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GEOHAZARDS IN GEOTHERMAL RESOURCE EXPLOITATION

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ABSTRACT

Geohazards need to be taken into account in exploitation of geothermal resources. Geohazards give rise to ground movements and may cause economic and social damage that affect human activities and other infrastructural installations. The hazards regarded in this case include volcanic activities, active fault movements, earthquake activities, landslides, gas fluxes and possibility of flash floods. Each geohazard has its own characteristic way of potential impact and hence classifying vulnerability of different regions and creating awareness on potential impact is essential. Geohazards mapping is necessary for geothermal fields in order to gather a data base, which is instrumental in deriving appropriate mitigation measures.

1. INTRODUCTION

A geohazard is a geological state that represents or has the potential to develop further into a situation leading to damage or uncontrolled risk. Geohazards are widespread phenomena and are primarily related to geological and environmental conditions. The events can be sudden (catastrophic) or gradual and capable of causing damage or loss of life and property. Geohazards can be caused by natural process or anthropogenic activities. Geohazards in geothermal environments have significant and sometimes profound consequences on surrounding landscapes and ecosystems, as well as, health of local population (Arya et al., 2005). The effects of geohazards on the landscape can range from complete burial of surface vegetation and pre-existing topography to subtle, short-term perturbations of geomorphic and ecological systems. In other cases, geohazard events may set in motion a series of landscape changes that could take centuries to millennia to be realized. The need to observe their behavior, understand them better and mitigate their effects become ever more urgent. The vulnerability of a particular geothermal environment to geohazard occurrence may vary depending on may reasons including proximity, topography, slope, vegetation, structure, etc. Arya et al. (2005) define vulnerability as the extent to which a community, service, structure, or geographic area is likely to be damaged or disrupted by the impact of a particular geohazard, on account of its nature, construction and proximity to hazardous or disaster-prone area.

Decades of research may have contributed towards betterment of our understanding on the processes of geohazard formation but still along way has to be covered to develop better mitigation procedures. This review provides a synthesis of some of the best-studied geohazards associated with geothermal resource exploitation and perhaps will serve as a starting point for future work on this topic.

2. POTENTIAL GEOHAZRDS IN GEOTHERMAL ENVIRONMENTS

2.1 Earthquakes

Earthquakes are one among the highly dangerous geohazards in geothermal environments. They pose severe threat due to their unpredictability and associated secondary impacts. Earthquakes are violent vibrations of the Earth's plate caused by sudden release of energy that build-up at and/or beneath the surface of the Earth's crust. Natural processes that modulate the spatial and temporal occurrence of earthquakes include tectonic/deviatoric stress changes, migration of fluids in the crust, Earth tides, surface ice and snow loading, heavy precipitation, atmospheric pressure changes, sediment unloading and groundwater loss (Ramkumar and Neelakantan, 2007). Such processes perturb stress on faults by only small amounts but, since rock failure is earthquakes is a critical process, nucleation of each event is ultimately brought about by a final, incremental change in stress. The intensity and magnitude of an earthquake is measured is terms of Mercalli and Richter scale, respectively.

Earthquakes generate allied geohazards such as landslides, tsunami, etc. Examples of tsunamis triggered by (usually undersea) earthquakes include the 1960 Great Chilean Earthquake and the 2004 Indian Ocean tsunami and landslides. Among the most famous of historical tsunami linked specifically to volcanic events arose from the Minoan (or Thera) eruption in the Santorini archipelago of the Aegean 3600 years ago. This event triggered a massive tsunami that hit Crete, 100 km to the south and is believed to have contributed to the destruction of the thriving Bronze Age civilization of the Minoans. More recently, tsunamis from the Krakatau (Krakatoa) eruption of 1883 contributed to the destruction of 165 villages and a significant fraction of the official death toll of more than 35,000 (the un-official death toll suggests that up to 120,000 persons were killed). Among the affected towns was Merak, a seaport in western Java, destroyed by a tsunami more than 40 m high. It is important to note that earthquakes are quite uncommon in the Eastern branch of the EARS, the largest of magnitude 4-5.5 occurring in Ethiopia in 1908 (Saemundsson, 2017). However, about 20 quakes of magnitude 6.4-7.4 have been reported in the Western branch of the EARS since 1970 (Figure 1).

