

PCAS 20 (2017/2018)

**Supervised Project Report
(ANTA604)**

*A review of glaciovolcanism with particular application to its
presence in Antarctica.*

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Word count: 7031 (excluding abstract and references)

Abstract/executive summary (ca. 200 words):

Glaciovolcanism is mainly controlled by the interaction between magma composition and ice properties. However, many other smaller factors will play a role in the progression of an eruption including temperature, spatial extent, and density. Glaciovolcanism can occur in many different scenarios including at the ice-substrate boundary, as a dyke intrusion, as a supraglacial flow, or as an intrusion into permafrost. All scenarios produce different eruption styles and different deposit characteristics. Glaciovolcanic deposits are well preserved and have distinctive features which act as valuable proxies of Earth's paleoclimate. The importance of glaciovolcanism in the modern world has recently been reinforced through the two catastrophic eruptions at Nevado del Ruiz, Chile and Eyjafjallajökull, Iceland. Hazards including Jökulhlaups, lahars, flooding, and tephra make glaciovolcanism important to understand and prepare for. However, the importance of these eruptions is not limited to hazards. Along with hazards they act as paleoclimate indicators, climate change variables, and Martian analogues. Antarctica is a continent with many known glaciovolcanoes, and probably even more unknown ones. Past eruptions on the continent have led to evacuation and destruction of national Antarctic bases. With an increase in tourism and occupation on the continent it is important to discern safety routines which will minimise the risk of glaciovolcanic hazards. Glaciovolcanism is also important in Antarctica because it can show the dynamics of the ice sheet since before the last glacial maximum due to analysis of well-preserved deposits. Overall, glaciovolcanism is a growing field of vital importance to humans and the environment.

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1. Introduction:

Volcano-ice interactions have been a constant part of Earth's geologic history for the last 2.5 Ma (Edwards, Gudmundsson & Russell, 2015). Volcano-ice interaction is formally referred to as glaciovolcanism and can be described as the volcanic interaction with all forms of ice and associated meltwater (Edwards et al., 2015; Head & Wilson, 2007; Wilson, Smellie & Head, 2013). The term glaciovolcanism is used interchangeably with subglacial volcanism in literature (Edwards et al., 2015) and encompasses eruptions occurring beneath and above ice sheets and glaciers, in ice filled calderas, around snow, or, in contact with permafrost (Edwards et al., 2015; Head & Wilson, 2007). Alaska, Antarctica, British Columbia and Iceland are known as being Earth's active glaciovolcanic centres (Curtis & Kyle, 2017; Edwards et al., 2015). Glaciovolcanism is dissimilar to subaerial volcanism in that the ice plays a significant role in controlling the progress of an eruption (Gudmundsson, Sigmundsson & Björnsson, 1997; Wilson et al., 2013). Ambiguity in literature lies around the exact mechanisms that govern glaciovolcanism (Edwards et al., 2015). We know different eruption styles produce different deposits which are not only distinctive from one another, but distinguishable from subaerial and subaqueous volcanism (Edwards et al., 2015; Wilson et al., 2013). When Eyjafjallajökull erupted in 2010, attention was brought to the potential hazards associated with glaciovolcanism (Day et al., 2010; Gudmundsson et al., 2010). Hazards associated with glaciovolcanism are most evidently jökulhlaups (Edwards et al., 2015; Geertsema, 2013; Gudmundsson et al., 2010), lahars (Lowe et al., 1986; Naranjo, Sigurdsson, Carey & Fritz, 1986; Smellie, 2002), and high tephra production (Day et al., 2010; Gudmundsson et al., 2010) – but are certainly not limited to these. Along with a hazard component, glaciovolcanism has the ability to create valuable paleoclimate proxies (Edward et al., 2015; Head & Wilson, 2007; Smellie & Edwards, 2016), interact in climate change (Smellie et al., 2014), and acts as a terrestrial analogue for Martian environments (Head & Wilson, 2007; McKenzie & Nimmo, 1999; Ogawa, Yamagishi & Kurita, 2003). These real world implications of glaciovolcanism has meant we are seeing an increasing interest in the academic world around glaciovolcanism (Edwards et al., 2015). The growing importance of glaciovolcanism calls for a review of the process and implications of glaciovolcanism.

Glaciovolcanism has been recorded in Antarctica as far as 28 Ma ago (Smellie & Edwards, 2016), making Antarctica the oldest active glaciovolcanic province on Earth. Evaluation of past glaciovolcanic events in the area has already given valuable insight into the past climate

(Edwards et al., 2015; Smellie & Edwards, 2016). Glaciovolcanism has rarely been recorded in Antarctica due to infrequency and inaccessibility (Smellie & Edwards, 2016; Wilson & Head, 2002). The 1967-69 Deception Island subglacial eruption on the South Shetland Islands is the most extensively studied on the continent (Smellie & Edwards, 2016; Wilson & Head, 2007). The rationale to focus on Antarctica in this review paper is to collate what evidence there is and to make an original judgement on the future implications glaciovolcanism will have on the continent.

This literature review will synthesise the current literature there is about glaciovolcanism. It will firstly look into the different types of glaciovolcanism that we are seeing, or have seen, around the world. This will lead to a discussion about the controls on glaciovolcanism and the characteristic deposits produced. After a thorough analysis of glaciovolcanism has been achieved this review will focus on the original interpretation of Antarctic examples, and explore why glaciovolcanism is important to understand on the Antarctic continent. Overall, a conclusion will be reached surmising the importance of glaciovolcanism in Antarctica's future. This analysis will be concluded by recommendations of where the science should go next in terms of exploring glaciovolcanism.

2. Discussion:

2.1 Controls:

To understand glaciovolcanism we must first consider the controls on the type of eruptions that occur. This section briefly covers the most influential controls on eruption dynamics including magma composition, and ice thickness.

