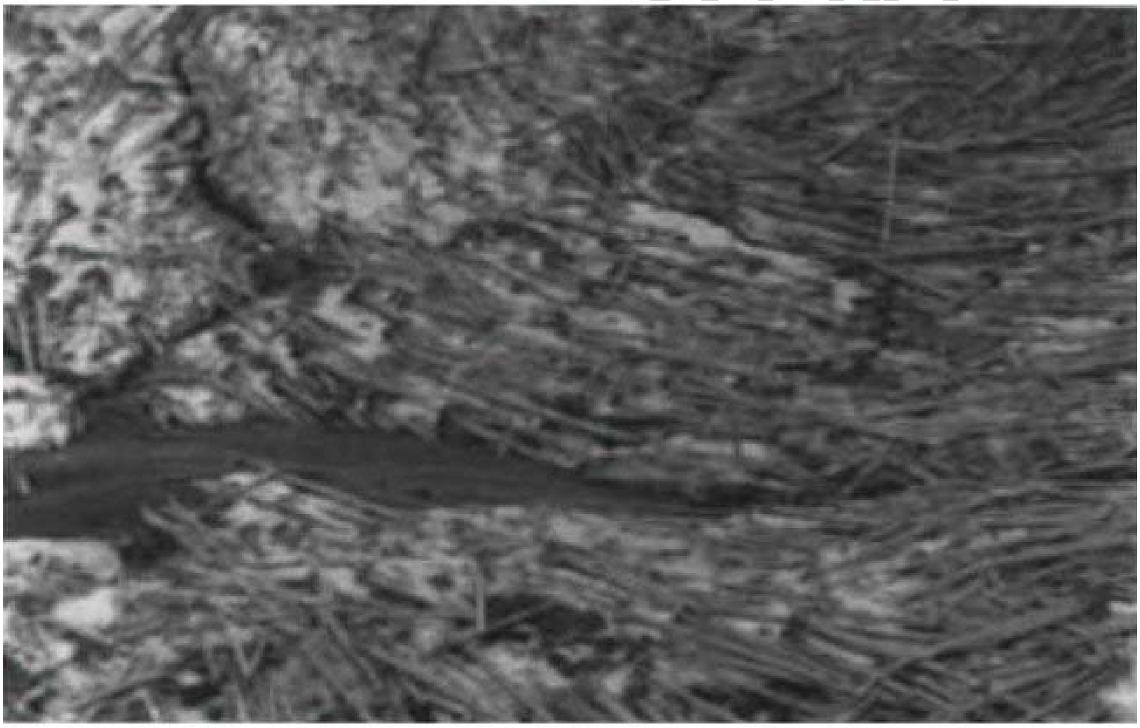

Figure 2. Trees felled by the lateral blast from the Mount St. Helens eruption, August 1980

They travel at high speeds: for example, the lateral blast associated with the Mount St Helens eruption initially traveled at 600 km h^{-1}, slowing to 100 km h^{-1} some 25 km from the volcano. They can occur with little or no warning within a period of a few minutes, and can affect hundreds of square kilometers. The material carried by lateral blasts can vary in temperature—it may be cold or hot enough to scorch vegetation and start fires. Such blasts kill virtually all life by impact, abrasion, burial, and heat. High concentrations of ash contaminate the air. Laterally directed blasts are the result of sudden decompression of magmatic gases or explosion of a high-pressure hydrothermal system. Release of gases may be caused by volatile pressures exceeding the weight of the overlying rocks, giving rise to explosion. The explosion may hurl rock fragments on ballistic trajectories, or generate pyroclastic flows or surges, or combinations of these.

Pyroclastic flows are hot dry masses of clastic volcanic material that move over the ground surface. Most pyroclastic flows consist of a dense basal flow, the pyroclastic flow proper, one or more pyroclastic surges, and clouds of ash. Two major types of pyroclastic flow may be recognized. Pumiceous pyroclastic flows are concentrated mixtures of hot to incandescent pumice, mainly of ash and lapilli size. Ashflow tuffs and ignimbrites are associated with these flows. Individual flows vary in length from less than 1 km up to some 200 km, covering areas ranging up to 20 000 km^2 and with volumes from less than 0.001 km^3 to over 1 000 km^3. Pyroclastic flows formed primarily of scoriaceous or lithic volcanic debris are known as hot avalanches, glowing avalanches, nuées ardentes, or block and ash flows. They generally affect a narrow sector of a volcano, perhaps only a single valley. Maximum temperatures of pyroclastic flow material soon after it has been deposited may range from 350 °C to 550 °C. Hence, they are hot enough to kill anything in their path. Because of their high mobility (up to 160 km h^{-1} on the steeper slopes of volcanoes) they constitute a great potential danger to many populated areas. Other hazards associated with pyroclastic flows apart from incineration include burial, impact damage, and asphyxiation.

