The Awakening: The geological implications of a volcanic event after a period of dormancy at Mount Ngauruhoe

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Abstract

From the late 19th century through to the mid-1970s, the young andesitic stratovolcano, Mount Ngauruhoe, could be expected to erupt at least once every decade. But, since the last eruption in 1975, Ngauruhoe has become quiescent. By coupling the study of the deposits of previous eruption events at Ngauruhoe with a comprehensive literature review of reawakening events at other stratovolcanoes, the eruptive style of an uncharacteristically dormant volcano was analyzed, and the vulnerability, hazards and risks associated with a reawakening event were assessed. Despite the 35 year long repose period at the volcano, Mount Ngauruhoe's next eruption will probably be of the same scale as those recorded historical eruptions. Thus, the proximal hazards will be confined within Tongariro National Park, and any tephra fallout will simply be an inconvenience.

Introduction:

Mount Ngauruhoe, better known as Mount Doom from *The Lord of the Rings* films, is a 2500-year-old andesitic stratovolcano located within the Tongariro Volcanic Complex on New Zealand's North Island. Each year, an estimated one million people visit Tongariro National Park (DOC). It is vital that these trampers and skiers understand the hazards and risks associated with the area. Since the first recorded eruptions in the mid-1800s, this volcano, considered one of the country's most active, had been known to erupt at least once every decade (DOC). But, since the last vulcanian eruption in 1975, the volcano has remained uncharacteristically quiet.

Throughout its short history, Ngauruhoe has had variable eruptive styles (Hobden, Houghton & Nairn, 2002). Whether effusive, strombolian, or vulcanian, different volcanic eruptions are associated with distinct hazards. This fact, coupled with the volcano's unusually long repose period, warrants an updated hazards and vulnerability study taking into account whether a reawakening event at Ngauruhoe indicates a larger, more explosive eruption.

The study of a volcano's past eruptive history is integral to any hazards study. And although much is known about Ngauruhoe's historical eruptions, especially those that occurred within the last 60 years, there is not much information on the eruption style, erupted volume, or eruption rate of the volcano's prehistoric flows. No datable material has been found in these prehistoric flows, and only relative ages can be inferred based on vegetation cover, flow morphology, and flow-contact relationships. A seismometer was only installed on the flanks of Ngauruhoe in 1976; thus, the relationship between earthquakes and eruptions on the volcano remains unknown (Hobden, 1997). And lastly, there has not been a period of quiescence greater than thirteen years in Ngauruhoe's recorded history (Simkin and Seibert, 1994).

Methods:

As stated earlier, because every volcano has its own personality, the best method of determining possible future volcanic hazards is to study its past behavior. Consequently, fieldwork was done on and around Ngauruhoe and Mangatepopo Valley, the glacial valley located below the volcano's northwestern flanks, investigating the characteristics of both the pre-historic and historical flows. The area and its lava flows were mapped in order to determine their relative ages, and eighteen samples were collected from the volcano's lava flows and pyroclastic avalanche deposits for geochemical (X-ray fluorescence) and textural analysis (thin sections).

This fieldwork was coupled with an intensive literature study not only on Ngauruhoe, but also on general volcanic hazards, comparable andesitic stratovolcanoes such as El Chichon in Mexico, Tungurahua in Ecuador and Galeras in Columbia, reawakening events and their precursors, and statistical methods for determining probabilities of both the timescale of a future eruption and its associated hazards. ArcGIS was utilized in the creation of the hazards maps.

Reawakening Events and Andesitic Stratovolcanoes Around the World

To help determine what to expect from a possible eruption at Ngauruhoe, volcanoes with similar magma composition, eruption history, and growth rate were analyzed. There have been many attempts by the academic community to define the period of repose that quantifies a 'dormant volcano,' but no consensus has been reached (Szakacs, 1994, Zobin and Jimenez, 2008, Ortiz et al., 2009). In this study, the term 'reawakening volcano' will then simply refer to events that occur after a volcano is quiescent for a notable period of time.