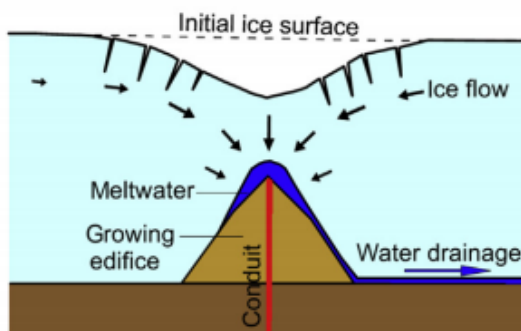
Like normal volcanoes, glaciovolcanoes can have a range of magmas from basaltic to rhyolitic (Moore & Calk, 1991). Basaltic subglacial eruptions have different processes to andesitic or rhyolitic subglacial eruptions (Edwards et al., 2015). In subaerial eruptions evolved magmas e.g. rhyolite have a tendency to be explosive due to their high viscosity (Edwards et al., 2015). However, McGarvie (2009) reports of known felsic glaciovolcanism in Iceland favouring an effusive eruption style. Considering a subglacial rhyolitic eruption has never been observed (Owen, Tuffen & McGarvie, 2013) isotope analysis has been used to understand this trend (Edwards et al., 2015). It is hypothesised that effusive eruptions are a consequence of water and gas content (Owen et al., 2013; Smellie et al., 2013). Analysed samples from explosive rhyolitic eruptions showed a high water content in melt inclusions and signs of degassing in a

closed system with fast magma ascent (Owen et al., 2013). In contrast, effusive eruptions showed a low water content, open system degassing, and slow magma ascent (Owen et al., 2013). This shows how the environment in a subglacial system could favour effusive eruptions in certain conditions. Whether the eruption is intrusive or extrusive comes down to dynamic interactions between the volcanic edifice and caldera (Tuffen, McGarvie & Gilbert, 2007). If the volcanic edifice fills the caldera cavity a more intrusive eruption style is favoured as less water comes in contact with the magma. However, if the cavity remains open it will fill with meltwater, the interaction of this meltwater with the magma will cause an explosive extrusive eruption (Tuffen et al., 2007). There is also academic consensus that more evolved magmas are less likely to produce fragmental deposits as opposed to basaltic magmas (Moore & Calk, 1991). A rhyolitic composition of magma does not necessarily dictate an explosive eruption, this is because in an ice system there are many more factors to consider. Subglacial basaltic eruptions act differently once again. The ice acts to confine the lava flow meaning that instead of lava spreading out large distances laterally, it builds up in one place resulting in anomalously thick deposits of basalt (Edwards et al., 2015). Because basalt has a relatively high melting point compared to more evolved magmas, when it makes contact with ice it is often hotter (Wilson & Head, 2002). This favours an increase in meltwater which leads to explosive eruptions and magma fragmentation (Wilson & Head, 2002). Overall, magma composition will control glaciovolcanic processes, but it is the interaction of many other variables within the system that determine their final effect.

Ice thickness will also control progress of an eruption (Edwards et al., 2015). 'Thick ice' can be thought of ice >500m thick, whilst 'thin ice' can be thought of ice <500m thick. Fig. 1. shows the difference in eruption styles. Thick ice eruptions are known to be common in Iceland and in Antarctica, and there is likely to be more unknown eruptions beneath the ice sheet (Smellie & Skilling, 1994). Thick ice by definition has the potential to generate more meltwater than thin ice (Hickson, 2000). At the same time, thin ice puts a lot less pressure on the magma (Edwards et al., 2015; Smellie & Skilling, 1994). These two factors mean that in an eruption under thick ice you are likely to have a deep passage zone (the passage zone is the transition from a subglacial to subaerial eruption) and undegassed volatiles (Edwards et al., 2015). The thin ice means that magma can penetrate to the surface more easily and hence generate more explosive eruptions due to degassing. It also means that effusive lava flows can run out longer distances (Edwards et al., 2015). The ice-atmosphere boundary can also be breached in a thick ice eruption but this is less likely. Other ice qualities such as density and temperature can affect the eruption also which adds to the intricacy of the system (Smellie & Skilling, 1994).

Magma composition and ice thickness are the two overarching variables which control glaciovolcanic eruption progress. However, it is clear that many factors work together alongside them to produce the final eruption outcome. This complexity is just one reason why glaciovolcanism is so hard to accurately understand.

(A) Class 1A : Thick ice
~0.5-1 km



(B) Class 1B : Thin ice
~200-500 m

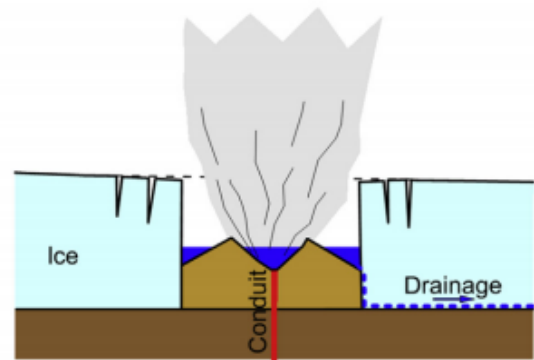


Fig. 1. This figure shows the difference in eruption progress beneath a thick and a thin ice sheet. A thick ice sheet will become depressed and subside immediately above the intrusion. The eruption will most likely be confined to a subglacial one. A thin ice sheet cannot usually contain the magma, exposing it to the atmosphere and creating an explosive eruption (Edwards et al., 2015).

2.2 Processes:

Glaciovolcanism can occur in a wide array of settings. The aim of this section is to explore different eruption scenarios and describe how they are unique from one another. There is a universal generic model which describes how a glaciovolcanic eruption occurs (Edwards et al., 2015). However, along with investigating this, the eruption processes including: ice – substrate boundary sills, dyke intrusions, supraglacial emplacement, and permafrost contact will be explored.

Generic model:

The generic eruption hypothesis is derived from several basaltic paradigms in the field

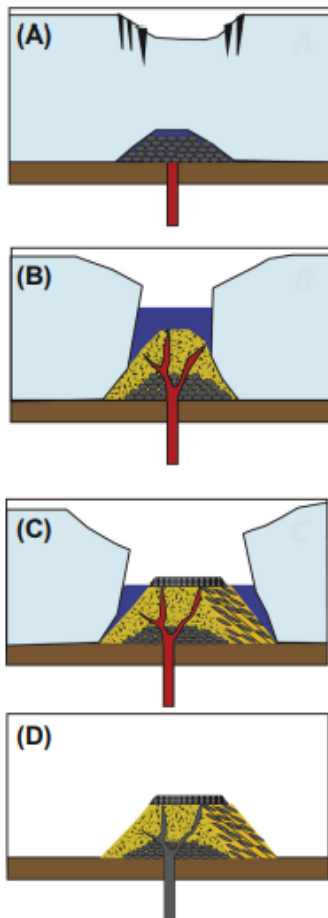


Fig. 2. This figure shows the four stages to a generic glaciovolcanic eruption. (A) Initial intrusion of magma into the ice. (B) Transition to a subaerial eruption and creation of the passage zone. (C) Formation of flowing lavas on top and confinement by the ice. (D) Melting of the ice sheet after an extended period of time showing a shape indicative of ice confinement known as a tuya (Edward et al., 2015).

