Volcanic Hazards and Geothermal Development

Jeffrey B. Witter

S. J. V. Consultants Ltd.
Delta, BC, Canada

Keywords

Volcanoes, eruptions, hazards, risk, probabilistic hazard assessment

ABSTRACT

Volcanoes can be attractive for geothermal energy developers thanks to the high temperature resources often found beneath them. However, volcanic eruptions and their effects pose a significant hazard to geothermal development and infrastructure. Examples of volcanic phenomena which can have a negative impact on geothermal power operations include: ash fall, lava flows, pyroclastic flows, lahars and sector collapse. In general, siting of geothermal installations is critical to avoid many volcanic hazards. In some cases, though, exploiting a geothermal resource and siting infrastructure outside of volcanic hazard zones may be incompatible. A review of the literature suggests that direct impacts of volcanic eruptions on geothermal infrastructure have so far been limited. However, in the world's top ten geothermal energy producing countries there is a clear positive correlation between the number of volcanoes with Holocene eruptions and geothermal MW capacity. Planned increases in geothermal development worldwide in the coming decades, coupled with the attractiveness of volcanically-hosted resources, suggest that volcanic hazards will become an increasing concern to developers. Fortunately, scientific researchers have recently developed a Bayesian event tree scheme to perform complete probabilistic volcanic hazard assessment for individual volcanoes. This method combines the probabilities of: an eruption, the occurrence of different types of hazardous volcanic phenomena, and the impact on specific areas that lie at specific distances from the volcano. A probabilistic volcanic hazard assessment can be quite useful to geothermal developers to help limit financial losses as it provides a quantification of the magnitude of volcanic risk for the project. These results can then be directly compared to other natural and non-natural sources of risk which can help senior management, investors, and others make informed risk decisions when working on geothermal projects in volcanic areas.

Introduction

Geothermal heat found in volcanic areas commonly comes from magma. This same magma can erupt and have a significant impact on nearby infrastructure and inhabitants. As geothermal development progresses in the coming years, it is likely that many geothermal developments could be exposed to volcanic hazards and some may suffer impacts from future eruptions. How concerned should geothermal developers be about volcanic hazards and what might they do about them? This paper has three parts. First, the different types of volcanic hazards are briefly described. Volcanic activity comes in diverse forms (e.g. ash fall, lava flows, etc.) and thus the potential impacts to a geothermal development can be varied. Second, examples of volcanic eruptions that have impacted geothermal projects in the past are discussed. These impacts may affect an existing geothermal installation or early-stage geothermal development activities. Third, some of the latest research in probabilistic volcanic hazard assessment (PVHA) is presented. An evaluation of volcanic hazard is most useful to the geothermal development community if hazards can be quantified in a meaningful way. Recent advancements in PVHA use a Bayesian Event Tree approach to calculate the probability of a volcanic eruption and the probability of associated volcanic phenomena (e.g. ash fall, lava flows, etc.) at specific locations around the volcano (Marzocchi et al., 2010). This type of probabilistic approach can be useful to senior management and investors in their efforts to assess the overall risk associated with a geothermal development in a volcanically active area.

Volcanoes and Geothermal Development

As a means of justification, it is instructive to take a brief look at the close spatial association between volcanoes, eruptions, and geothermal development. Active or potentially active volcanoes are often targeted in the search for high-temperature geothermal resources. One specific example of an existing geothermal installation at an active volcano is the 22 MW Momotombo geothermal power plant which sits on the south flank of Momotombo volcano (Porras et al., 2005). This volcano has had a long record of relatively small eruptions, interspersed with occasional, large explosive activity. The most recent eruption at Momotombo was in 1905 when lava flowed down from the summit crater to the NE base of the volcano (Siebert & Simkin, 2002-).

The spatial association between volcanoes, eruptions, and geothermal development on a global basis is shown in Figure 1. This histogram lists the top ten geothermal countries by MW capacity – all of these countries are home to numerous active or recently active volcanoes. For each country, MW capacity as of 2011 is shown as well as the estimated capacity additions through 2015. As a means for comparison, separate columns are plotted alongside showing the number of volcanoes which have had Holocene eruptions for each country. A Holocene eruption is one which has occurred within the last 10,000 years and is a common metric used to designate a particular volcano (or volcanic field) as one which will likely erupt again (Simkin & Siebert, 1984). The overall direct correlation between MW capacity and the number of Holocene eruptions is clear – countries with the largest number of erupting volcanoes (e.g. Indonesia and the Philippines) have significantly elevated geothermal capacities (installed and planned). By contrast, countries with fewer Holocene eruptions (e.g. Kenya, El Salvador) have lower geothermal capacities (Figure 1).

The United States and Japan are two interesting exceptions. Thanks to extensive development of sizeable, non-volcanic geothermal areas (e.g. the Basin and Range and the Salton Sea) the United States has a much higher geothermal capacity than one might expect looking at the number of Holocene eruptions alone. Japan, on the other hand, has the second highest number of volcanoes with eruptions recorded in the Holocene, but the third lowest installed geothermal capacity. This observation appears to be in agreement with the large geothermal development potential noted for Japan (est. 23,500 MW; Sugino & Akeno, 2010).