Tungurahua, Ecuador

The andesitic stratovolcano Mount Tungurahua stands over 5000 meters high in the Ecuadorian Andes. Hall et al. have comprised one of the most cited papers with respect to this young, active volcano. This frequently erupting volcano has erupted an estimated 17 times since it was first discovered in 1532, with a discrete eruptive episode happening each century (Hall et al., 1999). The current Tungurahua volcano is only 2300 years old, as it is actually the third cone in a complex of which the former two have succumbed to sector collapse (Hall et al., 1999). Tungurahua, which has an estimated growth rate of 1.5 x 10^3 m^3/year, threatens the tourist town of Baños — "The Gateway to the Amazon" (Hall et al, 1999). The eruption deposits at the volcano have not undergone any specific petrological evolution, as the silica composition has remained between 55-58% over the past 2300 years (Hall et al., 1999). Seventy percent of the latest volcanic cone's deposits have been pyroclastic avalanches; while 30% have been lava flows (Hall et al, 1999). Lahars and avalanches are considered the volcano's most prominent hazard, and the threat of sector collapse cannot be ruled out. Because of the viscosity of the lava, flows do not pose a great threat, but pyroclastic density currents directly threaten the city of Baños (Hall et al, 1999).

When Tungurahua erupted in 1999, it was considered a 'reawakening event' (Ruiz et al., 2006), as the previous eruption occurred in 1918. Although the repose periods between this volcano's eruptive cycle was about 80 years, this is not uncommon for Tungurahua. As stated earlier, it has experienced an eruptive period once a century: 1640-1641, 1773-1777, 1886-1888, 1916-1918, and 1999 - 2006 (Ruiz et al., 2006). When the volcano experiences reawakening events, it seems to do so cyclically, and the eruption products are somewhat easier to discern.

El Chichon, Mexico

El Chichon is an andesitic stratovolcano located in southeastern Mexico. The volcano erupted in 1982 after a 550-year long period of quiescence (Zobin and Jimenez, 2008). Not much was known about this volcano prior to the 1982 eruption—which has been classified as one of the ten largest eruptions of the last century. Zobin and Jimenez used the El Chichon eruption as their focus for a study on the characteristics of reawakening andesitic and dacitic volcanoes. They concluded that periods of quiescence could last anywhere from a few years to a few millennia, but that the largest eruptions often occur only when a volcano has remained inactive for over 100 years (Zobin and Jimenez, 2008). Moreover, the eruption size at a quiescent volcano was more likely to be on the smaller side if that volcano experienced increased seismic activity for at least a year prior to the eruption (Zobin and Jimenez, 2008). And, although the 1982 eruption was characterized as a VEI (Volcanic Explosivity Index) 5, according to Simkin and Siebert (1994) other eruptions on the volcano, such as those that occurred in approximately 1360, 780, and 2030 BC, have been estimated to be of the same size.

Galeras, Columbia

Galeras Volcano, located in southwestern Columbia, is approximately 5000 years old, active, andesitic, and characterized by vulcanian VEI 2 and 3 eruptions (Simkin and Siebert, 1994). Before an eruption in 1988, the volcano experienced a 52-year long period of quiescence (Cortes and Raigosa, 1997).

Between 1992 and 1993, six vulcanian eruptions occurred at Galeras, all VEI 1, and five of them preceded by earthquakes with characteristic tornillo signals (Narvaez et al., 1997). Tornillos are unique to andesitic volcanoes, and are associated with vulcanian and gas eruptions (Diego and Roberto, 1997). These signals are characterized by a long duration when compared to their amplitude and a slowly decreasing coda, which makes their signal look like a screw - hence the appellation "tornillo".

Narvaez et al. (1997), who have created tornillo sub-classification groups based on the specific type of screw-like signal, note that the one eruption during this two year period that was not preceded by a tornillo episode emitted much less volume than the other five (Narvaez et al., 1997). In studying these signals, Narvaez et al. (1997) determined that at Galeras, the longer and more frequently these unique earthquakes occurred, the more impending the eruption was. And, they suggest that the number of preceding tornillos that occur may allow for the predictability of the size of the eruption.