(Edwards et al., 2015). It assumes that the eruption breaches the ice-atmosphere boundary, is basaltic, and, the ice on top is 'wet ice' meaning the base is at the pressure melting point of ice (Wilson et al., 2013). It is also assumed that the ice thickness is >500m meaning exsolution of volatiles is negligible (Head & Wilson, 2007). Fig. 2. shows the four stages to a generic eruption. The first stage of the eruption involves propagation of magma into ice. This initial process is effusive and we see the formation of meltwater and pillow lavas. Next, the melting ice results in a decreasing pressure, and consequently magma fragmentation. Englacial lakes are likely to form at this stage due to gravitational collapse and subsidence of the ice. Once the ice-atmosphere boundary is breached, the volcanism becomes effusive and lava deposits itself in horizontal layers, it is now that the distinctive passage zone forms. Finally, over an extended time period the enclosing ice body will melt away leaving a structure with high vertical relief in comparison to the surrounding environment, often referred to in literature as a tuya.

A well preserved example of a generic eruption is the Hlodufell volcano in Iceland (Moore & Calk, 1991).

Ice – substrate boundary:

The generic model is most often not the exact case. Due to pressure differences between underlying rock and overlying ice, it is common for a propagating dyke to transform into a sill at the ice-substrate boundary, spreading out laterally (Wilson et al., 2013; Wilson & Head, 2002). The lateral dispersal of magma at the ice-substrate boundary is very effective at distributing heat to the ice, hence we see a lot of meltwater formation (Wilson &

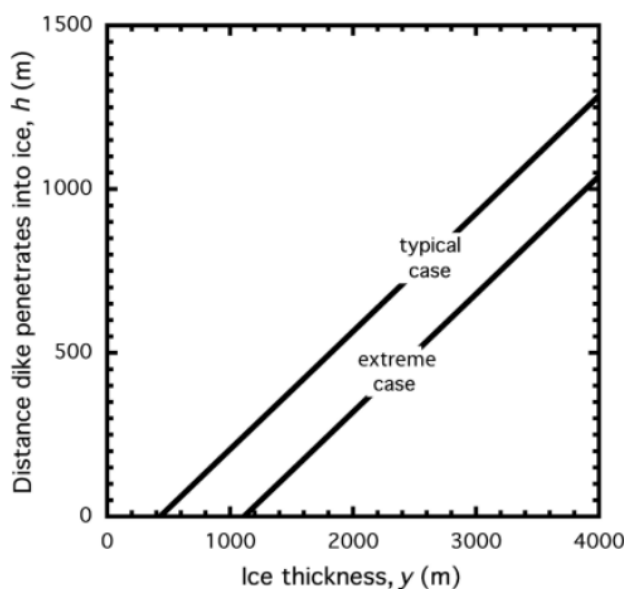
Head, 2002). The meltwater is not concentrated in one place, instead it has a large horizontal extent meaning subsidence of ice can occur over a much larger distance (Wilson & Head, 2002).

From here one of two things can happen. Lateral spreading can cease due to a change in pressure

or discontinuation in the magma supply (Wilson et al., 2013). Or, if the lateral spreading continues to the edge of the ice, then meltwater and magma will escape into a subaerial environment (Smellie & Edwards, 2016; Wilson et al., 2013; Wilson & Head, 2002). Once this happens, the pressure difference at the ice-atmosphere boundary will be enough to cause explosive magma fragmentation and floods of meltwater (Wilson & Head, 2002). Ice-substrate boundary eruptions create different hazards and deposits to the generic model but interact with ice in a similar way.

Dyke intrusions:

In the correct conditions, ice can act as a brittle substrate, allowing a propagating dyke to cut vertically upward through it like a rock (Wilson & Head, 2002). When initial ice intrusion occurs it is stable due to the thermal diffusivity (Wilson et al., 2013). However, as the intrusion continues, ice melt will occur as heat energy from the magma is transferred to the ice. This yields meltwater, meaning not only conduction, but convection of heat will occur (Wilson et al., 2013). Heat transfer rates have been estimated in this scenario (Höskuldsson & Sparks, 1997; Tuffen et al., 2007). Although different results were obtained a clear conclusion was that meltwater volume is greater than the volume of intruded magma (Höskuldsson & Sparks, 1997; Tuffen et al., 2007; Wilson et al., 2013). This large amount of meltwater generation decreases the amount of gravitational support a dyke has and favours collapse. The distance a dyke tip can penetrate into the ice is dependent on the pressure in the tip of the dyke. Fig. 3. shows a typical and extreme case for penetration depths into ice. In Antarctica, which exhibits the most extreme ice thickness on Earth, the thickness of the ice sheet is ~4 km at its highest and on average is ~2km (Andre, 2017). A typical dyke intrusion into ice at ~2 km would be ~550m



deep. These figures are speculation from modelling approaches as features from glacial dyke intrusions are restricted in the field (Calabazo, Strelin, Orihashi, Sumino & Keller, 2015; Edwards et al., 2015).

Fig. 3. Graph showing a typical and an extreme case of dyke penetration into the ice sheet. A typical case shows that the dyke will penetrate ~.32 times as deep as the ice thickness (Wilson et al., 2013).

Supraglacial emplacement:

When lava is deposited on top of ice it acts unlike the other glaciovolcanism we have investigated. The processes before involved magma propagating up through ice from beneath, but supraglacial processes can be extruded from a subaerial eruption and only the lava has to interact with ice (Wilson & Head, 2002). Instead of all the heat from the eruption being lost to the ice, a supraglacial lava flow can lose heat to both the ice and the atmosphere (Head & Wilson, 2007; Wilson et al., 2013; Wilson & Head, 2002). The top of the flow will lose heat quickly and soon attain a temperature value the same as the ambient temperature (Head & Wilson, 2007; Wilson et al., 2013) this means the lava flow cools at a much faster rate than other flows. Many eruptions can erupt in combination with a supraglacial one (Wilson & Head, 2002). A supraglacial flow is the most likely process to result in lahars and is also the most common eruption process (Head & Wilson, 2007; Wilson et al., 2013). For these reasons it is important to constrain supraglacial eruption processes.

Permafrost:

Permafrost is frozen soil (Bockheim, 1995). Intrusions into permafrost mean that heat will be transported not only through conduction but also convection, much like ice (Ogawa et al., 2003). However, it is dissimilar to ice in that convection will be occurring in a porous medium (McKenzie & Nimmo, 1999; Ogawa et al., 2003). Modelled heat convection in permafrost shows melting occurring in a 'mushroom' structure, and producing a significant amount of meltwater (Ogawa et al., 2003). The rocks within the permafrost compact at the bottom and water floods to the top (Ogawa et al., 2003). The melting of permafrost has the potential to create huge outwash floods if the permafrost is thick enough (McKenzie & Nimmo, 1999; Ogawa et al., 2003). On Earth permafrost is often thin <10m (Bockheim, 1995), but in some places including Antarctica and Mars it can be in the order of kilometres thick (Bockheim, 1995; Ogawa et al., 2003), meaning permafrost interaction is important to understand.

