Living in the Shadow of a Volcano:
Social and Environmental Impacts from an Eruption on Mt Erebus, Antarctica

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Supervised Project Report

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Abstract

Mt Erebus is the only active volcano on Ross Island. Though it is currently passively degassing, englacial tephrostratigraphy proves that there have been large eruptions in the past, with enough energy to throw out 4m sized blocks and have ash travel ~200 km away from the source. The potential for a future large eruption poses a threat to the two stations located at the tip of Hut Point Peninsula (McMurdo Station and Scott Base), and the surrounding environment.

A Strombolian eruption style, the most common style at Mt Erebus, produces hazards such as tephra fall, ballistics, and lahars. Using modelling software (ArcGIS and Tephra2) these hazards were mapped and have been shown to pose little direct threat to Scott Base due to its location on the Peninsula and distance away from the volcano. In a strong eruption scenario with high winds, the simulated tephra fall showed it reaching Scott Base with a maximum thickness of 0.05-1 cm. Despite this negligible impact on Scott Base, tephra fall and other hazards can injure personnel on the volcano and have a significant effect on the natural environment by changing the albedo of the snow and releasing aerosols into the atmosphere.

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Introduction

The aim of this study is to investigate the volcanic hazards that will affect the surrounding environment and people of Ross Island in the event of an eruption from Mt Erebus, the only active volcano in the area. This will be done through a study of the literature and through modelling of the main types of hazards that would occur during an eruption:

- Tephra fall
- Ballistics[1]
- Lahars

These hazards are modelled using data from past events similar to what would occur at Mt Erebus.

Modelling hazards from a potential eruption at Mt Erebus and understanding the effects on the environment and people in the surrounding area is essential when planning and preparing for a potential disaster. Monitoring of the volcano is an important part of this process as it may give early warning of an eruption.

While Mt Erebus has been exhibiting nearly constant minor activity for the past few decades englacial tephrostratigraphy studies have proven that Erebus has undergone larger explosive eruptions in the past, and there is a possibility for this to occur again in the future. Therefore, to prevent loss of life, it is vital that personnel of the bases are prepared for an eruption and have a thorough understanding of the hazards that could occur.

Geological Setting

At 3794m high Mt Erebus is the most prominent feature on Ross Island, Antarctica. All of the volcanoes that make up Ross Island are part of the McMurdo Volcanic Group (Cox, Turnbull, Isaac, Townsend, & Lyttle, 2012). This Group, exposed along edges of the West Antarctic Rift System, is made up of late Cenozoic volcanoes composed mainly of alkaline basaltic rocks.

[1] The terms ballistics and bombs are used interchangeably in this report, though ballistic is describing any large object thrown from the volcano while bomb is a grain size and specifically relates to liquid lava ejected from the vent, which then cooled in midair.

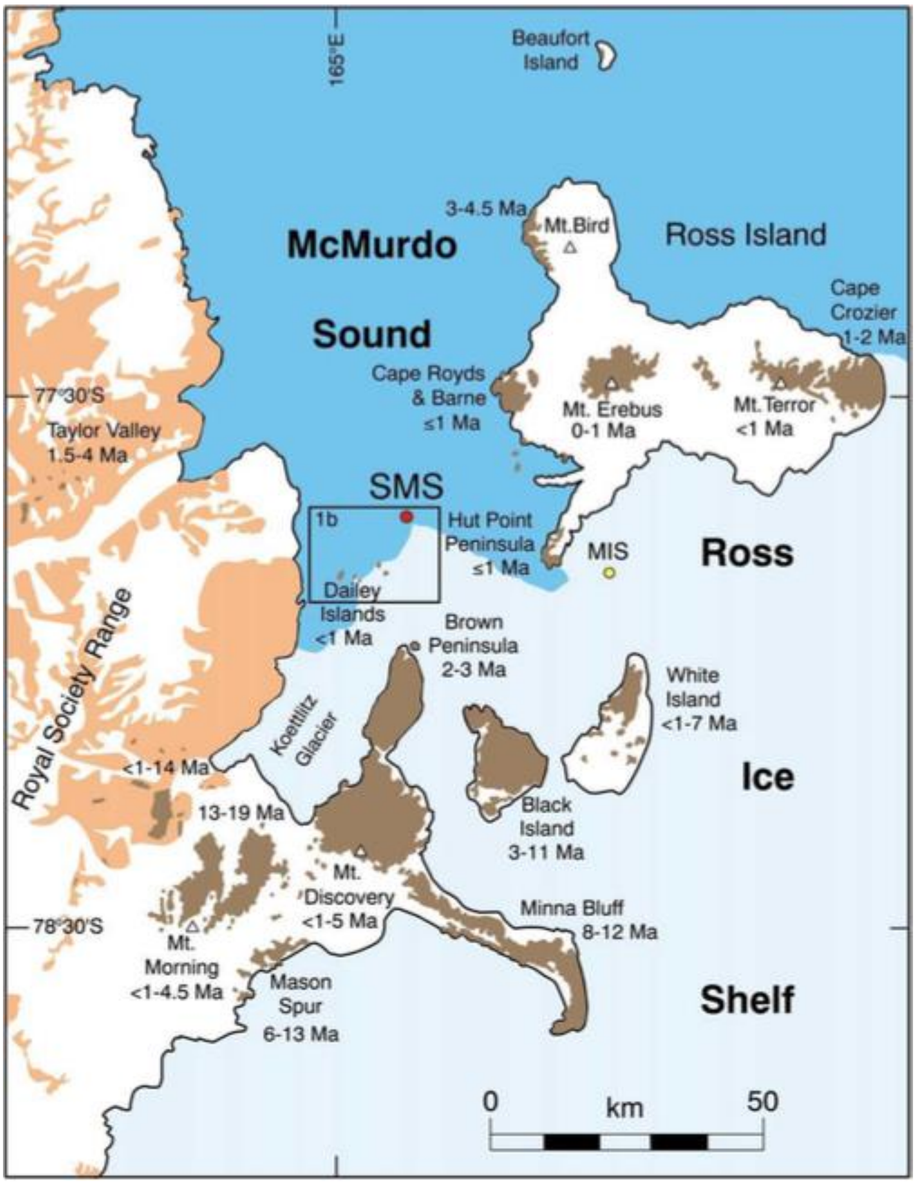

Figure 1. Map of McMurdo Sound. Dark brown sections represent exposed areas of the McMurdo Volcanic Group (Del Carlo et al., 2009).

Four large volcanoes form Ross Island (Mt Bird, Mt Terror, Mt Terra Nova, and Mt Erebus). These volcanics are primarily grouped into phonolite, tephriphonolite, and trachyandesite compositions, with small occurrences of other compositions such as basanite and trachyte (Fig. 2). The volcanics in this region include lava flows, dikes, scoria cones, and agglomerates (Cox et al., 2012). Ross Island is believed to have formed from intracontinental rifting and extension during the creation of the West Antarctic Rift System, and subsequent plume hotspot/plume activity, which continues to sustain the magmatism at Mt Erebus. It is suggested that the radial symmetry of the three volcanoes surrounding Mt Erebus is due to extension during crustal doming from the plume activity (Esser, Kyle, & McIntosh, 2004). The summit of the modern Erebus has two large craters, Main Crater and Side Crater. These align with a chain of ice towers, which have formed over active fumaroles, and the northeast-southwest orientation of these features are believed to represent an underlying rift zone fracture (Panter & Winter, 2008).