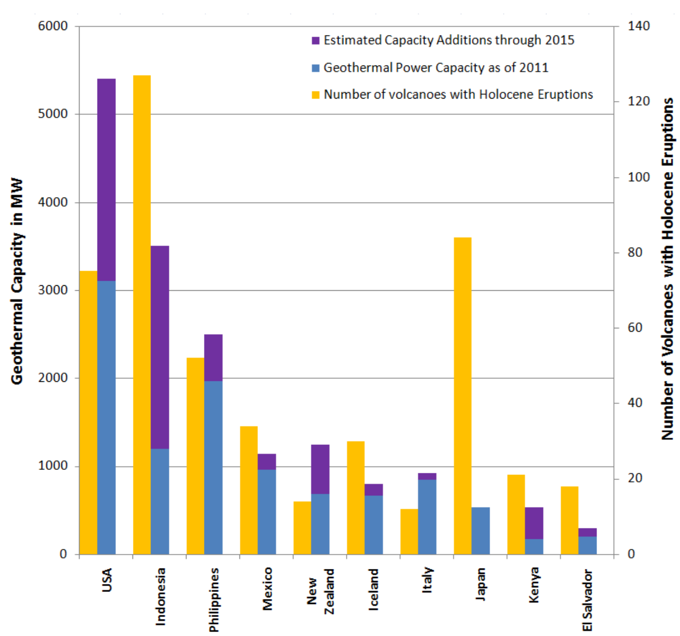

Figure 1. Histogram showing the existing and planned geothermal capacity for the top ten geothermal countries (data from Islandsbanki, 2011). Also shown for each country are the numbers of volcanoes with Holocene eruptions (data from Simkin & Siebert, 1994). See text for full explanation.

Considering this correlation between geothermal development and Holocene eruptions, concern for the potential impacts of future volcanic eruptions on geothermal installations is warranted. These concerns are not restricted to geothermal installations that sit immediately next to a potentially active volcano. Large quantities of wind-borne volcanic ash can easily be transported to destinations dozens of kilometres away. Various types of volcanic flows can travel more than 10 km away from their volcanic source. As more geothermal development occurs near potentially active volcanoes the chances of significant financial loss due to the impacts of an eruption will only increase. Examples of possible impacts from volcanic eruptions include: 1) temporary (i.e. days) power plant shut-down to clean volcanic ash off of equipment, 2) medium-term (i.e. weeks) power plant shut-down to repair damage to machinery from ash, and 3) long-term (i.e. months) power plant shut-down due to long-term, low level volcanic activity such as near continual ash fall or, possibly, restricted access to the power plant by local authorities due to its location within a volcanic hazard exclusion zone. In a worst-case scenario, eruptive phenomena from a large volcanic eruption could cause partial or total destruction and/or burial of a power plant and well field.

Types of Volcanic Hazards

Volcanic phenomena spawned by eruptions come in many types. As such, the specific hazards from the different volcanic phenomena can vary. Here, the different kinds of volcanic hazards and their potential impacts on geothermal installations and workers are reviewed. Some possible engineering solutions to neutralize volcanic hazards are briefly presented.

Ashfall

Volcanic ashfall is a term that describes volcanic ash that rains out of a volcanic eruption cloud, blanketing large areas of the landscape. In general, accumulations of volcanic ash become thinner with increasing distance from the source of the eruption. Volcanic ash is composed of pulverized volcanic glass and crystals less than 2 mm in size. It is a highly abrasive material that can cause damage to the internal moving parts of mechanical machinery, especially when sucked into air intakes. Wet volcanic ash is conductive and can short out electrical systems. Acidic volcanic gases commonly adsorb onto the surface of ash particles leading to corrosion of the materials blanketed by ash. In large quantities, volcanic ash can cause breathing problems for people, especially those with pre-existing respiratory conditions. Apart from the obvious ill-effects to machinery and workers, possibly the greatest hazard from volcanic ash to geothermal installations is roof collapse. Since volcanic ash is made of bits of rock, it is a heavy material even in relatively thin accumulations. Indeed, accumulations of >10 cm of dry ash or >5 cm of wet ash produce sufficient loads to collapse many types of roof (Newhall and Hoblitt, 2003). The most effective way to avoid roof collapse is to actively remove the accumulating volcanic ash from the roof or build a stronger roof to withstand greater loads. The hazards of volcanic ash to machinery may be difficult to neutralize since falling volcanic ash covers everything, it is fine-grained, and the slightest air movement can remobilize ash into interior spaces.

Lava Flows

Lava flows consist of partially molten, partially crystalline rock flowing on the land surface. They are extremely hot (700 – 1200 ºC) and generally bury and/or burn everything in their path. Lava flows come in two types: viscous and fluid. Viscous lava flows generally travel only short distances (i.e. 100's of m) from volcanic craters. Fluid lava flows, however, can travel greater distances (i.e. tens of kilometres). Although most fluid lava flows travel slow enough that they can be outrun by people, immobile installations caught in the path of flowing lava are often doomed. Flammable structures will be burned to the ground while non-flammable structures will either be bulldozed by the lava flow or entombed in solid rock as the fluid lava flows around the structure and accumulates in a thick pile. Attempts in the 20th century to divert or otherwise arrest the flow of fluid lava have had mixed results (Peterson & Tilling, 2000). Engineering efforts to protect a geothermal installation from flowing lava using a system of berms or protective walls would likely be very costly and in the end may be futile. Fortunately, flowing lava follows topography, thus siting geothermal installations on high ground is the most effective way of avoiding hazards from lava flows.