2.3 Deposit Characteristics:

After an eruption has occurred a subglacial deposit is still protected by ice until it melts away (Edwards et al., 2015) this means that where other deposits would have been subject to weathering and erosion, subglacial deposits are not and hence are well preserved. The deposit characteristics of subglacial eruptions are not only found on Earth. Remote sensing techniques are able to pick up less subtle features including vertical relief on other planets such as Mars (Edwards et al., 2015; Ogawa et al., 2003). These two qualities make the deposit characteristics

of subglacial eruptions vital to understand. This section aims to briefly touch on the types of deposits you should expect to see when looking at a subglacial eruption and how to interpret them.

Deposit characteristics of glaciovolcanism change not only with the type of eruption, but also the time (Edwards et al., 2015). Fig. 4. Shows how a typical glaciovolcanic deposit will change as the eruption progresses. Initially, there should be a layer of pillow lava that is compacted together tightly. On top of this you should find lapilli tuff and hyaloclastites (a fragmented glass breccia). These are the deposits that are formed in the subglacial stage of the eruption. When the magma penetrates the ice-atmosphere boundary you will see the formation of a passage zone (Edwards et al., 2015; Smellie, 2000). A passage zone is imperative in distinguishing paleoclimate as it shows the transition from a subglacial to subaerial eruption (Edwards et al., 2015). Over time a lava cap develops on top of this deposit (Smellie, 2000). When identifying a glaciovolcanic eruption in outcrop there are a few distinguishing features to look for (Edwards et al., 2015). Taking into consideration the processes that result in a deposit we can look for features that show: confinement by ice; contact with ice/meltwater and quick cooling; fragmentation processes; and transitions from a subglacial to a subaerial eruption (Edwards et al., 2015; Smellie, 2000).

Deposit characteristics that show ice confinement are varied. The vertical relief of the deposit can be very high, this means that the lava flows in the deposit will be anomalously thick – especially in a basaltic eruption (Edwards et al., 2015; Scanlon, Head, Wilson & Marchant, 2014; Smellie, 2000). Quickened cooling due to ice and meltwater is shown by thermal fractures, often in the form of columnar joints (Edwards et al., 2015; Scanlon et al., 2014). Other indicators include pillow lavas interbedded with hyaloclastites and a deposit with an abundance of vitric particles (Edward et al., 2015). Fragmentation is shown by an accumulation of very fine ash that can be either blocky or vesicular (Smellie, 2000). The sorting of these different ash types will be poor (Edwards et al., 2015; Smellie, 2000). When the eruption transitions from subglacial to subaerial several distinguishing features are made in the passage zone. In an effusive eruption the original pillow lavas and hyaloclastites are likely to be overlain by a subaerial horizontal lava flow (Scanlon et al., 2014), if the eruption ends up being explosive as opposed to effusive, instead of lava flows, you will get pyroclastic deposits overlying the original deposits (Edwards et al., 2015).

The characteristics listed above are typical of a basaltic deposit. However, this will not always be the case for deposits derived from more evolved magmas (Edwards et al., 2015; Wilson & Head, 2007). By looking at examples of evolved subglacial deposits, several criteria have been

created for distinguishing a more evolved subglacial magmatic eruption. An andesitic magma may have lava flows stacked on top of one another and pseudo-pillow fractures (Hargitai, Kereszturi & Smellie, 2014). In contrast, a rhyolitic magma may show small and radial jointing, and peperite (a sedimentary rock with fragments of igneous rock, formed in contact with wet sediments) (Edwards et al., 2014; Russell, Edwards, Porritt & Rayne, 2014).

Many of these deposit characteristics alone are not exclusively associated with subglacial eruptions (Hargitai et al., 2014). For example, hyaloclastites are common in subaqueous eruptions (Furnes, Fridleifsson & Atkins, 1980). By using a selection of these features together, it means it can be determined whether the eruption was subglacial or not. A subaerial eruption for example will not have characteristics typical of ice confinement or enhanced cooling (Edwards et al., 2015), whilst a subaqueous eruption will not have evidence of ice confinement or abundant evidence of magma fragmentation (Edwards et al., 2015).

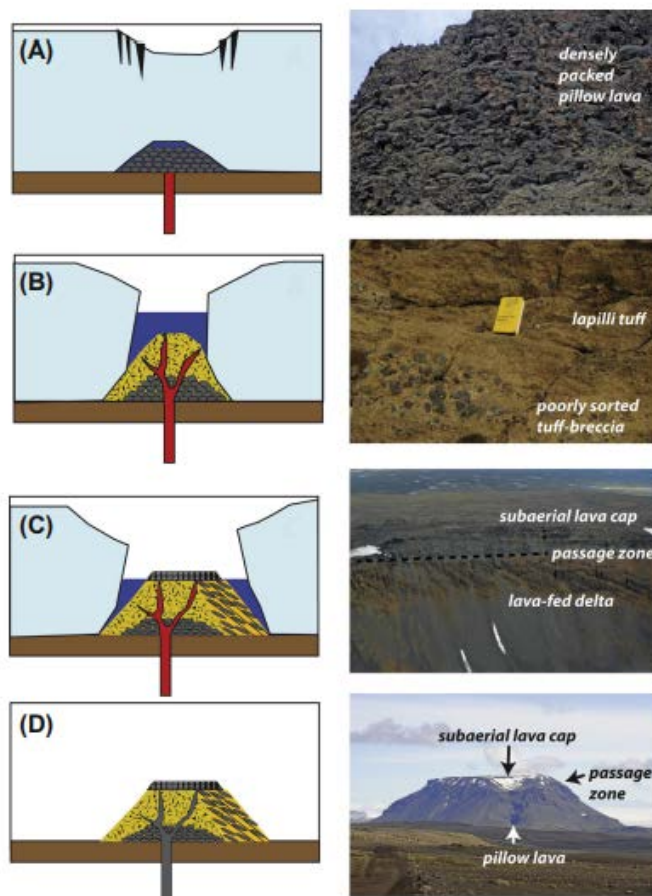


Fig. 4. Addition to Fig. 3. Showing the deposit characteristics you can expect to see at each stage during a generic subglacial eruption (Edwards et al., 2015).