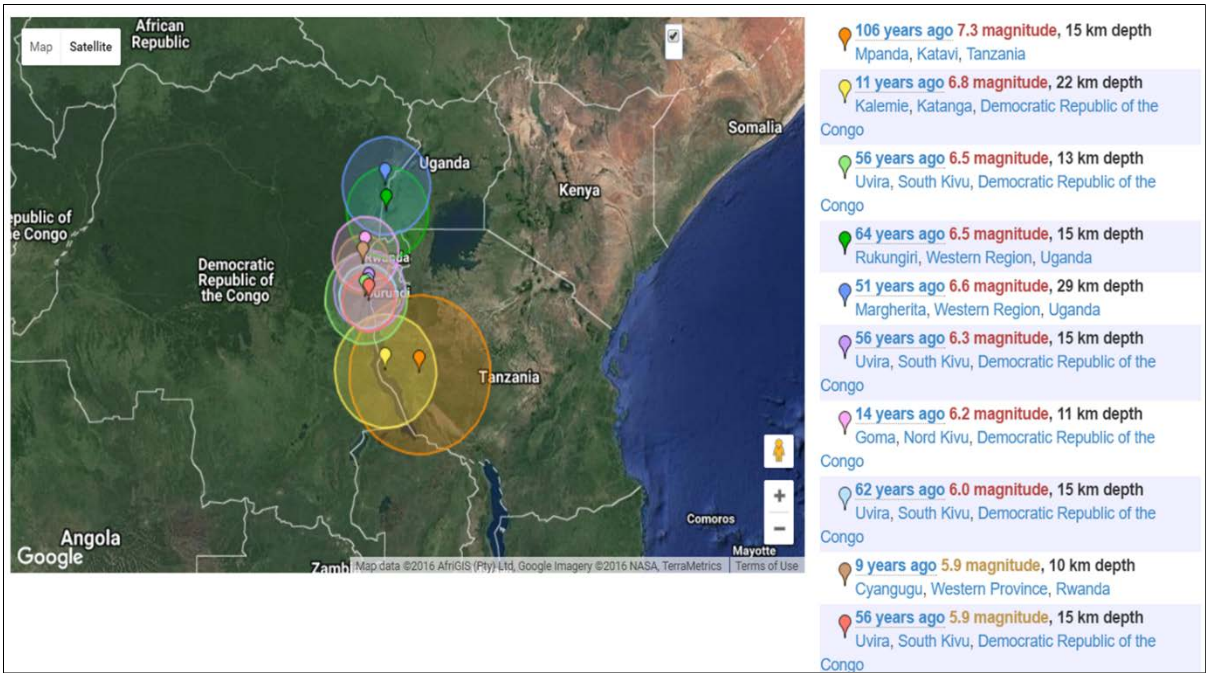

FIGURE 1: Major earthquake events along the Western branch of the EARS

2.2 Volcanic eruptions

Volcanoes are geomorphological features located along active plate margins either in continental and submarine regions spewing hot molten magma (Figure 2), toxic gas and pyroclastic materials. Volcanic activities are among the most dramatic of all natural phenomena, and they can affect human health through a range of direct and indirect pathways. The death toll over the past 500 years has been estimated to be more than 250,000, with major eruptions at Tambora in 1815, Krakatoa in 1883, and Pelée in 1902. The majority of casualties in the past few centuries are result of pyroclastic flows, lahars, and suffocation or building collapse from ash or debris; tsunamis, which may spread for hundreds of miles from the active site; and indirect consequences of eruptions, such as famine or infectious disease outbreaks.

FIGURE 2: Eruption of the Krafla volcano, Iceland

Although locations of volcanoes are precisely mapped, unpredictability of eruptions makes volcanoes one of the most devastating geohazards in geothermal environments. Eruptions of various sizes have significant impacts on the landscape that may persist for decades to millennia. The area affected by eruptions range from few hundreds of meters to few thousands of kilometres. The nature of the eruption (or other volcanic event) influences the duration of emissions, the chemical composition of the toxic compounds expelled, and the range of dispersal. Volcanic hazards stem from two classes of eruptions namely explosive (releasing large quantities of gas, hot ash, and dust, such as Mt. St. Helens) and effusive (associated with large lava flows but less dramatic outpourings of gas and dust, such as the basaltic volcanoes of Hawaii), or mixed (a combination of the two patterns). Volcanic products vary in terms of particle size, concentration, pH, and water solubility. All these factors can influence the bioavailability of toxins, and thereby processes that result in adverse health effects. Apart from the obvious thermal and physical injuries resulting from an eruption, volcanic materials may also contain toxic elements and compounds that disrupt biological systems. These compounds may be released in the form of gases, or carried with volcanic matter falling from eruptive columns or ash plumes. Some toxic compounds, such as radon, may persist in volcanic products (and continue to cause injury) long after the eruptive event ceases.