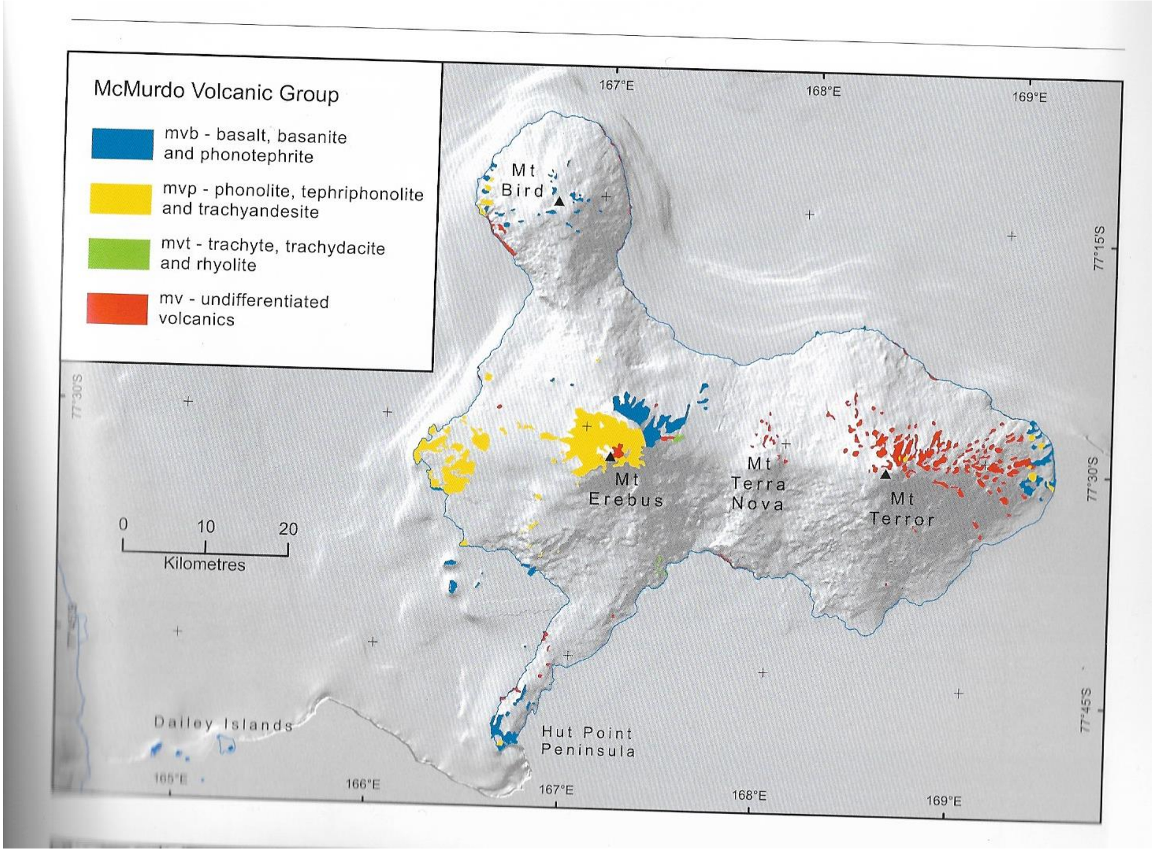

Figure 2. Map of Ross Island showing exposed rocks and types of rocks within the McMurdo Volcanic Group (Cox et al., 2012)

Volcanic History

Mt Erebus is a large, alkaline, intraplate stratovolcano[2]. During modern times its primary activity is continuous passive degassing from the convecting phonolitic lava lake in the Main Crater of the volcano (Sweeney, Kyle, & Oppenheimer, 2008).

[2] Stratovolcanoes are made up of lava and pyroclastic material, and have multiple layers from each eruptive event. Some eruptions occur on the flanks of the volcano, building it out sideways. These volcanoes are usually very steep and may be prone to slope failure (Oregon State University, 2017)

Magmatism began ~1.3 million years ago with the extrusion of lavas into the sea floor (Cox et al., 2012). This continued until 1 million years ago and built a broad low-lying shield volcano that makes up the lower 1600m of Mt Erebus (Esser et al., 2004). The morphology of this initial volcano indicates the extrusion of low viscosity lavas that were able to travel large distances. This was the first of three major stages in the volcanic history of Mt Erebus. The last two stages were more viscous and built two steep-sided cones on top of the broad shield (Esser et al., 2004). The second stage involved the formation of a secondary cone through explosive and effusive eruptions out of the Side Crater (Panter & Winter, 2008). A caldera eventually formed, destroying the summit of the proto-Erebus. (Fig. 3) The third stage involves Strombolian-phreatomagmatic activity and built the modern Erebus cone. Subsidence of the summit created a new caldera and later pyroclastic explosions have formed the current vent inside (Esser et al., 2004).

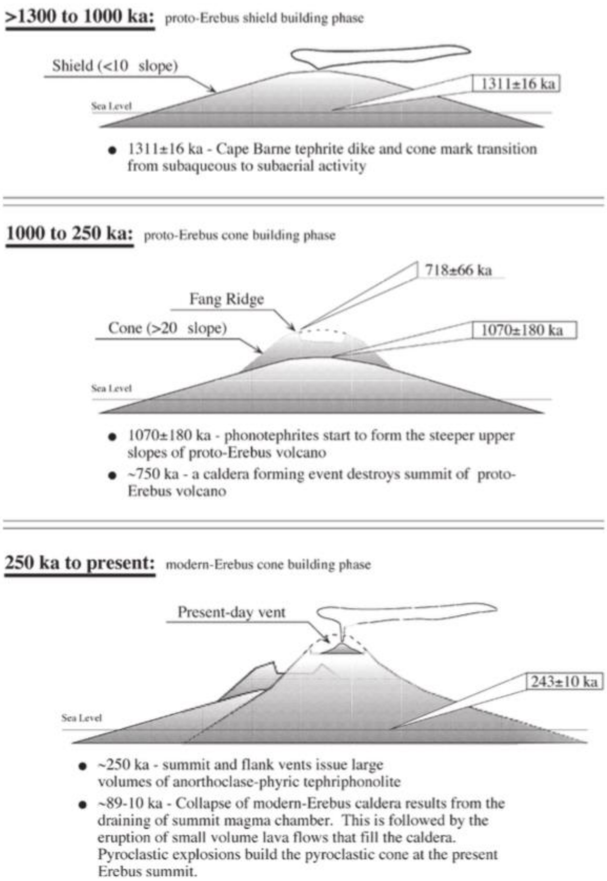

Figure 3. Diagram of historic cone building events. 1) Initial broad shield volcano. 2) Subsequent cone building from viscous lavas, caldera collapse of proto-Erebus summit. 3) Later formation of modern Erebus cone, and caldera creation during subsidence. Modern vent formed within new caldera (Esser et al., 2004).

Englacial tephrostratigraphy studies show that there have been approximately 43 explosive eruptions large enough to produce a record in ice core data (Harpel, Kyle, & Dunbar, 2008). The tephra found within ice layers is mostly from phreatomagmatic eruptions (eruptions that have interacted with water), with fewer from Strombolian eruptions. This is most likely because Strombolian eruptions produce less ash than phreatomagmatic eruptions so only unusually large Strombolian events would be present in the record. A mix of the two eruptions types is also commonly found (Harpel et al., 2008). These types of tephra formed when an initial phreatomagmatic eruption occurred, then changed to a Strombolian eruption as the water that was intensifying the eruption evaporated (Iverson, Kyle, Dunbar, McIntosh, & Pearce, 2014).
There is also evidence for past phreatoplinian eruptions (large, explosive eruptions enhanced with water interaction), where ash from Mt Erebus was found on the East Antarctic ice sheet ~200km away from the volcano. These events are rare and there has only been one recorded occurrence in the ice record of this type of eruption from Mt Erebus (Harpel et al., 2008; Iverson et al., 2014).

When James Ross first discovered Mt Erebus in 1841, the volcano was actively erupting in what is believed to be a Strombolian style with a large plume (Kaminuma, Ueki, & Juergen, 1985). The present eruptive activity of the volcano is dominated by smaller Strombolian eruptions from the lava lake with infrequent lava flows (Iverson et al., 2014). Strombolian activity usually produces frequent, moderate-sized eruptions from trapped gas building up pressure and exploding (Hickson, Spurgeon, & Tilling, 2013). This propels lava out of the vent, which cools and forms bombs. This eruption style produces ash, bombs and occasional lava flows. In recent eruptions, such as the 1984 eruption, the bombs found on Mt Erebus have been ~2m in size. Past eruptions, during earlier stages in the volcanic history, have produced much larger bombs, ~4m (Panter & Winter, 2008). This shows that Mt Erebus is capable of strong, explosive eruptions, despite its current state of passive degassing.

Hazards

This section provides a summary of the main hazards that are associated with Strombolian-style eruptions and the affect that these can have on the social and natural environment. Theses hazards include:

- Tephra fall
- Ballistics/bombs
- Lahars

While lava flows are also known to occur during Strombolian eruptions and on Mt Erebus, this hazard has not been included because the flows do not usually travel far or fast enough to pose a significant risk to people, infrastructure, or the environment.

Tephra fall

Tephra[3] is any material that is ejected from a volcano during an eruption and includes all grain sizes. For the purposes of this study, 'tephra fall' is used instead of the term 'ash fall' to include grain sizes larger than ash (>2mm) that may occur during a Strombolian eruption.

Ash is formed when volatiles within the magma exsolve to form gas bubbles as it rises up the conduit and decompresses. As more bubbles form a foam is created, and fragmentation eventually occurs. This fragmentation tears apart the magma into small particles that cool in the air to form ash (Thomas Wilson & Stewart, 2013).

Due to the fine nature of ash it can be carried up by an eruption plume (like that of a Strombolian or Plinian eruption) and can be transported significant distances depending on how high the plume was and how explosive the eruption. This can cause widespread damage to areas around the volcano, though the thickness and grainsize of the deposit decreases further from the vent (Thomas Wilson & Stewart, 2013).