2.4 Importance:

Hazards:

The glaciovolcanic eruptions at Eyjafjallajökull and Nevado del Ruiz were the most costly and deadly eruptions respectively in the last 100 years (Curtis & Kyle, 2017). This recent catastrophic glaciovolcanism has brought the importance of hazard and disaster management for such eruptions to the attention of academics and the public (Day et al., 2010; Edwards et al., 2015). It is likely that hazards will be most severe at the beginning of an eruption when extrusion rate and flow is the highest (Lescinsky & Fink, 2000). After this, hazards will subside but

risk for infrastructure and life remains (Edwards et al., 2015; Lescinsky & Fink, 2000; Smellie

& Skilling, 1994). What follows is a collation of hazards associated with glaciovolcanism and their sustained impacts on the surrounding environment.

First recorded in Iceland, Jökulhlaups, literally translated as ‘glacier burst’, are a hazard associated with glaciovolcanism (Geertsema, 2013). Whilst not exclusively glaciovolcanic, the increased meltwater production favours their occurrence (Edwards et al., 2015; Geertsema, 2013). A jökulhlaup describes a sudden outburst of water from beneath a glacier or ice sheet (Geertsema, 2013). This water can usually be attributed to meltwater production during an eruption and has a tendency to accumulate in lakes (Edwards et al., 2015). The body of water is contained until it reaches the margin of the glacier, at this point the water is released in a sudden and often catastrophic flood – a jökulhlaup (Geertsema, 2013). Once all the water has been released the open margin freezes over again, creating a cavity for more meltwater to build up in and create another jökulhlaup event (Geertsema, 2013). This effective drainage of meltwater can be attributed to both seasonality and/or glaciovolcanism (Geertsema, 2013). The unpredictability of glaciovolcanic derived jökulhlaups as opposed to seasonal jökulhlaups make them important to understand (Geertsema, 2013). Jökulhlaups have been best recorded in Iceland where they have caused civilian casualties and disruption to livestock and infrastructure (Gudmundsson et al., 2010). The most well-known jökulhlaup eruption as a function of glaciovolcanism is the 1996 Gjálp eruption in Iceland (Geertsema, 2013). This jökulhlaup lasted for four days (Gudmundsson et al., 1997). Because this eruption interfered with the seasonal periodicity of regular jökulhlaups people were not prepared and it meant lives were endangered where they otherwise did not have to be (Gudmundsson et al., 1997). Deception Island in Antarctica erupted in 1969, and despite the eruption occurring beneath thin ice, a large jökulhlaup and supraglacial flood ensued (Smellie, 2002). The jökulhlaup had an impact on national Antarctic base infrastructure and endangered lives. The hazards associated with jökulhlaups are not only anthropological in scale. 8,200 years ago jökulhlaups drained the North American glacial Lake Agassiz (Clarke, Leverington, Teller & Dyke, 2004; Geertsema, 2013). This is thought to have raised the sea level in the North Atlantic Ocean by 40 cm, and completely altered the thermohaline circulation of the ocean (Clarke et al., 2004; Geertsema, 2013). Jökulhlaups can also have run on effects such as triggering landslides and lahars (Edward et al., 2015; Geertsema, 2013).

Lahars are also a result of glaciovolcanism, although, like jökulhlaups, not exclusively (Major & Newhall, 1989). The excess meltwater produced during a glaciovolcanic eruption means that flooding can occur (Major & Newhall, 1989). Consequently, these floods are erosive and can pick up debris as they move down the volcano, becoming lahars as they do so (Lowe et al.,

1986; Naranjo et al., 1986). The pyroclastic debris ejected from the vent can also be caught up in this (Lowe et al., 1986; Naranjo et al., 1986). Lahars can be triggered in four ways: pyroclastic flows; surficial lava flows digging into the ice; basal melt of the ice sheet; and ejection of crater lake water (Major, 1989). Lahars can be devastating if they move into populated or civilised areas. In 1985, the subglacial volcano Nevado del Ruiz in Chile, erupted and created lahars which killed ~25,000 people and wiped out entire communities (Lowe et al., 1986; Naranjo et al., 1986). Even though this eruption was not huge, the ensuing lahars meant it was the most deadly in the past 100 years. Lahars are a dangerous and common hazard associated with glaciovolcanoes. Minimising effects of them means constant hazard mapping and monitoring of volcanoes.

Another associated hazard is an increase in tephra production. The reason this hazard is especially significant for glaciovolcanism again comes down to meltwater (Edwards et al., 2015). If any meltwater gets near the volcano vent it can create an explosive eruption (Gudmundsson et al., 2010). This will spew ash high into the atmosphere, and can become a globally important hazard. The best example of this is the 2010 eruption of Eyjafjallajökull, Iceland. Meltwater made it into the vent causing volcanic ash to travel nearly 10 kilometres high (Gudmundsson et al., 2010). This ash was then blown around the Earth affecting global aviation routes (Gudmundsson et al., 2010). It cancelled European flights for five days and the aviation industry was losing an estimated \$250 million per day of closure (Gudmundsson et al., 2010). Even though the areal extent of glaciovolcanoes on Earth is limited, tephra production means that they are able to become a serious hazard on a global scale.

Prediction and monitoring of glaciovolcanic hazards is in production (Wilson & Head, 2007). In many respects the same approach can be used that is taken toward volcanism. However, the circumstances make several hazards less predictable (Edwards et al., 2015). A combination of SAR (synthetic aperture radar), remote sensing, and GIS (global information systems) provide an opportunity to look through the top of ice sheets and understand what is happening below (Curtis & Kyle, 2017; Scharrer, Malservisi, Mayer, Spieler & Munzer, 2007). Seismic monitoring allows for unusual seismic activity due to magma ascent to be recorded (Curtis & Kyle, 2017). Overall, glaciovolcanism has recently come to the forefront of hazard management. The ability for it to cause widespread catastrophe makes it imperative that now more than ever we begin to discern appropriate prediction and monitoring techniques so all necessary precautions can be taken.

Paleoclimate:

Glaciovolcanic deposits can help to ascertain the dynamic advance and retreat of ice sheets in Earth's history (Edwards, 2010; Edwards et al., 2015; Smellie, Rocchi & Armienti, 2014). This is mainly made possible due to the presence of deposit characteristics exclusively belonging to the passage zones of glaciovolcanic eruptions (Edwards et al., 2015). From the passage zone, the spatial and temporal distribution of ice can be obtained, along with the ice thickness (Smellie, 2000). Using these three pieces of paleo ice data it is easy to apply models to what Earth was like in the past and how it has changed. Because of enhanced glaciovolcanic deposit preservation, it is becoming increasingly relied upon as a window into cryosphere related events prior to the last glacial maximum.