Lahars

Lahars are volcanic mudflows. They are composed of a mixture of water, volcanic ash, rock, and other debris and have the consistency of wet concrete. Lahars are generated at volcanoes in two ways: 1) by eruptions that melt snow and ice producing large quantities of water or 2) heavy rainfall on the steep, upper slopes of a volcano that then mixes with loose, recently deposited volcanic material. Lahars travel down river valleys but can be so voluminous that the river channels fill with volcanic debris, river banks are overtopped, and surrounding areas are inundated. Some lahars are hot enough to burn people (i.e. up to 100 ºC) but, most typically, they bury everything in their path in volcanic material a few metres thick. In some cases, lahars can be extensive enough to bury entire towns. Similar to lava flows, the most effective method of avoiding hazards from lahars is locating geothermal installations on high ground, well outside of a potential lahar inundation area.

Pyroclastic Flows

Pyroclastic flows are exceedingly hot mixtures of volcanic ash, gases, and rock that hurtle across the land surface at speeds of up to 200 km/hour (Oppenheimer, 2011). They are primarily generated during highly explosive eruptions when a vertical volcanic eruption column collapses downwards. Pyroclastic flows can also be generated from the collapse of the flank of a hot, growing lava dome. Pyroclastic flows are one of the most destructive of all volcanic phenomena in that they generally incinerate, destroy, and/or bury everything in their path. Small-volume pyroclastic flows easily travel a few kilometres from their source while larger pyroclastic flows can travel tens of kilometres. During smaller eruptions, pyroclastic flows generally flow along the ground and remain confined to valleys. However, in larger eruptions, the sheer volume of volcanic material can fill up entire valleys, allowing the pyroclastic flows to spread all across the landscape. Due to their high temperature (up to 500 ºC) and hurricane-like force, practical and cost-effective engineering solutions to pyroclastic flow hazards are generally limited. The best approach to mitigating pyroclastic flow hazards is proper siting of geothermal infrastructure. In some cases, however, the siting of future geothermal well fields and/or power plants entirely outside of pyroclastic flow hazard zones may be difficult to avoid.

Sector Collapse

Sector collapse of a volcano is one of the most catastrophic events which can occur at a volcano. A sector collapse is a giant landslide in which an entire wedge-shaped sector of a volcano slides off the mountain under its own weight. In addition to being very destructive, volcanic sector collapse is also a fairly common feature in the life of a volcano. Sector collapses are promoted by the presence of hydrothermally altered rock within the volcano: hot and acidic geothermal fluids naturally circulate inside a volcano causing competent rock to be broken down into soft clay. As a result, the volcano becomes gravitationally unstable and fails catastrophically. A sector collapse event can sometimes expose magma in the interior of the volcano which can then depressurize and erupt explosively. The sector collapse and explosive eruption of Mount St. Helens (USA) in 1980 is a classic example of this type of volcanic phenomenon (Lipman & Mullineaux, 1981). In other cases, a sector collapse is not accompanied by explosive eruption and the giant landslide is the only hazardous event. The primary hazard generated by volcanic sector collapse is that the volcanic material mobilized in the landslide can travel several kilometres from the volcano, destroying or burying everything in its path. There is generally no practical engineering solution to mitigate the hazards from a volcanic sector collapse. Like pyroclastic flows, the best solution is proper siting of geothermal infrastructure outside of sector collapse hazard zones. The great irony, however, is that the hot geothermal reservoir which rots the core of the volcano leading to the mountain's gravitational instability can be the very same geothermal reservoir targeted for exploitation. Therefore, there is a certain likelihood that future geothermal infrastructure may be situated within a sector collapse hazard zone.

Examples of Volcanic Activity That Have Had an Impact on Geothermal Development

Fortunately, based upon a review of the scientific literature and recent news reports, it does not appear that many geothermal operations have been impacted significantly by volcanic activity. However, with increased geothermal development in zones of active volcanism, the probability of impacts from eruptions will likely increase. Here, four examples are reviewed. In two of the examples, eruptions caused problems at existing geothermal power developments. In another example, an eruption occurred soon after a period of geothermal exploration and the fourth example describes an ongoing eruption that could potentially impact geothermal leasing decisions. These examples illustrate that an evaluation of potential volcanic hazards is valuable at all stages of geothermal development.

