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Why are some subglacial eruptions more explosive than others?

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A subglacial eruption is a volcanic event that occurs under snow or ice[1]. It could be a volcano that is at high latitude under an ice sheet or glacier, such as the Eyjafjallajökull and Grímsvötn eruptions (Fig.1, Fig. 2) or it could be an ice capped volcano at high altitude[2] such as Mt Hood (Fig. 3).

Figure 1: The Eyjafjallajökull 2010 ash plume[3]

Subglacial eruptions are particularly dangerous; they have all of the hazards of eruptions that take place in open air (subaerial eruptions) plus hazards due to the presence of ice and meltwater[2]:

1) When magma and water interact they tend to explode in violent 'fuel-coolant interactions'[9,10];
2) The fragmentation caused by the magma-water interaction produces large quantities of ash which can destroy crops and livestock, and disrupt aviation[10,11];
3) The sudden meting of ice can create incredibly destructive jökulhlaups (glacial floods) and lahars (mudflows)[10,12];
4) Subglacial volcanoes are more prone to instability (especially when the ice melts away), which can lead to devastating debris avalanches[2];
5) A subglacial eruption can destabilise the ice sheet above it, leading to break offs[13].

All of these hazards pose a massive threat for the millions of people that live within close distance of subglacial volcanoes[2] (Fig. 3). It is therefore important to understand what controls the behaviour of a subglacial eruption.

Figure 2: The Grímsvötn 2011 ash plume[14]

Q: The Grímsvötn 2011 eruption was ten times more powerful than the last eruption at Grímsvötn in 2004[4] and erupted material 100 times faster than the 2010 Eyjafjallajökull eruption[5] to produce an ash cloud over twice as high (17 km[6] cf 8 km[7]). Why was it such a powerful eruption?
A: There's no definite answer yet… but probably a wealth of contributing factors… (to be continued)

Q: Why did Eyjafjallajökull disrupt aviation more than Grímsvötn?
A: Eyjafjallajökull had a higher Si content which meant that it was highly explosive and so fragmented to produce a very fine grained ash which was particularly problematic to aircraft[8].

What we know already

The size and explosivity of subglacial eruptions is controlled by:

1) Composition – the higher the Si (silica) content, the more viscous (sticky) the magma is and the more explosive the eruption will be[15];
2) Ice thickness – the more ice there is to melt, the more water is available for violent fuel coolant interactions[13,16];
3) Cavity size - subglacial eruptions melt cavities into the base of the ice sheet. The larger the cavity, the more room there is for explosive fragmental behaviour[17].

Q: There were two phases to the 2010 Eyjafjallajökull eruption. The initial phase produced lava flows and fire fountains which attracted many tourists[18]. The second phase produced a large ash cloud that resulted in the biggest disruption to aviation since World War II[19]. Why did the behaviour change?
A: The first phase took place on the land between two glaciers, the second phase was under the ice sheet itself and therefore comprised explosive magma-water interaction. The composition also became more silica-rich[18].

Figure 3: Mt Hood with Portland in the foreground[20]

What we don't know - What role volatiles (volcanic gasses) have?

Volatiles are known to have a big role in subaerial eruptions; The more volatiles there are, the more explosive an eruption is[21]. Imagine shaking up two bottles of pop (one bubbly, one flat) and then removing the tops. In subglacial eruptions, however, it is unclear what role volatiles will play[22].

Some say that volatiles will reduce explosivity because gas bubbles are compressible so they will absorb some of the force of an explosion[9] (just like shock absorbers on a bike). Other people say that they will increase the explosivity of an eruption because bubbles create a larger surface area for magma-water interaction (Stevenson pers. comm., 2009).

Cue Jacqui….

We took five subglacial volcanoes from Torfajökull, Iceland (Table 1) that all erupted at very similar times, under very similar thicknesses of ice and have very similar compositions[13]. Four of these five were even thought to have formed during the same eruption[23]! And yet each volcano erupted in a very different way[13]. Why?