By assessing volcanic deposits along the Transantarctic Mountains from ~12 Ma, it was found that the base of the East Antarctic Ice Sheet had been transitioning regularly between cold and wet based (Smellie et al., 2014). This has profound effects on future Earth system models of ice melt and sea level rise (Bell, 2008) because it shows that this transition does not necessarily mean total ice sheet collapse as once previously thought (Smellie et al., 2014). The same has happened in North America. Constraining exact location and ages of ice sheets prior to the last glacial maximum is difficult (Edwards et al., 2015). However, the presence of persisting subglacial deposits help to show the history. These are just two examples of many that have used glaciovolcanic deposits to hypothesise Earth's paleoclimate.

Climate Change:

Like all volcanoes glaciovolcanism has an output of CO₂ into the atmosphere (Dixon, Filiberto, Moore & Hickson, 2002). Whilst this could have a small effect on climate change, the role glaciovolcanism has in producing meltwater could have a much bigger one on the stability of ice sheets (Bell, 2008). The East and West Antarctic Ice Sheet (WAIS) combined could contribute >70m to sea level rise (Fretwell, 2013). A major factor in determining their stability is their basal condition (Bell, 2008). If glaciovolcanic activity increases on the continent, more meltwater will become present beneath the ice sheet (Bell, 2008). This can encourage faster velocities of the ice sheet and hence greater melt (Bell, 2008). In 2017, the first proof of subglacial activity beneath the WAIS was found in ice core tephra, and brought into question the stability of the WAIS (Iverson et al., 2017). Technology improvements are helping us to see what exactly lies beneath the ice, and it seems the presence of volcanoes beneath it threatens ice stability (Iverson et al., 2017). For this reason, we must assume that glaciovolcanism has the potential to play a much bigger role in climate change than originally hypothesised.

Mars:

The importance of glaciovolcanism is not restricted to Earth. Suspected geologic analogues on Mars mean that to understand the history of Mars it is imperative to understand glaciovolcanism on Earth. Enhanced remote sensing on Mars (Head & Wilson, 2007; Ogawa et al., 2003) has led to the discovery of possible present and paleo ice caps on the Martian regolith, and in the crust (Ogawa et al., 2003). This has profound astrobiological implications (Head & Wilson, 2007) including the ability to observe environments where life may have once flourished. Certain deposits on Mars can be related to glaciovolcanic ones on Earth. For example, dyke intrusions (Fig. 5.) have been seen on the continent. Due to their vertical anomaly and steep ridges they have been interpreted as dykes intruded into a glacial ice sheet (Head & Wilson, 2007). However, before making assumptions it is important to consider base conditions on Mars are different to Earth, for example gravity is ~four times that of Earth's and the Martian atmosphere is a lot thinner (Cavagna, Willems & Heglund, 1998). Regardless, coming to an understanding of glaciovolcanism on Earth will be a step closer to understanding putative Martian analogues.

There is evidence on Mars of large floods occurring (Head & Wilson, 2007). There are two ways in which this could have happened. The first hypothesis is that there was a massive release of a confined aquifer (Head & Wilson, 2007), whilst the second one is that significant permafrost melting occurred from glaciovolcanism (Ogawa et al., 2003). As described before this process can create huge outflows of water and would have the ability to explain these massive Martian flood events. Ogawa et al., (2003) modelled the melting of permafrost and showed that it was capable of creating these mass flood events, especially given the permafrost on Mars was assumed to be in the order of 4km thick at the time of the floods.

The importance of glaciovolcanism on Mars is profound. It could potentially hold the key to understanding the geological past of the planet. Further pursuit of this possibility involves continued modelling of scenarios and investigation of parallels on Earth.

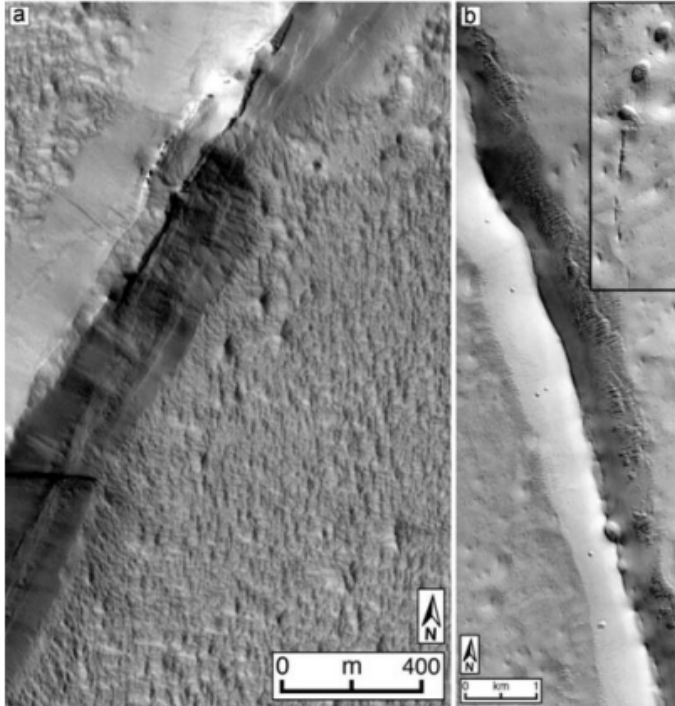


Fig. 5. Picture taken of the surface of Mars. This shows long, thin, and vertically steep ridges on the surface of Mars. This vertical anomaly is interpreted to have formed from a glacial dyke intrusion and subsequent melting of the ice sheet. It is evidence of ice confinement talked about in the deposit characteristics section (Head & Wilson, 2007).

2.5 Antarctic examples:

Overview:

Now that we have discussed the processes governing glaciovolcanism, this review will focus on its importance and presence in Antarctica. Until 2017 it was understood that there was a scattering of subglacial volcanoes in Antarctica, spanning 5000km from the South Sandwich Islands to Victoria Land (Smellie & Edwards, 2016). Recently, De Vries (2017) showed that there were 91 previously undiscovered subglacial volcanoes in the West Antarctic Rift system. Geologically, all Antarctic volcanoes

can be attributed to a subducting system on the Antarctic Peninsula (Barker, 1982; McCarron & Larter, 1998) and a large rifting system in West Antarctica (de Vries 2017, Smellie & Edwards, 2016). Volcanism in Antarctica is hypothesised to be encouraged by a large mantle plume beneath the continent (Seroussi, Ivins, Wiens & Bondzio, 2017; Smellie & Edwards, 2016). Volcanic centres in the Antarctic Peninsula are exclusively basaltic (Smellie & Edwards, 2016), whereas volcanic centres further south including Victoria Land and Marie Byrd Land have shown more felsic compositions including rhyolite (LeMasurier & Thomson, 1990; Smellie & Edwards, 2016; Wilch & McIntosh, 2000).