[3] The terms tephra and ash are used interchangeably in this report when not specifically referring to a tephra fall

As ash is made up of glass (rapidly cooled magma), it is highly abrasive, and when inhaled can trigger asthma attacks due to the acids, such as sulphuric acid, which are absorbed by the particles. Prolonged exposure to ash can also cause long-term health issues such as silicosis and chronic obstructive pulmonary disease (Horwell & Baxter, 2006). Ash has also been known to contaminate water supplies and damage infrastructure such as buildings and power lines (Stewart et al., 2006; T. M. Wilson et al., 2012). Ash also has a major impact on aviation; when ash is transported in the eruption plume to the same elevation as jets fly the fine particles are sucked into the planes engine and can cause jet engine failure and damage to turbine blades as it is abrasive and is able to be melted by the heat of the engines and clog moving parts (Prata & Tupper, 2009).

Ballistics

Bombs form when lava is explosively erupted from the volcano and large, viscous fragments cool while travelling through the air. The distance that the bombs travel is dependent on the explosivity of the volcanic eruption and the mass of the ballistic (Bertin, 2017). Due to the speed at which they are erupted from the volcano, ballistics are barely affected by wind or eruption column dynamics (Martí & Ernst, 2005). Due to their size and weight, they are unable to travel as far as ash and usually only affect areas within 5km of the vent (Blong, 1984).

Although ballistics only travel a small distance, they are incredibly destructive to the area where they land. Damage occurs due to the force of the impact of the bomb and can collapse building roofs and disrupt transport and other vital infrastructure (Martí & Ernst, 2005). Due to the high speed at which they travel (hundreds of metres per second) ballistics also threaten humans serious injury or death can occur if ballistics hit them (Fitzgerald, 2014).

Lahar

A lahar is a secondary volcanic hazard that can occur during an eruption or long after the event. It is made up of volcanic debris, such as ash and boulders, mixed with water, creating a flow. Many lahars originate when hot volcanic debris is deposited onto snow and ice, which then melts and carries the material downhill, reaching speeds of 10-40 m/s (Waitt, 2013).

Lahars are incredibly dangerous hazards due to their speed and density of rock debris. Although they are confined to valleys, lahars have killed tens of thousands of people and are capable of destroying and removing most structures from towns that are in their path (Waitt, 2013).

Methods

The identification of hazard distribution was done using programs such as ArcGIS and the Tephra2 tool from VHUB. During these hazard simulations the data that was used was based on previous eruptions for Mt Erebus or other Strombolian eruptions around the world if the data was not available for Erebus. The three main hazards that are associated with this type of eruption were mapped.

Tephra fall

Tephra fall isopach maps were created for Mt Erebus using Tephra2, an online simulation tool that uses an advection diffusion equation to forecast tephra dispersal (Connor, Connor, & Courtland, 2011). This is done using relevant inputs from the user about the eruption, particles and wind (Table 1). The output of these simulations is entered into ArcGIS to create an isopach map over Ross Island.

Many of the parameters entered into the software were gathered from the Tephra2 Users Manual where data for Erebus was unavailable (Connor et al., 2011). This data was suggested by the manual or was from a similar style eruption. The initial inputs were entered into the Tephra2 software, as follows:

Table 1. Input Parameters for Tephra2

Parameter	Values
Wind File	(See Table 2)
Plume Height	5000m [4]
Eruption Mass	$1x10^7$ kg or $1x10^{10}$ kg [5]
Max. Grainsize	-5 phi
Min. Grainsize	5 phi
Median Grainsize	3 phi [6]
STD Grainsize	5
Vent Easting	551871.8 (UTM)
Vent Northing	1393208.5 (UTM)
Eddy Constant	0.04
Diffusion Coefficient	100
Lithic Density	1000000
Pumice Density	1000
Column Steps	1000
Plume Model	100
Plume Ratio	0
Plume Height	0.1

The wind file was a text file that included values for the height, speed and direction of the wind (Table 2). There was no wind data specific to the summit of Mt Erebus, so data gathered during a 1980 atmospheric study at McMurdo Station (Keys, 1980), and data averaged over 14 years from a New Zealand operated weather station at Scott Base (Ant Scott Base Ews, #12740) were combined and simplified to create a hypothetical wind model with the most dominant wind direction at different elevations and common wind speeds.

Table 2. Combined wind data used in Tephra2 simulation, from NIWA (2017) and Keys (1980).

Height of wind (masl)	Speed of wind (m/s)	Direction of wind (degrees)
20	0 or 5 or 27 [7]	5
2700	0 or 5 or 27	180
3600	0 or 5 or 27	135
5100	0 or 5 or 27	315

[4] The normal height for a Strombolian eruption is usually expected to be approximately 1000m high (Hickson et al., 2013). Due to software issues however, the plume height had to be increased to 5000m, which is still feasible for an explosive Strombolian eruption.
[5] This mass is similar to that used in the Tephra2 Users Manual when simulating the 1992 Cerro Negro eruption, which was also of a Strombolian/Vulcanian style. This data was used because information regarding Mt Erebus was unavailable.
[6] (Harpel et al., 2008)
[7] Three different wind scenarios were modelled. With no wind; with little wind (5m/s); and with the maximum normal speed (excluding gusts), which the wind reached during the study period of the Ant Scott Base Ews (#12740) weather station (27m/s) (NIWA, 2017).

This simulation was run five times with different scenarios:

- Small eruption mass and no wind.
- Small eruption mass ($1x10^7$kg) and low winds (5m/s)
- Small eruption mass and high winds (27m/s)
- Large eruption mass ($1x10^{10}$kg) and low winds
- Large eruption mass and high winds

The output text files of the simulations were converted to an Excel spreadsheet and the 'load', which was calculated during the simulation was converted to thickness with the following equation:

$$Thickness\ (cm) = \frac{Load\ (kg/m^2)}{Density\ (kg/m^3)} \times 100$$

Density = 1000 kg/m^3

This spreadsheet was entered as XY data into ArcGIS[8], creating a grid of points that held the tephra data for each location. This layer was then converted into a shapefile[9] so it could be used and manipulated.
The Natural Neighbors[10] tool was run from the Spatial Analyst toolbox, which interpolates a raster surface from a series of points. This tool created an isopach map of the tephra thicknesses that may occur at different locations during the scenarios simulated in Tephra2.

Ballistics

The ballistics hazard zone was created in ArcGIS using a Digital Elevation Model (DEM) of Ross Island and data from an analogous event at Stromboli, Italy – the type locality for Strombolian eruptions.

Using the DEM of Ross Island, the lava lake was delineated as a polygon shapefile so it could be analysed. Three circular buffers[11] were then drawn around the vent to depict the potential areas that may be affected during different sized

[8] File > Data > Add XY Data
[9] Data > Export Data…
[10] Arc Toolbox > Spatial Analyst > Interpolation > Natural Neighbour
[11] Arc Toolbox > Analysis > Proximity > Buffer

explosive eruptions. The size of these buffers was based on data gathered during a study of an eruption at Stromboli (Gurioli et al., 2013). The three scenarios were as follows:

- Normal eruption at Stromboli (common) = bombs land with 100m of the vent
- Major eruption (less frequent) = within 1.5km of the vent
- Extremely explosive eruption (rare) = within 2km of the vent

Lahar

The drainage pathways for a potential lahar hazard were determined using the Laharz_py software through ArcGIS. This software calculates proximal hazard zones using a set of scripts (also referred to as tools) grouped within ArcMap (Schilling, 2014).

The first tool used, '*Create Surface Hydrology Raster*' creates a raster surface from the DEM, which identifies cell locations where the flow accumulation raster is greater than or equal to the stream threshold value. This value was 1000 based on the example provided in the users manual (Schilling, 2014). This tool automatically "fills" in the "sinks"[12] and generates the flow direction, flow accumulation[13], and a stream raster.

Due to software issues, the remaining tools from Laharz_py were not used; instead tools from the ArcGIS toolbox substituted them. To reflect the wide inundation zones of lahars, a 1km wide buffer was created across each drainage pathway. As the width of lahars have huge variation spatially, depending on the valley width and volume of the lahar, this number is only used to represent the large area that can be affected. This inundation zone is especially important when the lahar reaches wider valleys and shallower slopes where it is able to spread out.

[12] Incorrect elevation values which are created during the generation of the DEM.

[13] The accumulated flow in each cell from the weight of all cells flowing into the downslope cells (identified during flow direction) (ArcGIS, 2017).

Results

Tephra fall

The following maps are the outputs created using the Tephra2 software and ArcGIS. A total of 5 scenarios were simulated using varying eruption mass and wind speeds.

Eruption Scenario 1: Small eruption mass and no wind

Figure 4 shows a localised area where tephra falls out of the eruption column without being transported by wind. The thickest area of tephra is around the crater where much of the volcanic material would have fallen out first. The ash is only 1mm thick. This thickness of the ash decreases in a roughly concentric pattern away from the vent with the thinnest layer (excluding 0cm) only 0.01cm thick approximately 2km away from the eruption site.