Mount Ngauruhoe

Every volcano has its own unique personality. Thus, although Mount Ngauruhoe may have comparable andesitic volcanoes with similar growth rates, ages, or magma compositions, in order to best decipher what a specific volcano is capable of, its own eruptive history must also be characterized.

Eruptive History

Based on both personal field mapping and analysis and previous studies on Mount Ngauruhoe, some common eruptive characteristics can be determined. Ngauruhoe is a basaltic-andesitic to andesitic volcano;

the silica compositions of the sampled flows range from 54-58% SiO_2. The oldest flows are also those that extend farthest into Mangatepopo Valley. Most of the lava flows are aa or blocky in nature, yet, while doing fieldwork, a localized pahoehoe like flow was observed. It was also evident that the lava flows usually followed the existing topography.

Ngauruhoe's lava flow lengths range from .5 to 7km - the larger end being the older flows (Hobden, 1997). Many of the flows off the volcano are channelized (Hobden, 1997). Instantaneous lava eruption rates can vary from 1-4m^3/s. The eruption rate during the 1975 eruption was estimated at .7m^3/s. The thicknesses of eruption deposits are also variable, but they typically range between 3-5 meters, with some, like the 1975 pyroclastic avalanche deposit, as thick at 10 meters (Hobden, 1997).

Because there is no datable material in Ngauruhoe's eruption deposits, not much is known about any of the volcano's eruptive deposits before 1870. But, the 1949, 1954, and 1975 eruptions have been closely analyzed.

Both the 1949 and 1954 flows exhibited multiple levees and channels (Hobden, 1997). And, both the 1948-49 eruption and 1954 eruption were considered strombolian in size (Simkin and Seibert, 1994). Fire fountains were characteristic of the latter eruption, as were ash explosions with eruption columns over a kilometer in height. These eruption columns deposited minimal ash in Taupo, a major town located 65 kilometers west of the vent (Hobden, 1997).

During the 1975 vulcanian eruption, people taking pictures in the Mangatepopo car park, just over 7km away from the volcano's vent, were completely unharmed. But, bombs over a meter in diameter were ejected over 2.5 km away from the vent, and blocks 20m in diameter were later found around Ngauruhoe's summit (Hobden et al., 2002). A 7km high column was created during this eruption, and 1mm of ash was deposited 21km away. Approximately $1.5x10^6$ m^3 of material was deposited on the volcano's flanks during the eruption.

Discussion

General

Based on the geochemical data, there has been no obvious evolutionary trend in silica, magnesium or trace element content. Although there seems to be a slight rise in silica content, when a line was fitted to the data points, its R^2 value was less than 0.1. There is no evident evolution in flow morphology. Both pre- and post-Taupo ignimbrite deposits have ogive structures. And, interestingly, the pahoehoe-like lava has the highest silica content (57.9%) out of any of the samples acquired.

As shown in Figure 1, no relationship between repose period and VEI can be identified. A study of titanomagnetite textures, fast-ascent eruptions at New Zealand's own andesitic stratovolcano, Mount Taranaki, have been found to have a 1500 year periodicity (Turner et al., 2008). But unlike Taranaki or Tungurahua, there seems to be no periodicity in Ngauruhoe's eruptions. Of the forty-nine recorded eruptive events at Ngauruhoe, three were VEI 1, three were VEI 3 (all of these were historical eruptions - 1954; 1972; 1975), and 43 were VEI 2 (Simkin and Siebert, 1994). Moreover, based on the very limited data set of the 1949, 1954, and 1975 eruptions, there is no correlation between repose period and volume of material erupted. The random nature of Ngauruhoe's eruptions coupled with the anomalous thirty-five-year repose period make determining hazards slightly more difficult.