Krafla Caldera, Iceland

On September 8, 1977, magma moving through a subterranean dike intersected a geothermal borehole at the Námafjall geothermal field in Iceland (Larsen et al., 1979). Three tons of magma erupted through an 1138 m deep borehole in 20 minutes leaving a deposit of volcanic scoria and ash on the land surface around the well. The Námafjall geothermal field is located on the flank of Krafla caldera which had been experiencing a major volcanic rifting episode with associated faulting and magma intrusion since December 1975. Geothermal boreholes at Námafjall were spaced ~80-200 m apart and reached depths of 650-1800 m (cased down to ~500-600 m). The boreholes were deliberately placed in a highly faulted area and were drilled to intersect faults at favourable depths.

The eruption through the Námafjall geothermal borehole occurred in the middle of the night, beginning at 2345h. At this time, an explosion ruptured the elbow in the pipe that carries the steam-water mixture from the geothermal well. Through the dark, observers saw an incandescent column of magma spraying upwards 15-25 m accompanied by a continuous roar that lasted for ~1 minute. This was followed by a lull in activity for ~15 minutes. There were additional explosions which shot out glowing scoria from the ruptured pipe for another minute; then the eruption was finished. It is believed that the magma intersected the borehole below the casing in the 625 – 1038 m depth interval. The temperature of the magma upon eruption was estimated at ~1150 ºC (Larsen et al., 1979).

Specific impacts from the eruption through the borehole were remarkably limited. The superstructure of the borehole suffered only minor damage. This damage was repaired and eventually the borehole was put back into service (Larsen et al., 1979). After the repairs, the borehole continued to produce steam at a similar rate as before the eruption. Other impacts included: 1) due to extensional movement on faults in the Námafjall area, caused by the rifting episode, the main road was cut and became impassable and 2) the eruption produced a blanket of scoria and ash which covered an area ~50 m x 25 m with a maximum thickness of 8-10 cm at a distance of 15-20 m (Larsen et al., 1979). Clearly, the potential impacts from this eruption could easily have been much worse. For example, more than one borehole in the well field could have been affected, a much greater volume of material could have been erupted, or lava could have poured out onto the land surface encasing the well field and piping in lava.

Pacaya Volcano, Guatemala

The 20 MW Amatitlan geothermal power plant is located in Guatemala on the northwest flank of Pacaya volcano at a distance of ~3 km from the summit crater. Pacaya is one of the three most active volcanoes in Guatemala and has a record of volcanic eruptions dating back to the time of the Spanish conquest in the 16th century (Siebert & Simkin, 2002-). In the last several decades, activity has taken the form of small explosive eruptions accompanied by extrusion of lava flows. These smaller eruptions have been interspersed with larger explosive eruptions that partially destroy the volcanic cone.

Pacaya volcano experienced its most recent eruption in May – June 2010 (Siebert & Simkin, 2002-). The eruption commenced on May 27, 2010 ejecting ash and scoria into a vertical eruption column that reached 1500 m above the crater. Ash rained down on communities near the volcano forcing evacuations, as well as on Guatemala City ~30 km away, and on the international airport resulting in its closure for a few days. Lava flows generated during the eruption travelled down the southwest and southeast flanks of the volcano. Explosive activity died down somewhat by early June but low level activity (lava flows and gas emission) continued for much of the month. On July 20 and 21, there were two significant volcanic explosions which sent an ash-laden eruption column up to ~4,000 m above sea level depositing ash within a radius of 10 km. Following these explosions, activity died down and returned to primarily gas emission with occasional small explosions.

News reports state that the Amatitlan geothermal power plant temporarily shut down after the 2010 eruption at Pacaya (ThinkGeoEnergy, 2010). The eruption is reported to have caused only minor damage to the plant and operations were halted at the plant to protect equipment. The ThinkGeoEnergy news report stated that the plant would require “a thorough clean up prior to restarting,” presumably to remove accumulated volcanic ash.

Pinatubo Volcano, Philippines

Pinatubo volcano is the site of the second largest volcanic eruption of the 20th century. The eruption occurred in 1991 and produced massive amounts of volcanic ash, pyroclastic flows, and lahars and also caused hundreds of fatalities. A geothermal exploration program at Pinatubo, which began in the 1980’s, and included deep exploration drilling, was ultimately abandoned only 15 months prior to the cataclysmic eruption in 1991. The case of Pinatubo provides an example of a potential geothermal development catastrophe that, fortunately, did not come to pass.

In 1982, the Philippine National Oil Company (PNOC) began a geothermal exploration program at Pinatubo volcano (Delfin et al., 1996). At the time, very little was known about the volcano or its eruptive history. From 1982 – 1986, PNOC conducted a surface geothermal exploration program that included geological mapping, fluid chemistry, and geoelectrical studies. As part of the program, 12 groups of hydrothermal discharges (i.e. hot springs and steam vents) were studied. These hydrothermal discharges lay along a 25 km NW-SE oriented trend that crossed the summit of the volcano. From the initial exploration program, a subvolcanic geothermal system centred on the NW flank of the volcano was inferred with a temperature of at least 200 °C. A possible magmatic input to the geothermal system was hypothesized based upon high Cl concentrations measured in spring water samples (Delfin et al., 1996).