~98% of Antarctica is ice covered (Fretwell et al., 2013). The ice free land is often covered in thick layers of permafrost (Bockheim, 1995; Bockheim & Hall, 2002). 37% of the world's permafrost is in Antarctica (Bockheim & Hall, 2002). However, due to most land being beneath the pressure melting point under heavy ice sheets (Herterich, 1988), only 25% of the continent is covered in permafrost (Bockheim, 1995; Bockheim & Hall, 2002). This dictates that where there is permafrost, it is deep. The permafrost distribution around Antarctica can be seen in Fig.

6. Antarctic permafrost in ice free areas ranges from 100 – 1000m (Bockheim, 1995), whilst in ice covered areas it can be present but is less thick. It also happens, that due to convenience, most infrastructure on the continent is restricted to ice free areas (Bockheim, 1995). Therefore, it is essential intrusions into permafrost are considered when investigating Antarctic glaciovolcanism. Glaciovolcanism is a process that needs to be understood in order to (a) constrain a past geologic history of Antarctica, and (b) plan for future glaciovolcanic interactions on the continent.

Glaciovolcanism in Antarctica can be subdivided into four distinct regions of activity: The South Sandwich Islands; The Antarctic Peninsula; Marie Byrd Land; and Victoria Land (Smellie & Edwards, 2016). What follows is a succinct review of past and present glaciovolcanoes in these regions and their peculiarities.

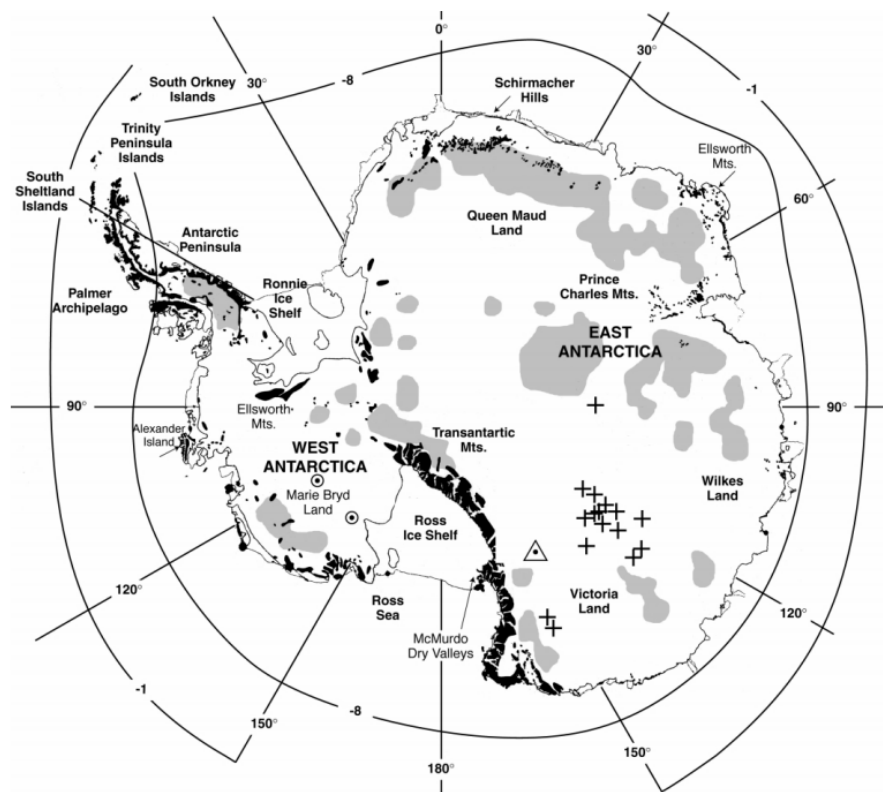


Fig. 6. Map of Antarctica showing areas of permafrost. The black areas are ice free and are known to have permafrost from 100 – 1000m thick. Assumed subglacial permafrost beneath the ice sheet is indicated by light grey. Crosses represent known subglacial lakes (Bockheim, 1995).

Volcanic Provinces:

The South Sandwich Islands were formed from an intra-oceanic volcanic arc (Barreiro, 1983; Smellie & Edwards, 2016). There are 11 main islands, of which, seven are permanently ice covered (Barreiro, 1983; Leat et al., 2016). Mt. Belinda was the most recent glaciovolcanic eruption, occurring between 2001 and 2007 (Leat et al., 2016). The marine sediments and ice core records show most glaciovolcanism on the South Sandwich Islands produces lava flows, but there are some examples of tephra producing eruptions (Leat et al., 2016; Smellie & Edwards, 2016). Most recent eruptions on the South Sandwich Islands have been erupted from a subaerial vent, so they fall into the classification of a supraglacial eruption, meaning only the lavas were glaciovolcanic (Smellie & Edwards, 2016).

The Antarctic Peninsula volcanic group includes James Ross Island and the tip of the Antarctic Peninsula. This area spans $\sim 700\text{km}^2$, and has been erupting for the last 12 Ma (Marenssi et al., 2010). Most glaciovolcanic deposits in this area consist of lava fed deltas, with a few tuffs and tuyas present (Smellie & Edwards, 2016). The biggest volcano in the area – Mt. Haddington has many glaciovolcanic deposits that can be easily accessed (Calabazo et al., 2015; Smellie & Edwards, 2016). This makes Mt. Haddington the single most important region for ascertaining the paleoclimate history and ice sheet evolution on the Antarctic Peninsula (Smellie & Edwards, 2016).

Marie Byrd Land spans an area $>180000\text{km}^2$, making it the largest glaciovolcanic area in Antarctica (Smellie & Edwards, 2016). The previous two areas have been dominated by basaltic volcanoes. However, Marie Byrd Land shows evidence of more evolved magmas (LeMasurier, Choi, Hart, Mukasa & Rogers, 2016; Smellie & Edwards, 2016). There are five active volcanoes in Marie Byrd Land (LeMasurier et al., 2016). However, recent remote sensing has proven a lot more active volcanic centres lie beneath the WAIS in Marie Byrd Land (de Vries et al., 2017). The history of volcanoes is not well constrained in this area due to extensive ice cover of up to 2km thick (Fretwell et al., 2013).

Victoria Land can be split into a Northern and Southern part, with the majority of volcanic activity occurring in the Southern part known as the McMurdo Volcanic Group (Smellie & Edwards, 2016; Vignaroli, Balsamo, Giordano, Rossetti & Storti, 2015). Much like the South Sandwich Islands, deposits are dominated by lava fed deltas (Smellie & Edwards, 2016). These sit on top of classic glaciovolcanic deposits including hyaloclastites (Smellie & Edwards, 2016). The deposits, whilst predominantly mafic, can often have thin layers of felsic material deposited on top (Smellie & Edwards, 2016). The importance of this area is that it acts as a

proxy to determine variation of the Antarctic Ice Sheet between wet and cold based phases at the time of previous eruptions (Smellie, 2000).