In January 2001, tornillos were recorded on a seismometer .5 km away from Te Maari Craters, just north of Ngauruhoe (Hagerty and Benites, 2003). The amount of these tornillos peaked in September 2001, yet no eruption followed (Hagerty and Benites, 2003). But, unlike in Galeras, Columbia, tornillos did not necessarily indicate an eruption event. Between July and November 1994, Purace volcano, also in Columbia, experienced 27 tornillo events. However, this was during the volcano's period of quiescence (Gomez and Torres, 1997). This discrepancy illustrates both the unique personality of each volcano and the fact that events that occur at one volcano do not necessarily indicate the same results at another. But, if one is interested in the hazards at a potential eruption from Tongariro Volcano, they are encouraged to read J. W. Cole and D. W. Hitchcock's 2007 paper on the subject.

In June 2007, GNS, New Zealand's USGS equivalent, raised the alert level from 0 to 1 at Mount Ngauruhoe due to increased seismic activity. The seismic activity remained elevated for almost two years, and on January 18, 2008, GNS released another bulletin asserting that the earthquakes at Ngauruhoe had increased from about 5-30 per day to 80 per day (GNS). But, on December 2, 2008, the alert level of the volcano was lowered back to 0, as the volcano's seismic activity decreased to normal background noise (GNS).

Application to Hazards

There are many factors that lead to the assumption that the next eruption at Ngauruhoe will be of the same scale as previous eruptions - a VEI 2 or 3. Forty-three of the past forty-nine recorded eruptions have been VEI 2. And, although the last few eruptions have been VEI 3, the hazards associated with these have not affected more people than those that were VEI 2. Moreover, it has been noted that the probability of a young, rapidly growing volcano producing a violent eruption is extremely low (Conner et al., 2006). Thus, even though Ngauruhoe has been uncharacteristically inactive for the past thirty-five years, the earthquake swarms from 2006 to 2008 coupled with the fact that the volcano itself is still extremely young indicate that the next eruption will probably be on the same scale as past eruptions. Therefore, the hazards associated with such will be similar.

The New Zealand Ministry of Agriculture and Forestry also conclude that the next event at Ngauruhoe would be similar in scale to the historical eruptions that occurred in 1954 and 1975. In an overview of North Island volcanoes, Dibble, Nairn and Neal (1985) conclude that the greatest hazard associated with an eruption at Ngauruhoe would be pyroclastic avalanches traveling at 30-40 m/s. Thus, those facing greatest risk during the next Ngauruhoe eruption would be trampers on the Tongariro

Crossing; and the number of people exposed to this hazard varies based on season (Figure 2). The most widespread hazard due to an eruption at Ngauruhoe would be tephra fall out, which can theoretically be carried up to 200km from the vent (Dibble et al., 1985).

The worst-case scenario eruption from Ngauruhoe would probably be about the same size event as the 10,000 year old eruption from North Crater (Neild et al., 1999). This eruption deposited lapilli east of Taupo. However, even if an event of this size occurred, all of the eruption's proximal hazards would still be confined within Tongariro National Park (Neild et al., 1999).

Hazards

The hazards maps were created based on the estimation that a future eruption at Ngauruhoe would be similar to those witnessed in historical times, despite the volcano's long repose period (Figures 3 & 4). As determined by the literature review, the most prominent factor in determining a volcano's eruptive hazards is its eruptive history.

Based on the extent of previous eruption deposits, a circle with a 3km radius has been placed around the vent as the ballistics zone. It is obviously advised that people should stay away from the Ngauruhoe's summit during an eruption. In the past, lava flows and pyroclastic avalanches have followed the volcano's existing topography down toward Mangatepopo valley, thus, although one should avoid the national park altogether during an eruptive event, if one happens to be on the Tongariro Crossing, he or she should clear out of valleys and climb to ridges. The lava flow and pyroclastic avalanche hazard zone has been determined based on the maximum extent of the Post-Taupo Ignimbrite deposit eruptions. Although none of the historical eruption deposits have reached this length, this hazards map is abiding by the adage, "better safe than sorry." During an eruption, trampers should not attempt the Tongariro Crossing.