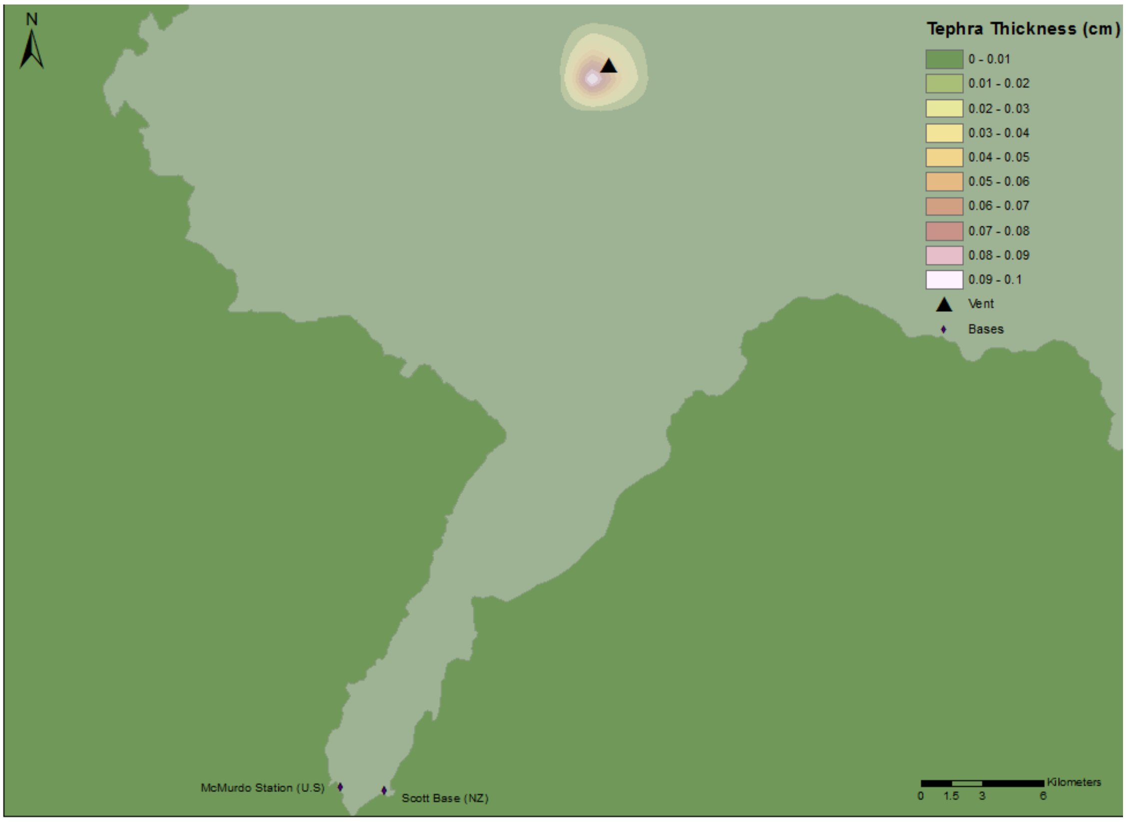

Figure 4. Isopach map of the thickness (cm) of tephra from a small eruption mass (1x10^7 kg) during a period with no wind.

Eruption Scenario 2: Small eruption mass and low winds

Figure 5 displays minor transport of ash by the light winds that were present during the eruption simulation. These winds were in a predominantly north to north-easterly direction based on the data gathered from Keys (1980), and the NIWA (2017) data. This map is similar to Figure 4 in that the thickest layer only reaches 1mm thickness. There is a larger area that is affected by the tephra fall due to the transport by wind. Ash downwind of the volcano reached distances of approximately 10km away from the vent.

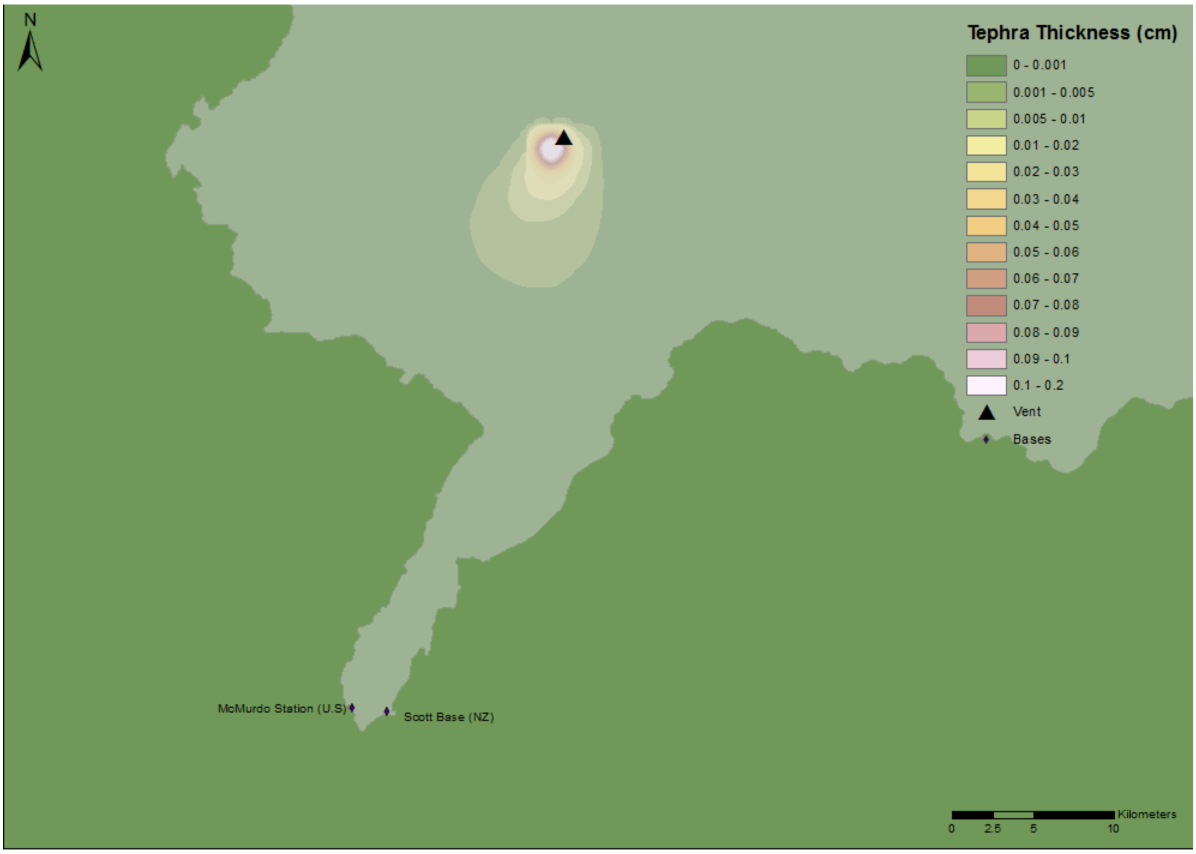

Figure 5. Isopach map showing the simulated thickness of tephra in the event of a small eruption (mass = 1x10⁷ kg) during light winds (5m/s).

Eruption Scenario 3: Large eruption mass and low winds

Figure 6 has a similar shape to Figure 4 as the shape of the tephra follows the dominant wind direction. As the mass of this eruption is larger than the previous simulations the thickness of the deposit is significantly thicker. Over 10km to the southwest of the vent the ash is around 5mm thick, with the thickness significantly increasing towards the vent. The thickest deposit of ash reached 180cm in the area close to the vent.