Importance:

The past glaciovolcanic history of Antarctica shows that attention must be given to glaciovolcanism. Not only will it play a role in melting ice sheets but many volcanic centres are situated near national Antarctic programmes and tourist operations (Fig. 7). Accurate hazard maps, precautions, and safety procedures must be put in place. It is also important that bases built within the vicinity of glaciovolcanoes have the correct infrastructure to withstand these hazards.

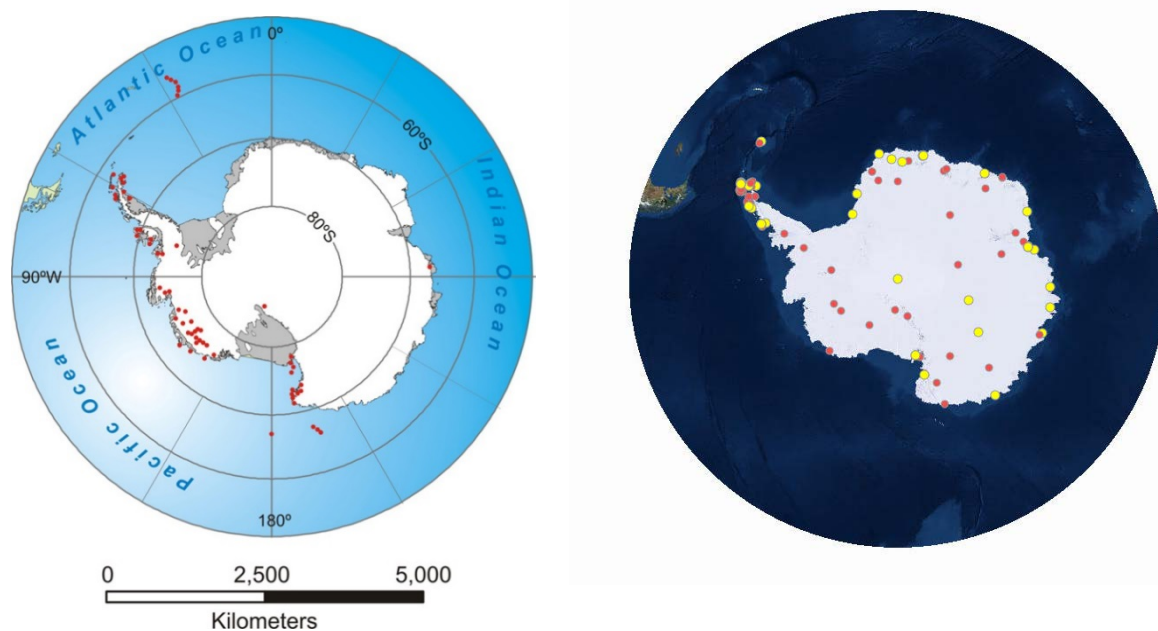


Fig. 7. Map on the left modified from Smellie (2002), red dots show known active volcanoes on the Antarctic continent. The map on the right is modified from COMNAP (2017) and shows the different Antarctic bases. Red dots are bases that winter over, yellow are summer only bases. There is a cluster of both bases and volcanoes on the peninsula and also near the Ross Sea.

The eruption of Deception Island, Antarctica in 1969 has been extensively researched due to its close proximity to many National Antarctic Bases (Bartolini, Geyer, Marti, Pedrazzi & Aguirre-Diaz, 2014). In the South Shetland Volcanic Group, Deception Island is the most active volcano (Smellie & Edwards, 2016). In the last 200 years it has erupted ~20 times (Bartolini et al., 2014; Morales, Almendros & Carmona, 2017). The 1969 eruption severely damaged beyond immediate repair all Antarctic bases on the Island which included the British, Chilean, and Argentinian bases (Bartolini et al., 2014). Due to its positioning in the Southern Ocean, Deception Island is an important place for commercial fishing vessels (Held & Blanchette,

2017) and tourism, with now over 40,000 visitors every year (Bartolini et al., 2014). Since the 1969 eruption, Britain, Argentina, and Spain have re-established bases on the island (Bartolini et al., 2014). Today, Deception Island now has five national Antarctic programme bases and three field camps (Bartolini et al., 2014), and as such appropriate precautions have been taken taking into consideration the active glaciovolcanic history of the island. Deception Island is the perfect example of why glaciovolcanism needs to be considered when planning Antarctica's future.

3. Recommendations:

The increasing interest associated with glaciovolcanism is sure to continue, especially with the expansion in planetary science, need for paleoclimate proxies and associated hazards.

Throughout academic history the processes and controls which drive glaciovolcanism were constantly being revised. This will continue into the future as we see extraordinary advances in technology. The ability for computer models to output scenarios, and the increased ability to analyse field samples in the laboratory are setting up an environment in which glaciovolcanic process is not too far away from academic consensus.

Glaciovolcanic eruptions have proved to be both deadly and costly. A new direction that the field of glaciovolcanism should take is toward hazard management. Hazard maps, precautions and evacuation procedures should be put in place for all areas within the vicinity of potential glaciovolcanic eruptions. Continued analysis of hazards will hopefully result in a more accurate prediction of when and how these events may occur. Effort should also be put into the utilisation of deposits as paleoclimate proxies in order to determine how the Earth might react in the short term future to climate change. An area where concentrated effort could go is science communication and outreach, so people who need to be educated about the importance of glaciovolcanism are. Overall, if the field keeps heading in the direction it is, it will not be long before many questions are answered, and risks are minimised.

4. Conclusion:

Overall, glaciovolcanism is a steadily growing academic field. Glaciovolcanism has been a large part of Earth's geologic history, and still today is impacting Earth. Glaciovolcanism can occur in different circumstances, and the two main controls which determine this include magma composition and ice thickness. Glaciovolcanism is important for several different reasons. Hazards associated with it including: jökulhlaups, lahars, tephra, and flooding have the

potential to directly affect human life and infrastructure. Glaciovolcanism is also important as a contributor to climate change, as a paleo climate proxy, and as a terrestrial analogue for Martian geology.

Antarctica has become increasingly important in this field of study. The four volcanic provinces in Antarctica all have associations with glaciovolcanism. Characteristic deposits on the continent have allowed scientists to come to conclusions about the paleoclimate on Earth, and also what this implies for the future climate. An awareness of glaciovolcanic hazards on the continent is vital when planning operations such as base logistics, tourism, and fishing operations. Research around glaciovolcanism will continue to increase in the future as we look for ways to minimise risk and understand the dynamic system of our Earth and surrounding planets.

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