During an eruption at Ngauruhoe, the most far-reaching hazard would be ashfall. New Zealand's prevailing winds come from the west, and it is likely that communities to the east of the Tongariro Complex would be most affected by the ashfall. Yet, even though the North Island is generally dominated by westerlies, the wind conditions over the North Island are still extremely variable (Kaye, 2007). Kaye (2007) cites two eruptions at Ruapehu volcano, one on October 11-12 and one on the October 14 to best illustrate this point. These eruptions were only two days apart, but tephra was deposited on completely different areas of the North Island. During the former eruption, ash travelled slightly northeast affecting the north half of the Hawkes Bay to Taupo (Kaye, 2007). The latter eruption occurred when winds were traveling to the southeast, therefore, the ash that was deposited missed Hastings altogether and landed mostly on Waipukurau. Moreover, the tephra fallout from an eruption at Ruapehu that occurred on the June 17 was deposited on Taupo, Rotarua, and Turanga, as the wind was coming from the southwest (Kaye, 2007).

Furthermore, it has been determined that the distance tephra travels perpendicular to the wind depends only on plume height, while the distance tephra can be carried downwind depends both on plume height and wind velocity (Carey and Sparks, 1986). The maximum column height witnessed during historical eruptions was 7km high. A medial hazards map has been created, based on graphs by Carey and Sparks, and wind speeds of 20 m/s and a plume height of 10km. Consequently, although the ashfall from Ngauruhoe will probably be deposited east of the volcano, the wind directions are so variable that anywhere from Turanga through to southern Hawkes Bay could be affected.

Conclusion

GNS currently monitors Ngauruhoe with one web camera, a seismic monitoring station, gas chemistry and airborne analysis, and two GPS stations. This constant monitoring is integral for both the safety of visitors to the National Park and determination of unrest at the volcano.

Tongariro National Park's busiest season is in the summer, when on any one day there may be over 200 people on the Tongariro Crossing. As risk is defined as the combination of hazard and vulnerability, the summer months lay claim to times of greatest risk. Moreover, there is no official entrance to Tongariro National Park - there are many paths that lead into the park. DOC currently has no way of monitoring the amount of people who come in and out of the area. Thus, it is essential that these trampers know the hazards associated with hiking the flanks of an active volcano.

Ngauruhoe has not exhibited any obvious evolutionary trends or simple periodicity to her eruptions. There has never been a repose period greater than thirteen years since eruptions from the volcano began to be reported. Consequently, determining the hazards of a 'reawakening event' at Ngauruhoe is difficult. However, based on the information inferred from previous deposits around Ngauruhoe and a literature review on stratovolcanoes, it seems that despite the uncharacteristically long repose period, the next eruption at Ngauruhoe will be of the scale of the historical eruptions, in which all the proximal hazards are confined within Tongariro National Park's boundary and the associated tephra fallout hazard would be minimal.

Acknowledgements - This study was supported by Frontiers Abroad. I am grateful to Stephen Brown (XRF), Rob Spiers (lapidarian), Dr. Anekant Wandrew (GIS) and Dr. Darren Gravely, and the Frontiers Abroad participants for their helpful review comments.