A pyroclastic surge is a turbulent, low-density cloud of gases and rock debris that hugs the ground over which it moves. Hot pyroclastic surges can originate from the explosive disruption of volcanic domes, caused by rapidly escaping gases under high pressure or by collapse of the flank of a dome. They can also be caused by lateral explosive blast. Hot pyroclastic surges can occur together with pyroclastic flows. Generally, surges are confined to a narrow valley of a volcano but they may reach speeds up to 300 km h^{-1}, making escape impossible. They give rise to similar hazards to pyroclastic flows. Cold pyroclastic surges are produced by phreatic and phreatomagmatic explosions. Vertical explosions can give rise to a primary surge, which moves away from the volcano in all directions. Subsequently, secondary surges may be formed when volcanic material falls to the ground. Surges decelerate rapidly and tend not to travel more than 10 km from their source. Fortunately, pyroclastic flows and surges tend to affect limited areas. Approximately 20 pyroclastic flows and surges occur every 100 years.

The distance that a lahar may travel depends on its volume and water content on the one hand, and the gradient of the slope of the volcano down which it moves on the other. Some may travel for more than 100 km. The speed of a lahar also is influenced by its water–sediment ratio and volume, as well as the gradient and shape of the channel it moves along. For example, speeds of up to 165 km h^{-1} have been claimed for some lahars generated by the Mount St Helens eruption of 1980, but their average speed over several tens of kilometers was generally less than 25 km h^{-1}. Because of their high bulk density, lahars can destroy structures in their path and block highways. They can reduce the channel capacity of a river and so cause flooding, as well as adding to the sediment load of a river. Hence lahars may prove as destructive as pyroclastic flows over limited areas. Destructive lahars average 50 per century.

Lava effusions of social consequence average 60 per century. Fortunately, because their rate of flow is usually sufficiently slow, and because they follow courses that are predetermined by topography, they rarely pose a serious threat to life. The arrival of a lava flow along its course can be predicted if the rate of lava emission and movement can be determined. Damage to property, however, may be total, destruction occurring by burning, crushing, or burial of structures in the flow path. Burial of land by lava flows commonly terminates its previous use. Lava flood eruptions are the most serious events of this kind, and may cover large areas with immense volumes of lava. The likelihood of a given location being inundated with lava at a given time can be estimated from information relating to the periodicity of eruptions in time and space, the distribution of rift zones on the flanks of a volcano, topographic constraints on the directions of flow of lavas, and the rate of covering of the volcano by lava. The length of a lava flow is dependent upon the rate of eruption, the viscosity of the lava, and the topography of the area over which it flows. Given the rate of eruption, it may be possible to estimate the length of flow. Each new eruption of lava alters the topography of the slopes of a volcano to a certain extent, and therefore flow paths may change. What is more, prolonged eruptions of lava may eventually surmount obstacles lying in their path that have acted as temporary dams. This may mean that the lava then invades areas that were formerly considered safe.

The formation of calderas and landslip scars after the structural collapse of large volcanoes are rare events (0.5–1 per century). They are frequently caused when magma reservoirs are evacuated during violent Plinian eruptions. Because calderas develop near the summits of volcanoes and subside progressively as evacuation of their magma chambers takes place, caldera collapses do not pose such a grave threat to life and property as sector collapses. Sector collapse involves subsidence of a large area of a volcano. It takes place over a comparatively short period of time and may involve volumes up to tens of cubic kilometers. Collapses that give rise to landslides may be triggered by volcanic explosions or associated earthquakes.

Hazards associated with volcanic activity include destructive floods caused by sudden melting of the snow and ice which cap high volcanoes, by heavy downfalls of rain (vast quantities of steam may be given off during an eruption), or by the rapid collapse of a crater lake. Far more dangerous are the tsunamis generated by violent explosive eruptions and sector collapse. Tsunamis may devastate coastal areas. Dense poisonous gases normally represent a greater threat to livestock than to humans. Nonetheless, the large amounts of carbon dioxide released at Lake Manoun in 1984 and neighboring Lake Nyos, Cameroon, in 1986 led to the deaths of 37 and 1 887 people respectively. Gases can also be injurious to the person, mainly because of the effects of acid compounds on the eyes, skin, and respiratory system. They can also kill crops. Acid rain can form as a result of rain mixing with aerosols and gases adhering to tephra. Such rain can cause severe damage to natural vegetation and crops, and skin irritation to people. Air-blasts, shock waves, and counter-blasts are relatively minor hazards, although they can break windows several tens of kilometers away from major eruptions.