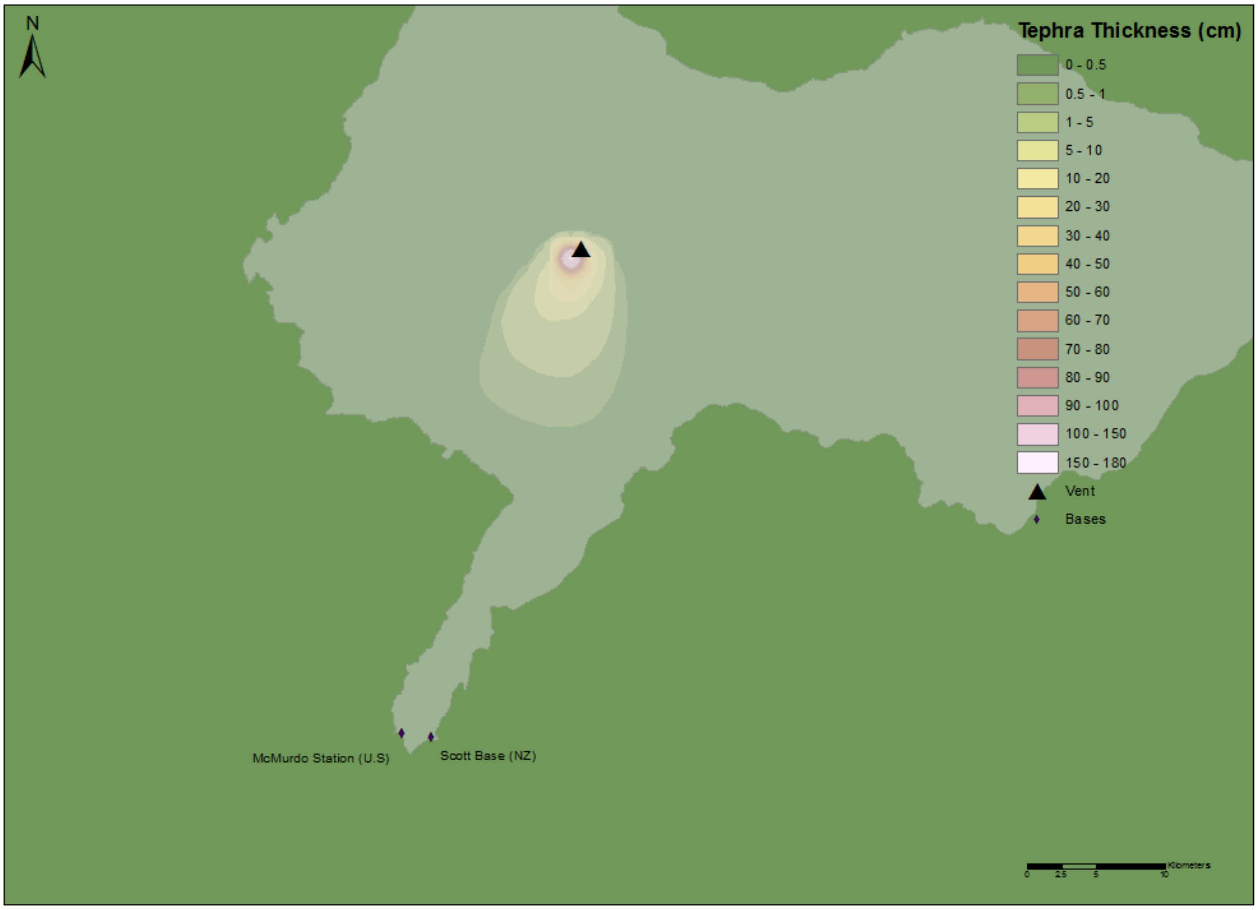

Figure 6. Isopach map showing the tephra thickness from a large eruption mass (1x10^{10} kg) and low winds (5 m/s)

Eruption Scenario 4: Small eruption mass and high winds

Figure 7 shows a tephra dispersal pattern in a southwesterly direction, similar to the previous maps. In this scenario ash reached approximately 10km away from the vent at a thickness of 0.015mm. Near the vent the thickest layer of tephra reached a maximum of 1mm. The strong winds have dispersed the very fine ash over a larger distance, though the resolution of this map does not distinguish these very fine layers (0 – 0.0015cm). The strength of the wind has not allowed the ash close to the vent to settle into a thicker layer, resulting in a very thin layer (0.1cm).

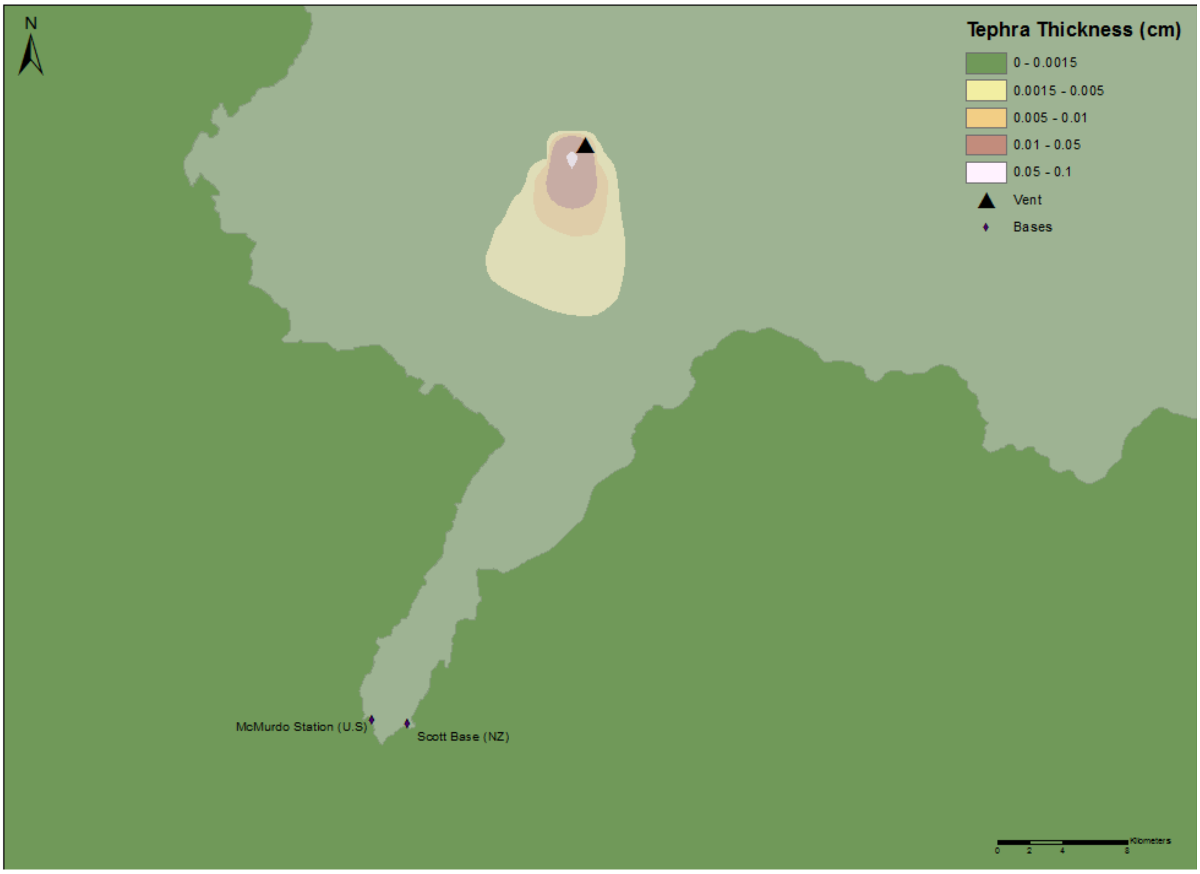

Figure 7. Isopach map showing the thickness of tephra for a small eruption mass with high winds (27 m/s).

Eruption Scenario 5: Large eruption mass and high winds

Figure 8 shows widespread tephra dispersal, the large mass (1×10^{10} kg) being transported over 50 km away from the vent in a south to southwesterly direction by the strong winds (27 m/s). The thickness of ash that would reach Scott Base and McMurdo is approximately 1cm thick, with a significant increase towards the vent. Around the eruption site the ash reached 70cm thick. The two airfields at the southern tip of Hut Point could be covered with between 0.1mm – 1cm of ash if this eruption were to occur.

Note that the unusual shape of the isopachs in the lower left corner of the map is due to a processing error in the Tephra2 software.