Deep, exploratory drilling and well-testing occurred in 1988-1990 (Delfin et al., 1996). Three wells were drilled on the flanks of the volcano all within 1-2 km of the summit. The wells were 2100 – 2700 m deep and encountered temperatures of 261 – 336 °C. The wells primarily penetrated low permeability andesite and dacite rocks. In addition, the borehole fluids were found to be acidic (pH = 2.3 – 4.3) NaCl waters. Although one of the wells was estimated to have a capacity of 7 MWe, the combination of the generally poor permeability encountered and the acidic nature of the geothermal fluids led to the conclusion that the wells drilled would not be commercial. Thus, the geothermal program at Pinatubo was abandoned in March 1990 (Delfin et al, 1996). At the time, there were no obvious indications leading volcanologists to suspect an eruption would occur at Pinatubo in the near future (Wolfe and Hoblitt, 1996).

Pinatubo volcano had no record of historical eruptions prior to 1991 (Siebert & Simkin, 2002-). Geologic studies that occurred after the geothermal exploration program found evidence for at least six major eruptive periods at Pinatubo (Newhall et al., 1996). Most of the previous eruptions at Pinatubo were of such a magnitude to produce voluminous pyroclastic flows that were even more extensive than those produced in the 1991 eruption. The first characteristic indications of a coming eruption at Pinatubo occurred in April 1991 when a series of steam explosions occurred from vents along a 1.5 km long fissure on the north flank of the volcano. The climactic phase of the eruption occurred on June 15, lasted 9 hours, generated an ash cloud 400 km in diameter with a maximum height of 34 km, and caused the collapse of the volcano's summit leaving behind a 2.5 km diameter caldera (Wolfe & Hoblitt, 1996).

The 1991 eruption of Pinatubo erupted ~5 km^3 of magma (Scott et al., 1996) which is equivalent to ~10 billion tons of rock (i.e. ~3 billion times more rock than was erupted through the Námafjall borehole). Volcanic ash deposits up to 33 cm thick fell as far as 10½ km from the volcano; ash deposits >10 cm in thickness (enough to collapse roofs) blanketed an area of ~2000 km^2 (Paladio-Melosantos et al., 1996). Pyroclastic flows descended on all sides of the volcano to a distance of up to 16 km, filled pre-existing valleys to depths of up to 200 m, and impacted an area of ~400 km^2 (Scott et al., 1996). Lahars flowed down all major drainages around the volcano to distances of more than 50 km, inundating arable land as well as homes and destroying bridges (Major et al., 1996).

The three abandoned geothermal exploration wells were all located within only a few hundred metres of "ground zero" of the 1991 eruption of Pinatubo. The well heads were likely completely destroyed and/or buried. Clearly, had the Pinatubo geothermal development project proceeded beyond the exploration stage, any geothermal power plant and associated transmission infrastructure located reasonably close to the deep exploration well field would have been obliterated and/or interred by pyroclastic flows and become a total loss. It was nothing less than good fortune that the subsurface geothermal conditions encountered by the exploration program proved to be unsuitable leading to abandonment of the project prior to the destructive eruptions.

Puyehue – Cordón Caulle Volcanic Complex, Chile

On June 4, 2011, an explosive eruption commenced at the Puyehue – Cordón Caulle volcanic complex located in southern Chile (Siebert & Simkin, 2002-). The Cordón Caulle rift hosts one of the largest active geothermal areas in the southern Andes (Lara et al., 2006; Sepulveda, 2004). Many explosive eruptions have occurred at the Puyehue – Cordón Caulle volcanic complex, including two major historic eruptions in 1921-22 and 1960 (Lara et al., 2006; Singer et al., 2008). In the first two days of the 2011 eruption, volcanic ash columns nearly 14 km high deposited ash several centimetres thick up to 100 km away (Siebert & Simkin, 2002-). Greater thicknesses of ash were deposited closer to the volcano. During this initial activity, winds carried volcanic ash predominantly to the east but also to the west, south, and northeast. Eruptions at Cordón Caulle continued at a lower level for several months with abundant ash emission. Satellite observations indicate that ash plumes drifted predominantly towards the northeast, east, and southeast; however, variable wind patterns distributed ash in virtually all directions to distances ranging from tens to hundreds of kilometres (Siebert & Simkin, 2002-).

It appears that the Puyehue – Cordón Caulle area has been recognized by the geothermal industry as a zone of potential geothermal exploration and development. According to publicly available Chilean government records, geothermal exploration lease applications were submitted for three areas located on the flanks of Cordón Caulle (Figure 2). The three proposed geothermal exploration areas are all located within 20 km of the crater created during the 2011 Cordón Caulle eruption. As a result of the eruption, all three of these areas have been impacted to a greater or lesser extent by falling volcanic ash. Pyroclastic flows generated by the 2011 eruption reportedly travelled 10 km to the north (Siebert & Simkin, 2002-), likely reaching one of the geothermal exploration areas (Figure 2). These observations raise the question: how would an ongoing, low-level volcanic eruption and accompanying ash fall impact a field-based geothermal exploration program? How would the 2011 eruption influence any potential desire for a developer to move forward with geothermal development in the Cordón Caulle area and how would one assess the risk of potential future eruptions?