The active life span of most volcanoes is probably between one and two million years. Since the activity frequently follows a broadly cyclical pattern, some benefit in terms of hazard assessment may accrue from determination of the recurrence interval of particular types of eruption, the distribution of the resulting deposits, the magnitude of volcanic events, and the recognition of any short-term patterns of activity. Four categories of hazard have been distinguished in Italy:

- Very high frequency events with mean recurrence intervals (MRI) of less than two years. The area affected by such events is usually less than 1 km^2.
- High frequency events with MRI values of 2–200 years. In this category damage may extend up to 10 km^2.
- Low frequency events with MRI values of 200–2 000 years. Areal damage may cover 1 000 km^2.
- Very low frequency events are associated with the most destructive eruptions and have MRI values in excess of 2 000 years. The area affected may be greater than 10 000 km^2.

The return periods of particular types of activity of individual volcanoes or centers of volcanic activity can be obtained by thorough stratigraphic study and dating of the deposits in order to reconstruct past events. Used in conjunction with any available historical records, these data form the bases for assessing the degree of risk involved. However, it is unlikely that such studies could ever be refined sufficiently for the time of renewed activity to be predicted accurately. Furthermore, because it is unlikely that humans will ever be capable of significantly influencing the degree of hazard, reduction of risk can only be achieved by reducing exposure of life and property to volcanic hazards.

Hazard zoning involves mapping deposits that have formed during particular phases of volcanic activity, and their extrapolation to identify areas that would be likely to suffer a similar fate at some future time. The zone limits on such maps normally assume that future volcanic activity will be similar to that recorded in the past. Unfortunately, however, this is not always the case. Volcanic hazard maps have been produced in Indonesia have defined three zones, namely, the *forbidden zone*, the *first danger zone*, and the *second danger zone* (Figure 3). The forbidden zone is to be abandoned permanently since it is affected by nuées ardentes. The first danger zone is not affected by nuées ardentes, but may be affected by bombs. Lastly, the second danger zone is that likely to be affected by lahars. This zone is subdivided into an abandoned zone, from which there is no escape from lahars, and an alert zone, where people are warned and from where evacuation may be necessary.

Volcanic risk maps indicate the specified maximum extents of particular hazards such as lava and pyroclastic flow paths, expected ash-fall depths, and the areal extent of lithic missile fall-out. Local and national governments need them so that appropriate land uses, building codes, and civil defense responses can be incorporated into planning procedures. Events with a MRI of less than 5 000 years should be taken into account in the production of maps of volcanic hazard zoning, and data on any events that have taken place in the last 50 000 years are probably significant. Two types of map would be of use for economic and social planning. One would indicate areas liable to suffer total destruction by lava flows, nuées ardentes, and/or lahars. The other would show areas likely to be affected temporarily by damaging but not totally destructive phenomena, such as heavy falls of ash, toxic emissions, or pollution of surface or underground waters.