In the EARS, volcanic eruptions are different as regards to area and type (Saemundsson, 2017). For example, further north in Djibouti and Ethiopia, basaltic fissure eruptions are predominant along elongate volcanic systems such as Ardoukoba, which last erupted in 1978, and Dabbahu, which last erupted between 2005-2008. History of volcanic eruptions in Kenya (as studied by Leat, 1984; Scott, 1980; and Naylor, 1972) has provided a list of volcanoes and when they were last active as shown in Figure 3.

2.3 Gas fluxes

Steam, from both magmatic and superficial sources (such as overlying lakes or groundwater), are the most common gas emissions associated with geothermal environments. Other, often very toxic, gases are also emitted during eruptive events, and there are numerous accounts of volcanic gases causing death. Some urban centres, such as Rotorua in New Zealand, are built around geothermal fields, thereby raising the risk of toxic gases (including CO_2, H_2S, and radon) to enter buildings directly from the ground. In terms of adverse effects on human health, gas fluxes may be classified as follows: gases that act as inert asphyxiants (e.g. CO_2); those with irritant effects on the respiratory system (i.e. directly injurious) include the hydrogen halides (e.g. hydrofluoric acid) and oxides of sulphur (e.g. SO_2); and those that combine both the properties and act as noxious asphyxiants.

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
The Barrier	1032	3385	2.32, 36.57	1921
Central Island	550	1804	3.5, 36.042	-
Chyulu Hills	2188	7178	-2.68, 37.88	1855
Mount Elgon	4321	14178	-1.1, 34.5	
Elmenteita Badlands	2126	6975	-0.52, 36.27	Holocene
Emuruangogolak	1328	4357	1.5, 36.33	1910
Homa Mountain	1751	5745	-0.38, 34.5	Holocene
Mount Kenya	5199	17057	0°9'S 37°18'E	-
Korosi	1446	4744	0.77, 36.12	Holocene
Likaiu	915	3000	2.17, 36.36	-
Longonot	2776	9108	-0.914, 36.446	1863
Marsabit	1707	5600	2.32, 37.97	Holocene
Menengai	2278	7472	-0.2, 36.07	6050 BC
Namarunu	817	2680	1.9, 36.27	6550 BC
North Island (Kenya)	520	1706	4.07, 36.05	-
Nyambeni Hills	750	2460	0.23, 37.87	Holocene
Ol Doinyo Eburru	2856	9370	-0.63, 36.23	-
Ol Kokwe	1130	3707	0.63, 36.08	Holocene
Olkaria	2434	7985	-0.904, 36.292	1770
Paka	1697	5568	0.92, 36.18	6050 BC
Segererua Plateau	699	2293	1.57, 37.9	Holocene
Silali	1528	5013	1.15, 36.23	5050 BC
South Island (Kenya)	800	2625	2.63, 36.6	1888
Suswa	2356	7730	-1.175, 36.35	-

FIGURE 3: List of volcanoes in Kenya and their eruption histories (Saemundsson, 2017)

2.4 Fault movement

Identifying sites for possible surface fault rupture is critical at the stage of site selection in any geothermal system. Many active faults are complex, consisting of multiple breaks (Figure 4). Hence, identifying areas with active fault traces is generally essential from engineering and structural point of view. Most surface fault rupture is confined to a relatively narrow zone a few feet to few tens of feet wide, making avoidance the most appropriate mitigation method. The evaluation of a given site with regard to the potential hazard of surface fault movement is based extensively on the concepts of recency and recurrence of faulting along pre-existing faults. However, it should be kept in mind that certain faults have recurrent activity, whereas, other faults may be inactive for thousands of years before being reactivated. Other faults may be characterised by creep-type rupture that is more or on-going. The magnitude, sense and nature of fault rupture also vary for different faults or even along different strands of the same fault. As a practical matter, fault investigation should be directed at the problem of locating existing faults and then attempting to evaluate the recency of their activity. As such, no structural development for human occupancy should be undertaken on the trace of an active fault.

2.5 Landslides and lahars

A wide variety of ground movements principally driven by gravity along a sloping terrain, located anywhere from mountains to coastal and deep sea can termed as landslide (Figure 5). However, other factors such as slope instability created by earthquakes, volcanic explosion, blasting, loss/sudden removal of vegetation cover on a sloping terrain, variation of hydrostatic and pore water pressure, erosion by rivers, glaciers and waves, heavy rain, liquefaction, etc, can aide in and/ or initiate a landslide. The pre-conditional factors build up specific sub-surface conditions that make the area/slope prone to failure (Bhandari, 2006). Volcanic debris following eruptions, including the rubble from lava flows and unconsolidated ash, is often unstable and prone to collapse. Seismic events or heavy rainfall may accelerate the landslides of such material.