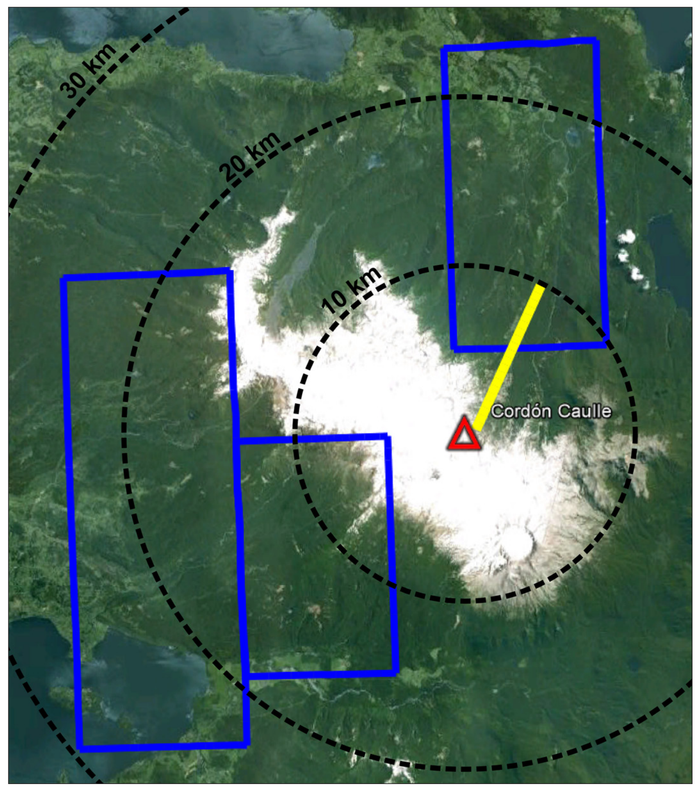

Figure 2. Google Earth image showing the location of the 2011 eruptive vent of Cordón Caulle (red triangle), proposed geothermal exploration areas (blue rectangles), and the inferred path of reported pyroclastic flows from the 2011 eruption (yellow line). Ashfall from the 2011 eruption has occurred downwind from the volcano primarily towards the NE, E, and SE; however, varying wind directions have distributed ash in virtually all directions. Ash plumes were commonly observed drifting tens to hundreds of kilometres from Cordón Caulle.

What to Do About the Volcanic Hazards?

Considering the four examples described above, what can geothermal energy developers do to address volcanic hazards that could threaten investments in geothermal projects? In order to answer this question, it is instructive to learn from the efforts of the volcanological community whose research aims to define the hazards and evaluate the risks to towns and villages located near active volcanoes. For the past several decades, the standard approach to volcanic hazard assessment has been to create a map showing the age, type, thickness, and areal extent of volcanic deposits (i.e. lava flows, pyroclastic flows, ash fall etc.) around a volcano. Following the geological principle of uniformitarianism (i.e. the past is the key to the present), it is assumed that future eruptions will most likely impact areas similar to those impacted in the past. This approach is useful to identify which volcanic hazards are most common (e.g. lava flows vs. pyroclastic flows) at a certain volcano and provide a qualitative description of the range and type of previous activity. A volcanic hazard map can be used for long-term land use planning or they can be used to recommend evacuation areas when an eruption is threatening. This type of hazard map can also be useful to geothermal developers exploring for resources in volcanically active areas as they provide an initial view into the nature and severity of potentially dangerous eruptions at the volcano in question.

Unfortunately, volcanic hazard maps do not provide information about the probability of a future eruption or the probability of a specific consequence from an eruption (e.g. lahar or ash fall). Nor can they characterize the probability that a specific volcanic phenomena will impact a certain area of the volcano a certain distance away. A quantitative, probabilistic approach is very useful for emergency management professionals attempting to accurately assess community risk. This same method could also be valuable to geothermal development professionals and others for evaluating volcanic hazards and assessing all the risks associated with a geothermal development project.

Over the last several years, scientific researchers have developed just such a quantitative, probabilistic volcanic hazard evaluation tool (Newhall & Hoblitt, 2002; Marzocchi et al., 2004; Marzocchi & Woo, 2007; Marzocchi et al., 2010). A *probabilistic* approach is needed because the complexities, nonlinearities, and uncertainties inherent to volcanic systems make it virtually impossible to predict eruptive phenomena in a *deterministic* fashion. The method is called probabilistic volcanic hazard assessment (PVHA). PVHA uses a Bayesian Event Tree scheme that considers not only the probability of an eruption, (including the size of the eruption) but it also incorporates the probability of occurrence of hazardous phenomena accompanying the eruption (such as lava flows, pyroclastic flows, ash fall, lahars, etc.) and the impact on the surrounding landscape. The Bayesian approach is a mathematical method, based on Bayes theorem, which enables different sources of information to be merged (e.g. theoretical models of eruptive processes, geological field data, historical eruption data, and volcano monitoring data). The approach also allows both aleatoric and epistemic uncertainties to be incorporated into the hazard assessment. Aleatoric uncertainty deals with the intrinsic unpredictability or stochastic nature of volcanic phenomena while epistemic uncertainty is that which is limited only by the amount of data or knowledge we have about the phenomena. The event tree structure provides a graphical representation of events in which branches in the tree are alternative steps in a sequence of volcanic activity (Figure 3). The event tree format also allows all relevant possible outcomes of volcanic unrest to be included. Probability distributions are estimated at each node in the event tree and a full PVHA is attained by combining the probabilities at each node. A public domain software package called BET_VH (Marzocchi et al., 2010) calculates probabilities and generates a visual output of the PVHA results in map view.