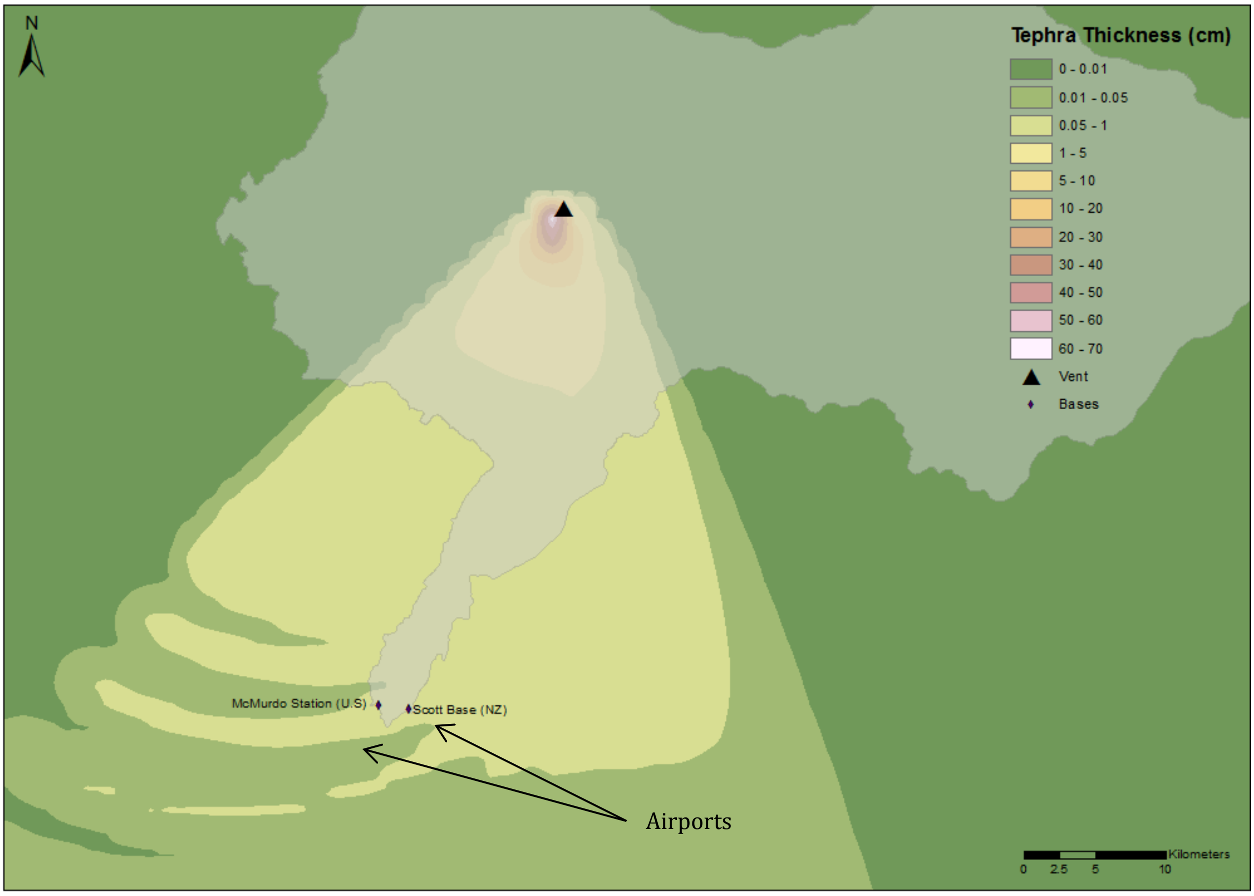

Figure 8. Isopach map showing the tephra thickness from a large eruption mass with high winds

Ballistics

Figure 9 shows the ballistic hazard around the summit of Mt Erebus during three different types of eruption:

- Normal eruption
- Major eruption
- Extremely explosive eruption

The more frequent normal eruption only affects the area in the 100m directly surrounding the vent, and most of the bombs do not make it out of the crater. The less frequent major eruptions have bombs reaching distances of 1.5km away from the vent. This takes the ballistics over the old caldera rim, which may allow them to travel further due to gravity. Bombs from the very rare extremely explosive eruption reach up to 3km away from the vent, which also takes them out of the caldera and onto the steep slopes of the upper Erebus cone where they may roll down.

It is important to note that while the buffers are circular, a directed blast may only distribute ballistics in one direction, leaving the other areas mostly ballistic-free. The circular buffer is to give an indication of the overall area that may be affected and to account for all directions of directed eruption.

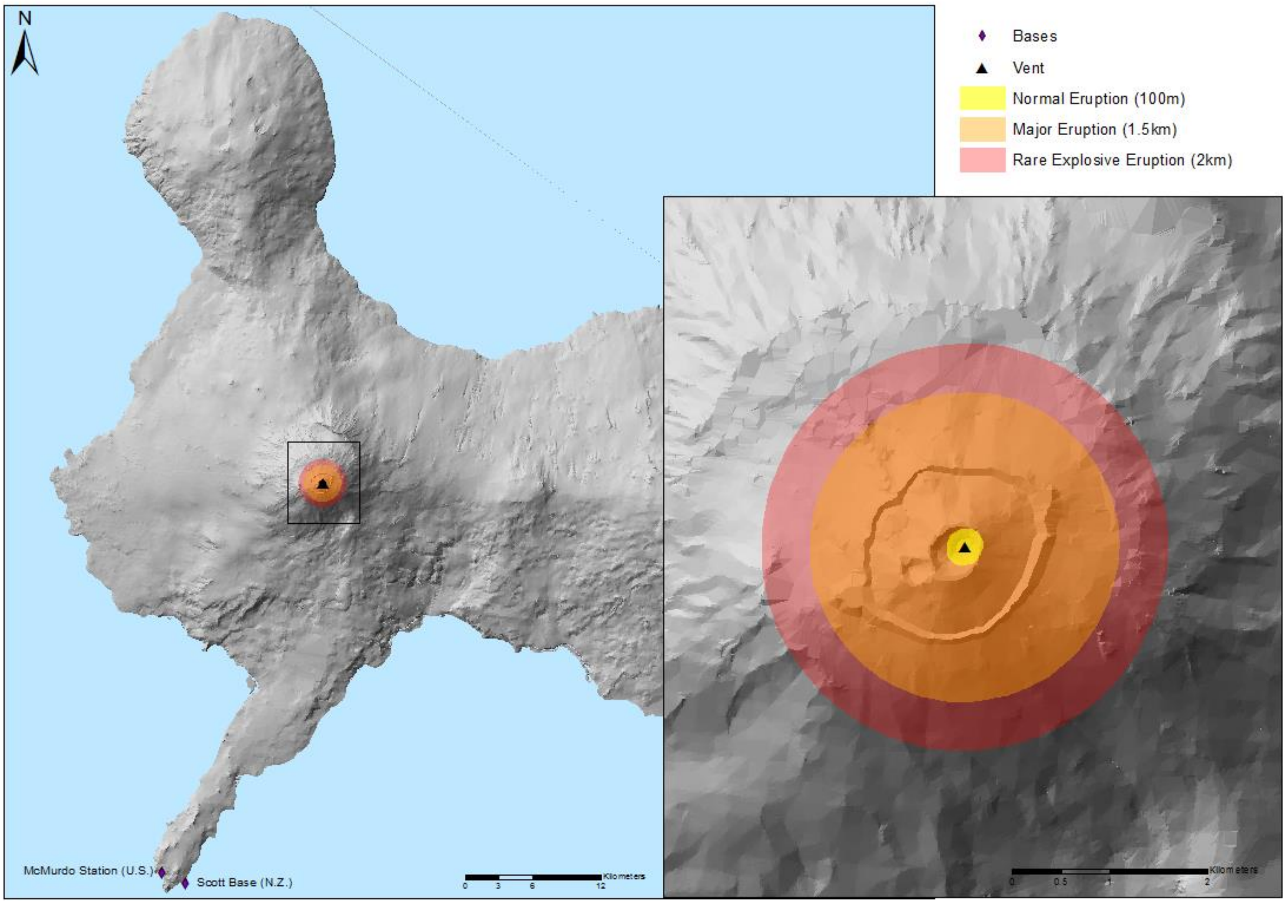

Figure 9. Map with inset showing the ballistic hazard for three different eruption intensities.

Lahar

Figure 10 shows the major pathways that lahars could travel based on flow accumulation. The upper areas of the volcano had narrower flow paths and lower flow accumulation values that were not identified by the Laharz_py tool. The drainage paths delineate where lahars will affect areas around the base of Erebus and where they will most likely flow onto the ice shelf. The hazard zone buffer along the flow accumulation pathways defined by Laharz_py gives an estimate of the areas that would be affected if a lahar were initiated during an eruption at Mt Erebus. This map shows that lahars have the ability to flow down all the sides of the volcano, thus able to affect a large area. The two stations are not in the path of any lahars travelling downhill, however once the lahar reaches flat ground it spreads out and inundates a wide area so the bases may be affected.