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Figures

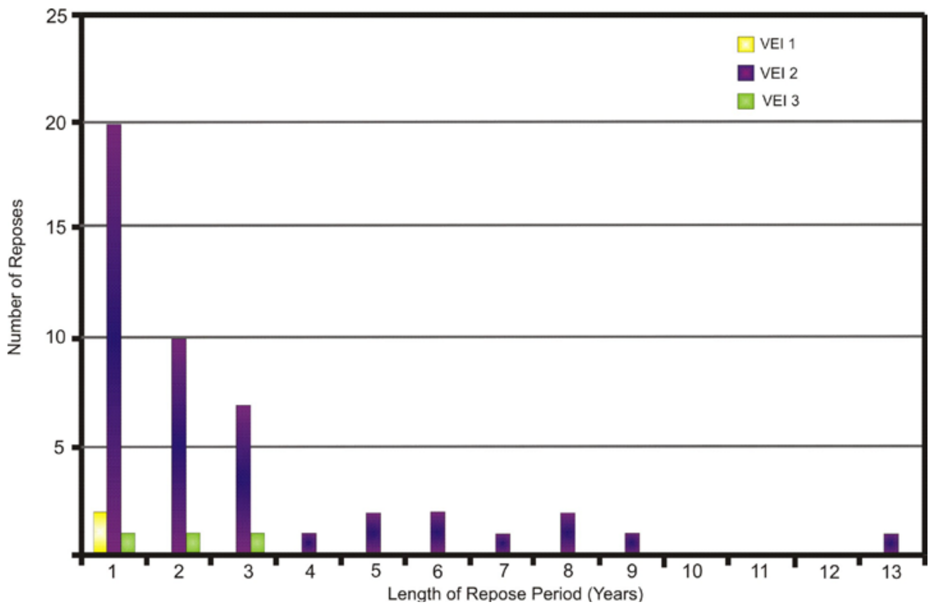

Figure 1. The size of the eruption is evidently unrelated to the length of the repose period.

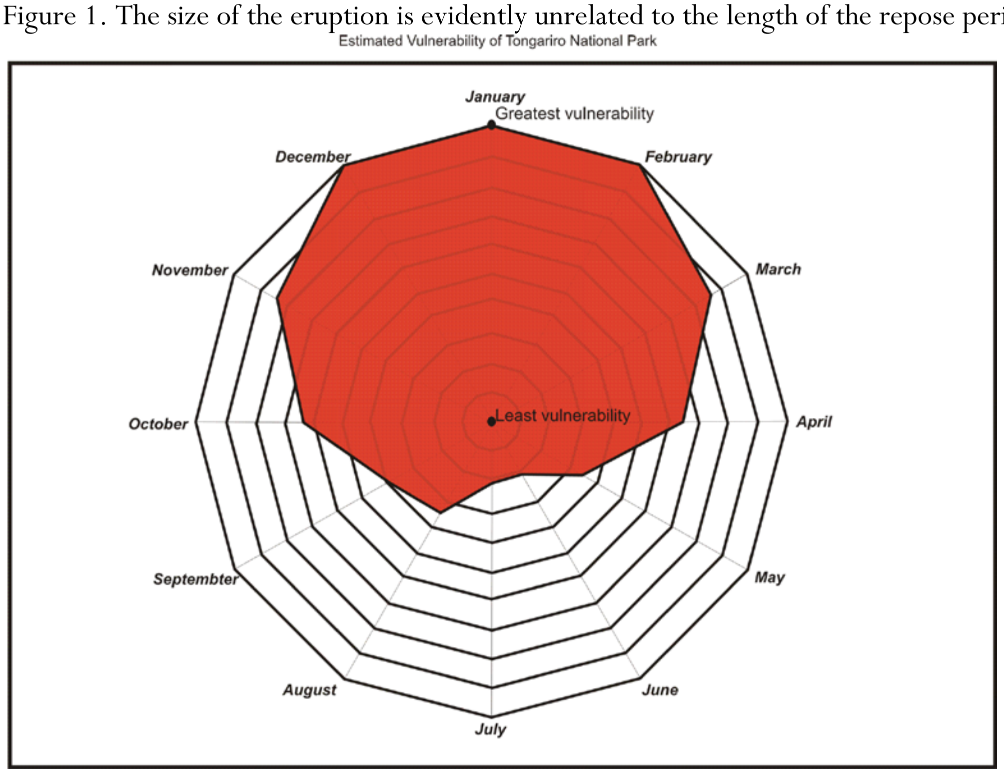

Figure 2. Estimated vulnerability of Tongariro National Park based on seasonality.