The PVHA method has been applied to Vesuvius, Italy (Marzocchi et al., 2004), Campi Flegrei caldera, Italy (Selva et al., 2010, 2011) and the Auckland Volcanic Field, New Zealand (Sandri et al., 2011). It has also been coupled with cost-benefit analysis to rationalize decision making processes associated with volcano risk management (Marzocchi & Woo, 2009). One distinct benefit of PVHA is it allows the quantification of volcanic risk so that it can be directly compared to other natural and non-natural sources of risk.

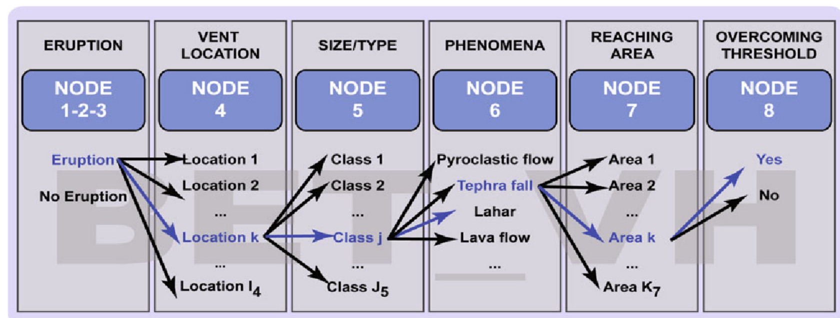

Figure 3. Structure of an event tree for probabilistic volcanic hazard assessment (adapted from Marzocchi et al., 2010). The event tree includes: whether or not an eruption occurs, the location of the volcanic vent, the size and type of eruption, the kind of volcanic phenomena involved (e.g. lava flow, lahar, etc.), whether the volcanic phenomena reaches a certain sector or distance from the volcano, and whether a specific hazardous threshold is exceeded or not (e.g. >10 cm of ash accumulation?).

Conclusions

There is a clear correlation between high temperature geothermal resources and active volcanism as illustrated in Figure 1. Geothermal developers will likely be attracted to prospective areas that also lie within a volcanic eruption hazard zone. Up until now, the impacts of eruptions on geothermal development have been relatively few and minor. However, these potential impacts will likely be a growing concern as geothermal development proceeds in the coming decades. Indeed, the eruption of Pinatubo is an excellent example of a geothermal development disaster averted. Fortunately, a new tool, probabilistic volcanic hazard assessment, has been recently developed to provide a quantitative evaluation of the volcanic hazard including the size and type of eruption, volcanic phenomena involved, and the impact on the surrounding landscape. This tool could be very useful to various members of the geothermal community to help quantify risk when working in volcanically active terrains.

Acknowledgements

Thanks to Nathalie Vigouroux for helpful comments on an early draft and to reviewer Gene Suemnicht for constructive comments that improved the quality of the manuscript.

References

Delfin F.G., H.G. Villarosa, D.B. Layugan, V.C. Clemente, M.R. Candelaria, J.R. Ruaya, 1996. "Geothermal Exploration of the pre-1991 Mount Pinatubo Hydrothermal System." *In:* Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines, *eds:* C.G. Newhall and R.S. Punongbayan, University of Washington Press, Seattle, p. 197-212.

Íslandsbanki, 2011. "United States Geothermal Energy Market Report." Íslandsbanki Geothermal Energy Team, Reykjavík, Iceland, October 2011, 24 pp.

Lara L.E., H. Moreno, J.A. Naranjo, S. Matthews, C. Pérez de Arce, 2006. "Magmatic evolution of the Puyehue–Cordón Caulle area (40°S), Southern Andean Volcanic Zone: From shield to unusual rhyolitic fissure volcanism." Journal of Volcanology and Geothermal Research, v. 157, p. 343-366.

Larsen G., K. Grönvold, S. Thorarinsson, 1979. "Volcanic eruption through a geothermal borehole at Námafjall, Iceland." Nature, v. 278, p. 707-711.

Lipman P.W., D.R. Mullineaux, 1981. "The 1980 Eruptions of Mount St. Helens, Washington." United States Geological Survey Professional Paper 1250, United States Government Printing Office, Washington, D.C., 844 pp.

Major J.J., R.J. Janda, A.S. Daag, 1996. "Watershed disturbance and lahars on the east side of Mount Pinatubo during the mid-June 1991 eruptions." *In:* Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines, *eds:* C.G. Newhall and R.S. Punongbayan, University of Washington Press, Seattle, p. 895-919.

Marzocchi W., L. Sandri, P. Gasparini, C. Newhall, E. Boschi, 2004. "Quantifying probabilities of volcanic events: The example of volcanic hazard at Mount Vesuvius." Journal of Geophysical Research, v. 109, B11201, 18 pp.