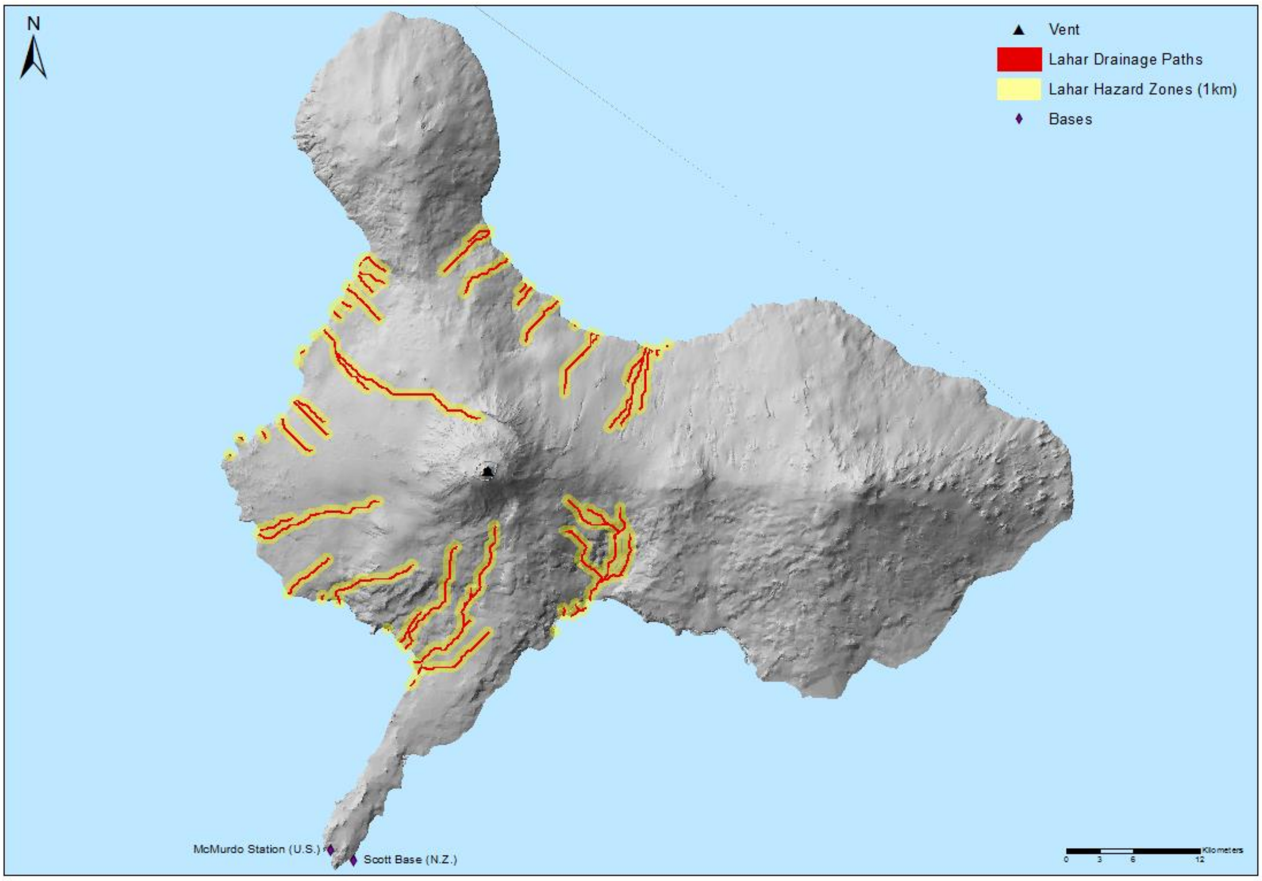

Figure 10. Map showing lahar pathways around Mt Erebus with buffers to indicate potential inundation

Discussion

Natural Impacts

This section discusses the impacts that different hazards of a volcanic eruption at Erebus would have on the natural environment.

Tephra fall

When ash is deposited onto snow or ice it lowers the albedo of that surface (Harpel et al., 2008). This increases the ablation rates of this area as the solar radiation is absorbed by the dark material rather than reflected by the white surface and is re-emitted as longwave radiation, heating the surrounding area.

This may have a negative environmental impact on Ross Island if large quantities of ash spread over a wide area, such as during Eruption Scenario 5, and cause heightened melt on the glaciers of Ross Island. As overall accumulation in Antarctica is low compared with other regions this may have a long-term impact on the overall mass balance of the glaciers on Mt Erebus.

While there has been little research done on the impact that volcanic ash has on ocean water, it has been noted that it increases the turbidity and acidity in freshwater systems (Stewart et al., 2006). Assuming this can be applied to ocean water, an eruption at Mt Erebus may impact the ocean surrounding Ross Island and the marine organisms that live there. The turbidity (ash suspended in water) of nearby water may increase as the settles into the ocean. Though sea ice may delay this process, as it melts it will gradually release the ash into the water column. Increased turbidity has the potential to reduce sunlight reaching deeper water. This could inhibit growth in organisms that rely on sunlight, such as phytoplankton. As the surface of ash particles are highly acidic due to aerosols released by the volcano, the accumulation of ash in water has the potential to lower the pH (Stewart et al., 2006). Many organisms in the Antarctic oceans are calcitic, and these invertebrates are highly vulnerable to ocean acidification as their shells are only weakly calcified because calcium ions are difficult to extract from cold waters (McClintock et al., 2009). Being calcitic, these shells are easily dissolved in acid. Therefore, in the event of an eruption, ash entering the ocean could have a significant effect on the survival of many species. However, depending on the size of the eruption, there might not be a significant or long-term impact as the ocean currents would eventually disperse the ash. It is likely that acid from the particles would be diluted in the large turbulent body of water, therefore negating ash's affect on calcitic organisms

In previous global eruptions ash has been known to kill vegetation when deposited as it blocks sunlight and oxygen to the plants, as well as causing breakage (Dale, Delgado-Acevedo, & MacMahon, 2005). In this scenario, the ash being erupted from Mt Erebus may block sunlight or oxygen to the mosses and microbes that inhabit the geothermally warmed areas of the volcano, therefore inhibiting photosynthesis. This was observed after the 1980 Mt St. Helens eruption where mosses, lichens and algae died after being buried by 20mm or less of ash (Ayris & Delmelle, 2012). An eruption with a large mass, such as Eruption Scenario 3 and 5, would produce this thickness of ash, potentially destroying the delicate plant community.

Ballistics
Though no studies have been done on the effect that ballistics have on the natural environment, it is a realistic assumption that, as ballistics do not travel far from the source, the projectiles only pose a localised risk to the environment surrounding the vent. Similar to tephra fall, they will primarily impact the vegetation in the geothermal areas around the vent. If the bombs directly or semi-directly collide with the moss, it will kill the plant due to the high velocity at which they travel.

Lahar
Lahars are incredibly destructive events to both infrastructure and to the environment. Like the tephra fall and ballistics, lahars will kill any vegetation it flows over as it travels downhill due to the speed, density, and heat of the flow. Any debris that the lahar leaves behind, and the lahar deposit itself may also inundate the mosses and kill them off in a similar way to the tephra fall.

Lahars can range in temperature, anywhere from 0°C to 100°C, though they are commonly 50°C, hot enough to melt snow and ice around the flanks of Mt Erebus. This would carve out channels in the glaciers and snow, and create an excess of meltwater runoff from the flanks. In the model, lahars can be seen to flow out from Ross Island. Once they spread out they may also melt and weaken the ice in these areas, especially if its sea ice. Though the extent to which this affects the ice depends on the size of the lahar once it has spread out and the temperature it is by the time it reaches the ice.

Lahars also have the potential to impact wildlife once they reach the sea ice and ice shelf. As a lahar spreads out, the material may interact with seals or penguins on the sea ice. For the majority of the area, this would likely be a transient impact as the locations where the lahars enter the sea ice do not appear to be near any of the known seal or penguin colonies, apart from Cape Royds where there is an Adélie penguin colony situated close to a lahar outlet (D. J. Wilson et al., 2014).

Other natural impacts

During a volcanic eruption a volcano can emit significant amounts of sulphur, nitrogen, acids, and other gases (Mather et al., 2004; von Glasow, Bobrowski, & Kern, 2009). In the troposphere sulphate particles from a volcanic plume can brighten clouds reflect sunlight back into space. This process increases the albedo of the atmosphere, reducing the amount of sunlight that reaches the surface, therefore cooling the Earth's surface (von Glasow et al., 2009). In an event of an eruption at Mt Erebus this effect may not be as dramatic as with a larger eruption, however there is still a potential for localised cooling around the Ross Island region, especially during a large eruption such as in Eruption Scenario 5. The current degassing of the Mt Erebus vent displays a low sulphur emission rate, due to the evolved nature of the phonolitic magma as sulphur is removed during fractionation (Sweeney et al., 2008). However, there is a potential for increased sulphur emissions in the future as the amount of sulphur varies as magma is intermittently recharged at depth. The addition of primitive melt may increase sulphur solubility and emission rates (Sweeney et al., 2008).

Bromine is another gas is emitted during a volcanic eruption and can significantly impact atmospheric chemistry. Hydrogen bromide (HBr) is emitted from a volcano, and once it enters the atmosphere bromine oxide (BrO) is created through autocatalytic formation from the HBr (Boichu, Oppenheimer, Roberts, Tsanev, & Kyle, 2011). This reaction consumes ozone (O_3) resulting in ozone depletion in the atmosphere around the plume; Boichu et al. (2011) observed ozone depletion 30km from Mt Erebus during normal volcanic activity.

Social Impacts

Tephra fall

As previously mentioned, ash can cause a range of respiratory issues when inhaled due to its high acid and silica content (Horwell & Baxter, 2006). This impact was first truly observed after the 1980 Mt St Helens eruption where there was a 2-3 increase in hospital admissions due to respiratory issues (Horwell & Baxter, 2006). During a large eruption with high winds (Eruption Scenario 5) at Mt Erebus the inhalation of ash would be a major concern as significant amounts of ash particles are deposited at the two stations, increasing the likelihood for inhalation and subsequent respiratory issues. During smaller eruptions or eruptions with light winds (Eruption Scenario 1, 2, 3, and 4) the ash dispersal is more localised to areas around the volcano, reducing the probability for inhalation of ash. Though there is still a chance if there are scientists working on the volcano at the time of the eruption. The health hazard may also be exacerbated by the dry conditions of Antarctica. The dry ash can be repeatedly disturbed if it is not weighted down by rainwater. A snowfall may eventually blanket the ash, preventing remobilisation.