Samples from each volcano were taken to the Secondary Ion Mass Spectrometry (SIMS) facility at Edinburgh University. This enabled us to measure the H_2O (water), Cl (Chlorine) and F (fluorine) content of our samples. Melt inclusions are tiny droplets of melt from the magma chamber that become trapped in crystals as they grow. They are thought to record the initial volatile content. By comparing these to the matrix glass (surrounding lava) we can get the full degassing history of our samples[22].

Table 1: Information about the volcanoes in this study (colour coded to match Fig. 4)

Volcano	Behaviour	Size (km^3)	Did it burst through the ice sheet?	Age (years)
Angel Cake	Effusive	<0.1	No[13]	70,000 [27]
Bláhnúkur	Effusive[24]	<0.1 [24]	No[24]	95,000 [28]
Dalakvísl	Explosive → Effusive[25]	<0.2 [25]	Getting close[25]	70,000 [27]
Socket Tuya	Explosive	~1	Yes[13]	70,000 [27]
SE Rauðfossafjöll	Explosive[26]	~1 [26]	Yes[26]	70,000 [27]

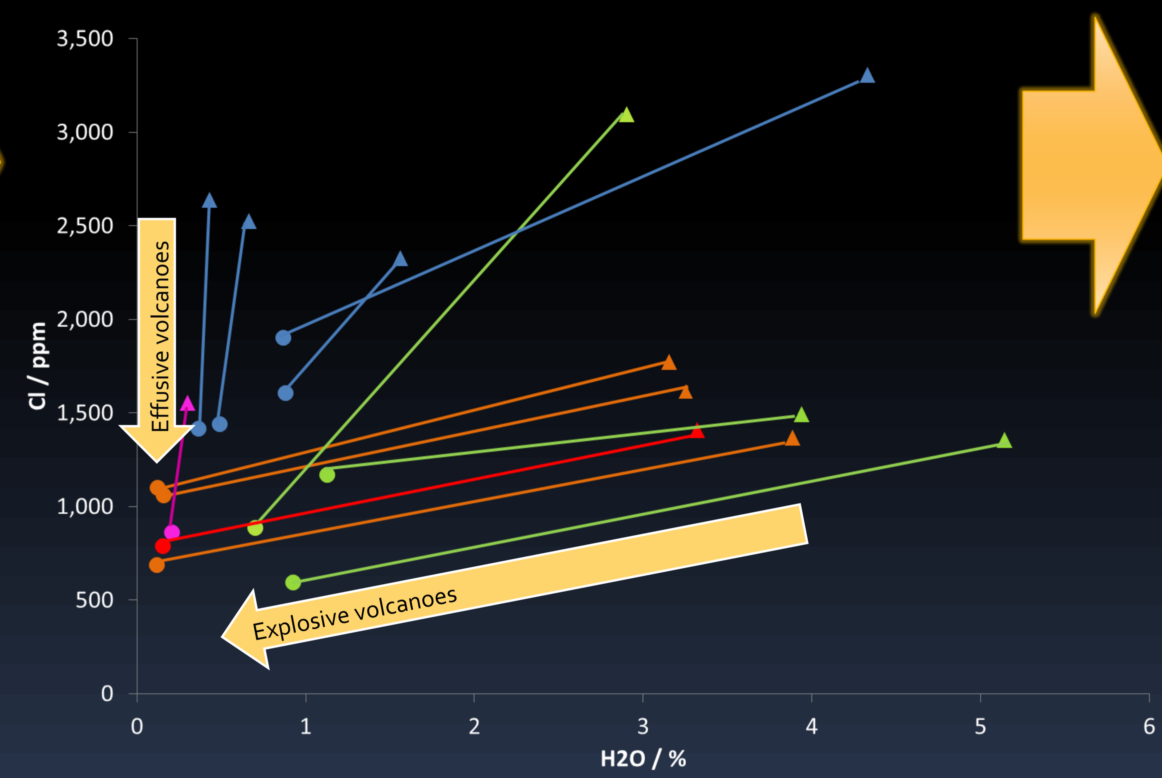

Figure 4: Water plotted against chlorine. The different colours depict the different volcanoes shown in Table 1. Triangles mark melt inclusion data (initial volatile content) and circles mark matrix glass data (final volatile content). The lines mark degassing paths and the connect the melt inclusion to the matrix glass for each sample. The two large arrows show the general trends of the explosive and effusive volcanoes.