Medial Hazards Map of Mount Ngauruhoe, New Zealand: Maximum Extent of Tephra Fallout

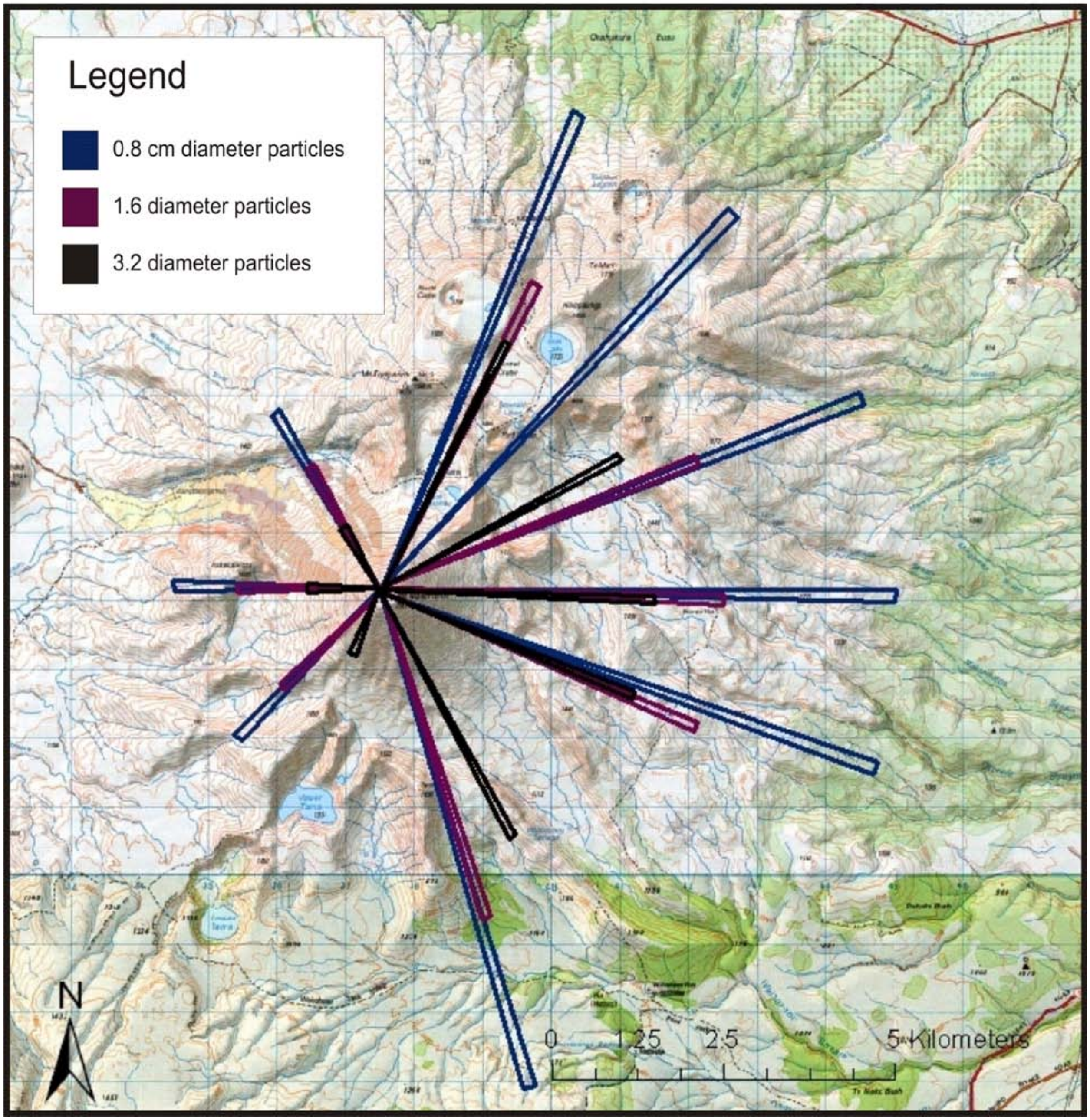

Figure 3. Medial tephra fallout hazards for Mount Ngauruhoe based on work done by Carey and Sparks (1986).