Volcanic ash has also been known to significantly damage infrastructure, such as power lines, water supplies, wastewater networks, and buildings (T. M. Wilson et al., 2012). This is due to loading of the infrastructure and subsequent breaking, and shorting of electrical equipment due to the conductivity of the ash particles. At Scott Base there are no exposed water sources, wastewater networks or power lines, therefore reducing the impact that tephra fall has on the infrastructure at this location. The primary concern would be loading of ash on the roofs of buildings. Eruption Scenario 5 modelled the maximum ash thickness at Scott Base to be 0.05-1 cm, well below the threshold for structural damage (Wilson, Stewart, & Leonard, 2013). As this region does not get rain, the ash would stay dry and light, making it unlikely to cause significant damage to any of the infrastructure at Scott Base.

A major impact that tephra fall from a Mt Erebus eruption could have is on aviation. As mentioned in an earlier section, ash can significantly damage aircraft through abrasion of surfaces, and accumulation and abrasion in engines. Ash that is caught in the engines is melted due to the high temperatures of the machinery, then resolidifies on turbine nozzle guide vanes which results in compressor stall, and potential loss of engine thrust (Miller & Casadevall, 2000). At Ross Island, the air fields which are used to fly into and out of McMurdo Station and Scott base are located just below the southern tip of the island (Fig. 8). This exposes them to ash that could occur during an eruption like Eruption Scenario 5. This ash would accumulate on the airfields, and may be sucked into engines if planes were landing or taking off during an eruption. This could cause significant damage to the planes and have major consequences on the ability for people to leave Ross Island or for teams to arrive to help with recovery.

Ballistics

As mentioned previously ballistics have been found to only pose a localised risk in this Mt Erebus Eruption scenario. As there are no people living on the volcano, and no infrastructure (with the exception of Lower Erebus Hut in the volcano caldera), ballistics will not significantly impact the social environment. This may change if there are scientists on the volcano at the time of an eruption. In this context, ballistics are a considerable hazard to those within the hazard zone, as they can cause serious injury or death if they hit someone (Fitzgerald, 2014).

Lahar

Due to their immense speed and density, lahars cause death and significant damage to any infrastructure or people that are in its path, such as during the 1985 Nevado del Ruíz lahar, which killed most of the town (Waitt, 2013). If an eruption on Mt Erebus were to occur it is unlikely that a resulting lahar would significantly impact Scott Base, as the lahar drainage pathways do not travel along Hut Point Peninsula (Fig. 10). Instead, the lahar is directed straight down the slope and onto the ice. Any infrastructure such as roads or huts that are in the path of the lahar would be destroyed or inundated. Scientists on the volcano at the time of the eruption would also be in immediate danger from the lahar, especially if they are in valleys.

Monitoring Methods

Monitoring volcanoes is an important aspect to mitigating risk and to better understand the volcano. Often monitoring equipment identifies changes in the volcano's properties, which may foreshadow an eruption. A range of methods have been used to monitor Mt Erebus' volcanic activity, both in the short term during scientific studies and in the long-term.

Seismic monitoring

Seismic activity is an important precursor to volcanic eruptions. As magma moves upwards it opens fractures and the pressure increases causing increased seismic activity (Martí & Ernst, 2005). Seismicity has been measured on Mt Erebus continuously since 1980 using geophones that pick up the tremors caused by magma movement (Dibble, Kyle, & Rowe, 2008; Kaminuma et al., 1985). Swarms of earthquakes often occur prior to a small eruption on Mt Erebus (Kaminuma et al., 1985). This monitoring of seismic activity may allow warning to be given before an eruption occurs. This could significantly reduce the chances of lives being lost as scientists and personnel in the vicinity of the volcano can be removed before an eruption occurs.

Visual monitoring

Visual surveillance of eruptive activity is an important part of monitoring the volcanic activity and identifying morphological changes in the crater. During a study conducted Dibble, Kyle, & Rowe (2008), the vent of Erebus was monitored using a monochrome infrared-sensitive video camera. This allowed observations to be made about the eruption, such as the eruption times and maximum flight time of bombs. The observed eruptions were correlated with seismic information gathered at the same time and earthquake patterns were identified for each eruption (Dibble et al., 2008). Mt Erebus has the potential to be monitored remotely using satellites in the future. Satellite remote sensing would allow frequent and year-long measurements of the thermal structure of the volcano (Rothery & Oppenheimer, 1994). Remote sensing would reduce the risk to scientists and visual monitoring equipment in the event of an eruption.

Deformation

Volcanic deformation is one of the main precursory signals for volcanic eruptions (Martí & Folch, 2005). The deformation of the surface of a volcano is caused by an increase in pressure in the magma chamber. This pressurization can act as a potential eruptive trigger, making the monitoring and interpretation of surface deformation vital to volcanic eruption forecasting (Martí & Folch, 2005). During a study conducted by Otway, Blick, & Scott (1994) volcanic deformation on Mt Erebus was monitored using triangulation, trilateration, and tilt-leveling surveys. The horizontal and vertical deformation was measured, and it was found that periods of deformation usually coincided with increased seismicity and volcanic activity. Compared with other volcanoes this deformation is localised to the area and does not display a strong correlation to near-surface activity. This indicates that there was no significant change in the size or pressure of the magma chamber at shallow depths during these small eruptions, though it does not indicate what is happening at depth (Otway, Blick, & Scott, 1994).

Gas monitoring

Gas chemistry is another important factor that could indicate a change in eruptive activity. Changes in certain gas fluxes, such as SO_2, could indicate an intrusion of fresh magma into the magma chamber (Martí & Folch, 2005). This may indicate changing eruptive activity (Boichu, Oppenheimer, Tsanev, & Kyle, 2010). Mt Erebus is regularly monitored and SO_2 emissions are frequently measured with occasional CO_2 and CO tests (Oppenheimer et al., 2005). Gas emissions for Mt Erebus are gathered from in situ measurements, or using UV spectrometers. This remote sensing technique collects light from thin cross sections within the plume and can track inhomogeneities in the cloud, thus identifying changes in gas flux (Boichu et al., 2010).

Recommendations

Based on the information covered in this report this section provides a series of recommendations for Scott Base in order to prepare for a volcanic eruption at Mt Erebus, and mitigate damage and injury during an eruption. It is important to note that Scott Base already has a hazard plan in place for a volcanic eruption, and the following recommendations are only intended to supplement it and suggest areas where more detail would be beneficial.

The first recommendation is to provide a more detailed hazard plan. The plan that Scott Base has in place currently is sufficient for a small to moderate eruption in that it provides a simple process for what to do if an eruption were to occur. In a larger eruption there needs to be a plan that goes into greater detail on each hazard that may occur and what to do for each scenario. This is likely to prepare the base staff more thoroughly for such an event.

In relation to preparing staff with a hazard plan, staff and scientists should also be educated when they arrive in Antarctica about the possible hazards from an eruption and how to respond to each one. This is especially important for scientists and personnel who are going to spend an extended period of time on the volcano where they are more at risk from the volcanic hazards.

There should be an easily accessible supply of emergency equipment such as facemasks and goggles for use during an eruption and for clean up. There should be enough for all personnel on the base in case they are required to go outside during or soon after an eruption. As tephra fall was shown to be the only hazard that directly affected Scott Base, it is important to thoroughly prepare for it, especially due to the respiratory issues that it can cause.

These are only minor recommendations as Scott Base already has a thorough hazard plan set up for a volcanic eruption. Additionally, there would likely be few emergency operations working out of Scott Base as the Emergency Operation Centre at McMurdo would be activated and would coordinate with Scott Base in the event of an eruption (P. McCarthy, Antarctica New Zealand programme coordinator, personal communication, December 30, 2016).

Conclusion

This report has covered the volcanic hazards that may occur during a hypothetical eruption at Mt Erebus, the spatial distribution of these hazards, and the affect that they will have on the surrounding environment and people. Monitoring methods used to forecast eruptions were also discussed and finally, this report provides recommendations directed at Scott Base in order to mitigate the risk of a volcanic eruption.

Based on the models produced in this report, it can be concluded that it is unlikely that Scott Base will be directly affected by a volcanic eruption unless it is unusually large. However, any personnel on the volcano during the eruption are at high risk of injury or death. The base can also be indirectly affected by restricted air transport due to the tephra hazard. This could hinder evacuation and recovery efforts in the area.

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