As figure 4 demonstrates, our samples show a wide variety of initial water contents (shown by the triangles); ranging from 0.30 wt% for Angel Cake to 5.15 wt% for Dalakvísl. H_2O is the most influential of the volatile species in determining eruptive style[21] and as Fig. 4 shows the explosive eruptions (shown in red and orange) had higher initial H_2O compared to the effusive (non-violent) eruptions (in pink and blue) with the exception of just one Bláhnúkur sample.

There are also different H_2O-Cl relationships between the explosive and effusive eruptions. H_2O-Cl relationships reveal information about the degassing path; whether volatiles have been lost on the way to the surface (open system degassing) or whether they have remained in the magma (closed system degassing) to produce a more explosive eruption[29]. In Fig. 4 there is a clear difference between the H_2O-Cl trends of the explosive eruptions, which have low gradient degassing paths and the effusive eruptions, which have near vertical degassing paths.

Dalakvísl (in green on Fig. 4) was a mixed eruption that was thought to have started explosively and then became effusive[25]. Two of the samples seem to have very similar volatile data to the explosive volcanoes, whilst the third has volatile data more similar to the effusive Bláhnúkur (in blue). Furthermore, the most volatile rich Dalakvísl sample was collected from an explosive deposit and the volatile poor sample from a more effusive area.

Our data is the first evidence that volatiles play a similar role in subglacial eruptions as they do in subaerial eruptions. That is that:

1) The higher the initial volatile content, the more explosive the eruption will be
2) Closed system degassing results in more explosive volcanism than open system degassing i.e. If the volatiles are lost en route, the eruption will not be as explosive.

These findings have great significance for understanding the hazards associated with subglacial eruptions.

Therefore, it seems that, at Torfajökull at least, some subglacial eruptions are bigger than others because of the role of volatiles described above. Could it be that the volatile content and degassing path were contributing factors to the power of the 2011 Grímsvötn eruption??

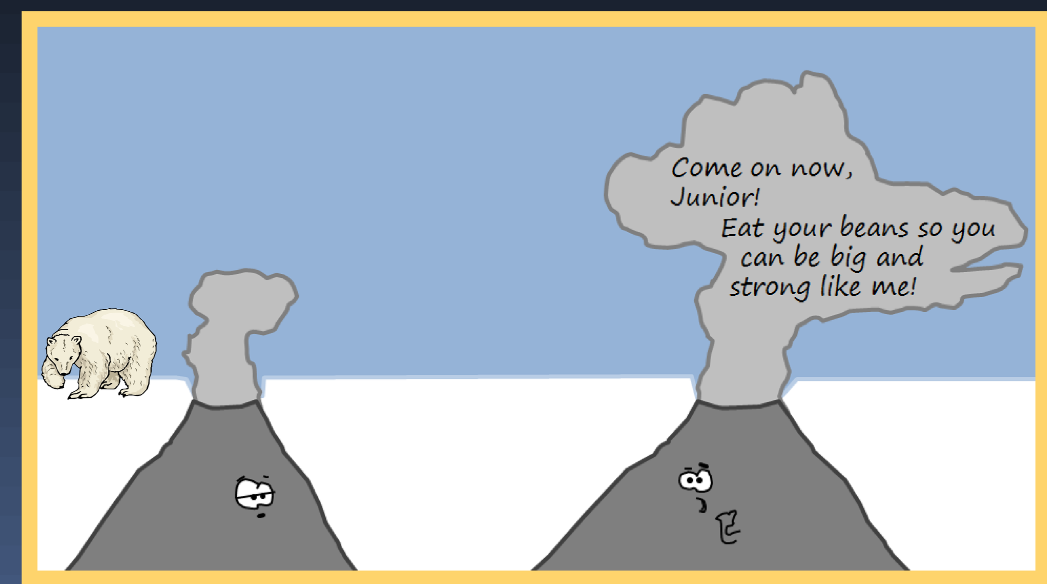

Figure 5: Cartoons of Eyjafjallajökull (left) and Grímsvötn (right)

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