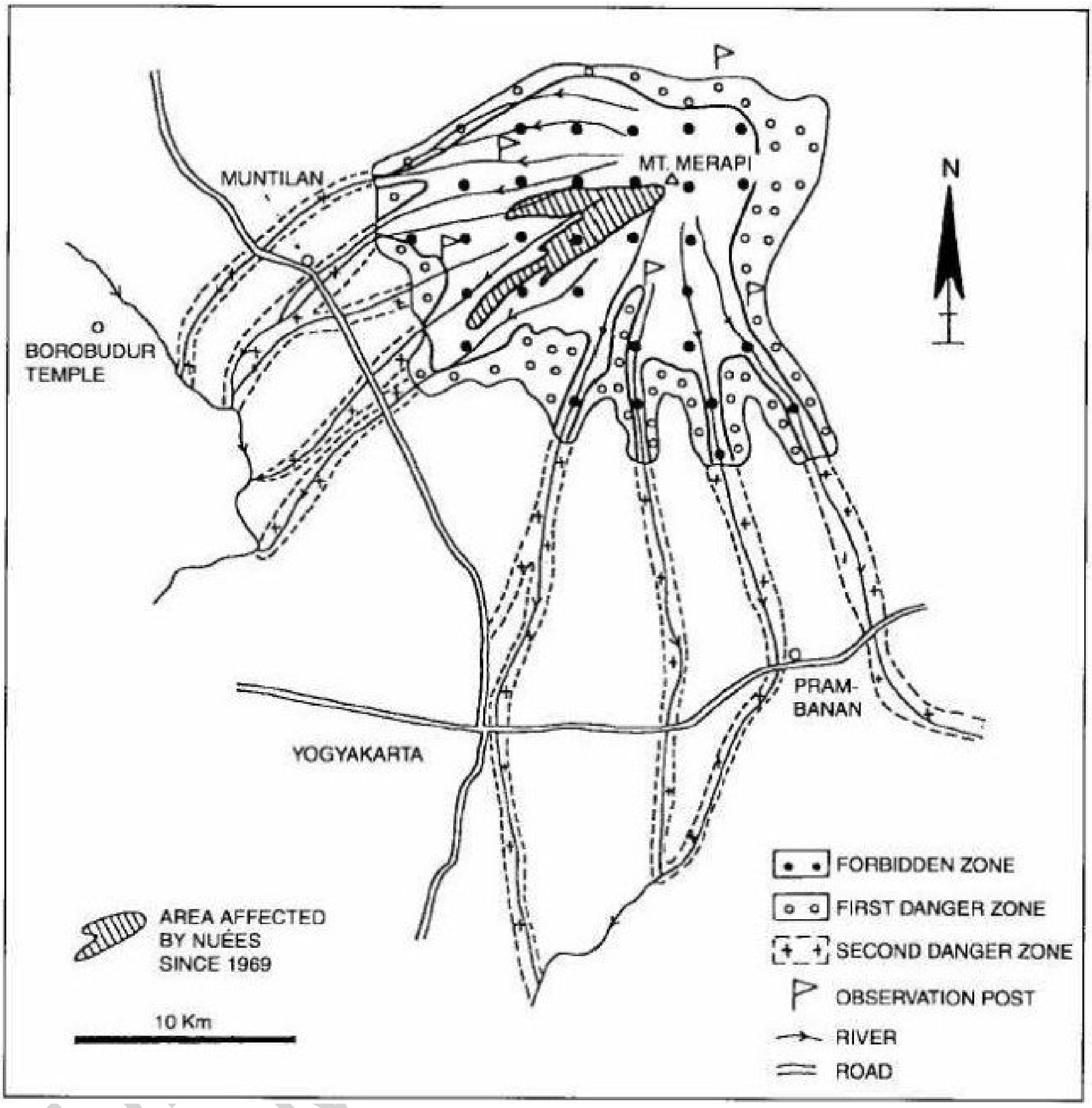

Figure 3. Volcanic hazard map of Merapi volcano, Indonesia. Source: after Suryo, I. and Clarke, M.G.C. (1985). The occurrence and mitigation of volcanic hazards in Indonesia as exemplified in Mount Merapi, Mount Kelat and Mount Galungging volcanoes. *Quarterly Journal of Engineering Geology*, **18**, 79-89.

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Biographical Sketch

Fred Bell graduated with a B.Sc. and M.Sc. from the University of Durham and received his Ph.D. from the University of Sheffield, United Kingdom in 1974. More recently, he received a D.Sc. from the University of Natal. He is a Fellow of the Royal Society of South Africa, a Fellow of the Institution of Civil Engineers and the Institution of Mining and Metallurgy, and a Fellow of the Geological Society, being both a chartered engineer and a chartered geologist. He is the recipient of several awards.

Professor Bell now is a Visiting Research Associate at the British Geological Survey. Previously, he was Professor and Head of the Department of Geology and Applied Geology, University of Natal, Durban, South Africa, during which time he also was a Distinguished Visiting Professor, Department of Geological Engineering, University of Missouri-Rolla, USA.

Professor Bell's research subjects have included ground stability, subsidence, ground treatment, engineering behavior of soils (clays, expansive clays, saprolites, tills, laminated clays, dispersive and collapsible soils, sands), engineering behavior of rocks (sandstones, carbonates, evaporites, shales, basalts, dolerites, granites), cement, lime and PFA stabilization of clay soils, acid mine drainage, mining impacts, landfills, derelict and contaminated ground, rock durability in relation to tunneling, slope stability, aggregates, building stone, and geohazards.

In his professional capacity Professor Bell has been involved in a variety of work in the United Kingdom, southern Africa, and Malaysia concerning site investigations; foundations; settlement problems on clays, fills and sands; old mine workings and subsidence; longwall mining and subsidence; ground treatment; groundwater resource assessment; slope stability; use of mudrocks for brickmaking; assessment of various rock types for aggregates; contaminated ground; acid mine drainage; landfills; and dam sites.

Professor Bell is author/editor of 17 books: several reprinted, one in its fourth edition, one translated into French, two into Italian and yet another into Malay, and an Indian edition (in English). He is also author of over 200 papers on geotechnical subjects. He has served on the editorial boards of five international journals and has been a series editor for three publishers.