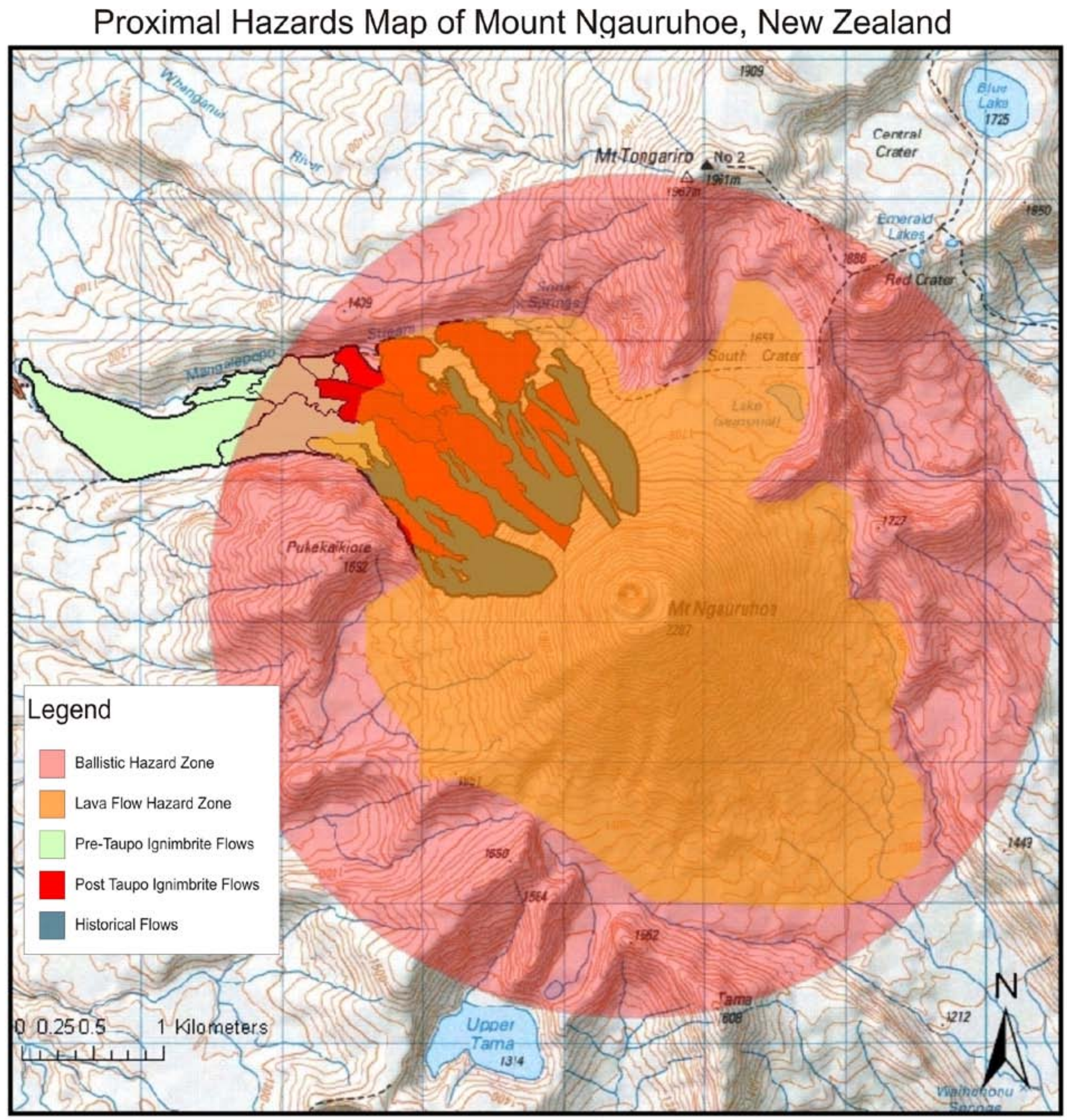

Figure 4. Proximal Hazards Map of Mount Ngauruhoe with previous eruption deposits also mapped.