Marzocchi W., G. Woo, 2007. "Probabilistic eruption forecasting and the call for an evacuation." Geophysical Research Letters, v. 34, L22310, 4 pp.

Marzocchi W., G. Woo, 2009. "Principles of volcanic risk metrics: Theory and the case study of Mount Vesuvius and Campi Flegrei, Italy." Journal of Geophysical Research, v. 114, B03213, 12 pp.

Marzocchi W., L. Sandri, J. Selva, 2010. "BET_VH: a probabilistic tool for long-term volcanic hazard assessment." Bulletin of Volcanology, v. 72, no. 6, p. 705-716.

Newhall C.G., A.S. Daag, F.G. Delfin, R.P. Hoblitt, J. McGeehin, J.S. Pallister, M.T.M. Regalado, M. Rubin, B.S. Tubianosa, R.A. Tamayo, J.V. Umball, 1996. "Eruptive history of Mount Pinatubo." *In:* Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines, *eds:* C.G. Newhall and R.S. Punongbayan, University of Washington Press, Seattle, p. 165-196.

Newhall C.G., R.P. Hoblitt, 2002. "Constructing event trees for volcanic crises." Bulletin of Volcanology, v. 64, no. 1, p. 3-20.

Oppenheimer C., 2011. "Eruptions that shook the world." Cambridge University Press, Cambridge, United Kingdom, 392 pp.

Paladio-Melosantos M.L.O., R.U. Solidum, W.E. Scott, R.B. Quiambao, J.V. Umbal, K.S. Rodolfo, B.S. Tubianosa, P.J. Delos Reyes, R.A. Alonso, H.B. Ruelo, 1996. "Tephra falls of the 1991 eruptions of Mount Pinatubo." *In:* Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines, *eds:* C.G. Newhall and R.S. Punongbayan, University of Washington Press, Seattle, p. 513-536.

Peterson D.W., R.I. Tilling, 2000. "Lava Flow Hazards." *In:* Encyclopedia of Volcanoes, *ed:* H. Sigurdsson, Academic Press, San Diego, p. 957-972.

Porras E.A., T. Tanaka, H. Fujii, R. Itoi, 2005. "Numerical Modeling of the Momotombo Geothermal System, Nicaragua." Proceedings World Geothermal Congress, Antalya, Turkey, 24-29 April 2005, 16 pp.

Sandri L., G. Jolly, J. Lindsay, T. Howe, W. Marzocchi, 2011. "Combining long- and short-term probabilistic volcanic hazard assessment with cost-benefit analysis to support decision making in a volcanic crisis from the Auckland Volcanic Field, New Zealand." Bulletin of Volcanology, v. 74, no. 3, p. 705-723.

Scott W.E., R.P. Hoblitt, R.C. Torres, S. Self, M.M.L. Martinez, T. Nillos, 1996. "Pyroclastic flows of the June 15, 1991 climactic eruption of Mount Pinatubo." *In:* Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines, *eds:* C.G. Newhall and R.S. Punongbayan, University of Washington Press, Seattle, p. 545-570.

Selva J., A. Costa, W. Marzocchi, L. Sandri, 2010. "BET_VH: exploring the influence of natural uncertainties on long-term hazard from tephra fallout at Campi Flegrei (Italy)." Bulletin of Volcanology, v. 72, no. 6, p. 717-733.

Selva J., G. Orsi, M. Antonio Di Vito, W. Marzocchi, L. Sandri, 2011. "Probability hazard map for future vent opening at the Campi Flegrei caldera, Italy." Bulletin of Volcanology, v. 74, no. 2, p. 497-510.

Sepúlveda F., K. Dorsch, A. Lahsen, S. Bender, C. Palacios, 2004. "Chemical and isotopic composition of geothermal discharges from the Puyehue–Cordón Caulle area (40.5°S), Southern Chile." Geothermics, 33, p. 655-673.

Siebert L., T. Simkin, 2002-. "Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions." Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3, (http://www.volcano.si.edu/world/).

Simkin T., L. Siebert, 1994. "Volcanoes of the World." 2nd edition, Geoscience Press, Inc., Tucson, Arizona, 349 pp.

Singer B.S., B.R. Jicha, M.A. Harper, J.A. Naranjo, L.E. Lara, H. Moreno-Roa, 2008. "Eruptive history, geochronology, and magmatic evolution of the Puyehue–Cordón Caulle volcanic complex, Chile." Geological Society of America Bulletin, v. 120, no. 5-6, p. 599-618.

Sugino H., T. Akeno, 2010. "2010 Country Update for Japan." Proceedings World Geothermal Congress, Bali, Indonesia, 25-29 April 2010, 7 pp.

ThinkGeoEnergy, 2010. "Ormat shuts down plant in Guatemala after volcanic eruption." Website http://thinkgeoenergy.com/archives/4887, posted June 2, 2010.

Wolfe E.W., R.P. Hoblitt, 1996. "Overview of the eruptions." *In:* Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines, *eds:* C.G. Newhall and R.S. Punongbayan, University of Washington Press, Seattle, p. 3-20.