FIGURE 2: Active fault movement in high temperature Krafla geothermal field in Iceland

A fast-moving, and potentially lethal, consequence of volcanic eruptions is the lahar. These torrential flows of mud, water, and debris wash down the sides of the volcano and are often associated with crater lakes, melting snow or ice, or heavy rainfall events, with or without a concurrent eruptive event. Lahars from some volcanic lakes may be hot and are often acidic. For communities situated in the path of lahars, the opportunities for timely warnings may be limited—sometimes with lethal consequences. In a lahar generated from the 1919 eruption of Kalut in Indonesia, 5000 people died. Those caught in the flow suffered from drowning, suffocation while entrapped, or severe trauma from penetrating wounds and fractures. In New Zealand, a lahar from Mt. Ruapehu in 1953 washed out a rail bridge shortly before the arrival of the main train servicing the North Island (Bhandari, 2006). The front carriages plunged over the edge of the washed-out bridge with a catastrophic result: 151 killed out of the 285 people on board.

2.6 Flash floods / Torrents

According to Arya et al. (2005), flash flood represents a temporary inundation of large regions as the result of an increase in reservoir, or of rivers flooding their banks because of heavy rains, high cyclones, storm surge along coast, melting snow or dam bursts. Two types of flash floods can be distinguished namely; (i) land-borne floods, or

FIGURE 1: Landslide near one of the geothermal prospects in Indonesia

river flooding, caused by excessive run-off brought on by heavy rains and, (ii) sea-borne floods, or coastal flooding, caused by storm surges, often exaggerated by storm run-off from the upper water shed. Flash floods is a recurrent geohazard and is particularly aggravated by the nature of the overlying material. During flooding, supply roots and other infrastructure get affected (Figure 6) due to which flooding also produces endemic diseases that intensifies the severity of the flood impact, particularly health hazards to fauna and flora including humans.

FIGURE 3: A deep crevasse caused by flash floods due to the loose cover of the pyroclastic material. The steam line and fence will be washed away if no remedial measures are taken.

2.7 Hydrothermal explosion

Hydrothermal explosions, although not common have been registered at several geothermal fields around the world. These explosions are associated directly to fumarolic areas where water can accumulate or in areas with a high water table. They are not very recurrent but in some cases such as El Zapote fumarole in the Ahuachapan geothermal area, have been reported after every strong rainfall season. These types of explosions are low energy explosions associated to geyser type activity or caused by a sudden burst of accumulated steam. They mainly expel hot wet mud and rocks that are found inside the fumarole that caused the explosion and their deposits only reach a few tenths of meters away from the vent.

Even though hydrothermal explosions are low energy explosions they can be deadly and cause damage to infrastructure if located near a vent. A hydrothermal explosion that occurred in 1990 at the Agua Shuca fumarole area in the Ahuachapan geothermal field, killed close to 20 people that lived right next to the mud pool that was the source of the eruption (Figure 7). Since these types of eruptions are associated to fumarole areas, they generally do not represent much of a hazard to geothermal infrastructure. However, in order to reduce any possible hazard, all visible fumaroles areas and areas of hydrothermal alteration should be mapped in detail so that they are taken into account when construction is being planned.

3. MONITORING AND MITIGATING GEOHAZARDS

Mitigation, a cornerstone of emergency management, is defined as taking sustained actions to reduce or eliminate the long-term risks to people and property from hazards. The following are some of the mitigation measures that should be taken into place:

FIGURE 4: Hydrothermal explosion in Ahuachapan geothermal area

- Providing an early warning system of potential health hazards and thereby allow a preparation period for resident populations.
- Identifying places prone to site effects, landslide and other geological hazards at local to national levels, particularly in places that buildings and construction are at risk.
- Developing criteria and regulations for construction and development in geothermal areas prone to ground movement, site effects and geological hazards and reflect the results into master, comprehensive and conductive plans.
- Preparing mitigation methods (technically and practically) based on local conditions, social and economic situation.
- Promoting public knowledge of geohazards and related risks and planning for making relief activities, if such accidents occur in the future.
- Preventing of construction of important facilities at hazardous area (geological hazards prone areas), except in special cases by considering the necessary engineering provisions.
- Reducing the population density in geohazard prone areas.
- Developing the monitoring, earlier warning and automatic shutdown systems (for lifelines such as gas and water) in the areas where such facilities are subject to geological hazards.

4. CONCLUSIONS

- Geohazards are real and should not be assumed.
- Occurrence of different geohazards depends on the geological setting of a particular area.
- Mapping for potential geohazards is necessary for early detection.
- Surveillance of our geothermal fields is deemed quite important.

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