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The chemistry and element fluxes of the July 2011 Múlakvísl and Kaldakvísl glacial floods, Iceland

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ABSTRACT

This study describes the chemical composition and fluxes of two ~2000 m^3/s glacial floods which emerged from the Icelandic Mýrdalsjökull and Vatnajökull glaciers into the Múlakvísl and Kaldakvísl rivers in July 2011. Water samples collected during both floods had neutral to alkaline pH and conductivity from 100 to 900 μS/cm. The total dissolved inorganic carbon (DIC), present mostly as HCO_3^-, was ~9 mmol/kg during the flood peak in the Múlakvísl but stabilized at around 1 mmol/kg; a similar behaviour was observed in the Kaldakvísl. Up to 1.5 μmol/kg of H_2S was detected. Concentrations of most of the dissolved constituents in the flood waters were comparable to those commonly observed in these rivers. In contrast, the particulate suspended material concentration increased dramatically during the floods and dominated chemical transport during these events. Waters were supersaturated with respect to a number of clays, zeolites, carbonates, and Fe hydroxides. The most soluble elements were Na, Ca, K, Sr, Mn, and Mg, whereas the least soluble were Ti, Al, and REE. This is consistent with the compositions of typical surface waters in basaltic terrains and the compositions of global rivers in general. The toxic metal concentrations were below drinking water limits, suggesting that there was no detrimental effect of flood waters chemistry on the environment. Increased concentration of DOC, formate, and acetate in the flood waters suggests substantial subglacial microbiological activity in the melt water prior to the floods. Reaction path modelling of the flood water chemical evolution suggests that it experienced subglacial water–rock interaction for at least a year in the presence of limited amounts of acid gases (e.g. SO_2, HCl and HF). This suggests that the heat source for glacier melting was geothermal rather than volcanic.

1. Introduction

Iceland is the largest landmass found above sea level at mid-ocean ridges. There are over 30 active volcanic systems with a total average eruptive frequency of at least 20 eruptions per century and magma output rate of 5 km^3 per century (Thordarson and Höskuldsson, 2008). High-temperature geothermal systems are located in the central parts of active volcanic and rifting belts with only three located close to their margins (Arnórsson et al., 2008). Due to elevation and favourable location with respect to humid air masses, the most active volcanoes and geothermal areas in Iceland are covered by glaciers. The heat from subglacial magma intrusions and exothermic rock alteration reactions melts the overlying ice, forming depressions in the glaciers called cauldrons (Steinthórsson and Óskarsson, 1986; Björnsson, 2003). Melt water often collects at the base of the glacier; eventually there may be sufficient melt water to lift the ice, resulting in a glacial flood.

There are two main causes of glacial floods — called jökulhlaups in Icelandic[2]: (1) subglacial geothermal activity during which ice is melted continuously and accumulates in periodically drained subglacial lakes and, (2) subglacial volcanic eruptions where melt water is produced rapidly due to thermal energy released during magma cooling and fragmentation (Gudmundsson et al., 2008). The former tend to be smaller in volume and more common than the floods originating from volcanic eruptions (Björnsson and Kristannsdottir, 1984; Gudmundsson et al., 2005, 2008). Drainage occurs during semi-regular intervals and not all flood events are detected. During subglacial volcanic eruptions, floods can be abrupt, loaded with suspended particulate material, and sometimes can contain high concentrations of dissolved metals and volatiles (Kristmannsdóttir et al., 1999; Gislason et al., 2002; Snorrason et al., 2002; Stefánsdóttir and Gíslason, 2005; Sigfússon, 2009). Some of these floods can be of 'Amazonian' size; with maximum flow rates of 3000–700,000 m^3/s (e.g. the glacial flood from Katla in 1918 and the glacial flood in the Jökulsa a Fjöllum between 2500 and 2000 years ago; Tómasson, 1996; Snorrason et al., 2002; Waitt, 2002; Gudmundsson et al., 2005; Russell et al., 2010). Because of their

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[2] In Icelandic 'jökull' is a glacier, and 'hlaup' means flood.

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potentially large impact on the environment, glacial floods have been extensively studied with respect to natural hazards, fluid mechanics, sediments, dissolved constituents, and suspended particulate transport (Gudmundsson et al., 1997; Maizels, 1997; Björnsson, 1998, Kristmannsdóttir et al., 1999; Geirsdóttir et al., 2000; Roberts et al., 2000; Gislason et al., 2002; Björnsson, 2003; Alho et al., 2005; Stefánsdóttir and Gíslason, 2005; Russell et al., 2006, 2010).

The chemical composition of waters affected by geothermal and volcanic activity (groundwaters, surface waters and flood waters) is influenced by its interaction with surrounding rocks, heat, and gas supply, and overburden pressure which affects gas solubility. During subaerial volcanic eruptions, the proton and metal salts adsorbed on tephra surface will dissolve when exposed to rain- and surface-waters (Frogner et al, 2001; Delmelle et al., 2007; Flaathen and Gislason, 2007; Jones and Gislason, 2008; Gislason et al., 2011; Olsson et al., 2013). The metal salts are commonly sulphates, fluorides, and chlorides, which originate from magmatic gases such as SO_2, HF, and HCl (Óskarsson, 1980, 1981; Seymonds and Reed, 1993). The dissolution of salts releases these metals and protons. This might significantly increase the concentrations of some elements, including F and Al, leading the fluids to be toxic (Flaathen and Gislason, 2007). During subglacial eruptions, some portion of the magmatic gases dissolves directly into the melt waters affecting the flood water chemical composition (Gislason et al., 2002; Sigfússon, 2009). Numerous studies have focused on the role of volcanic and geothermal degassing on the mobilization of rock constituents in surface- and groundwaters (Federico et al., 2002, Aiuppa et al., 2003; Cioni et al., 2003, Marini et al., 2003; Federico et al., 2004; Aiuppa et al., 2005; Taran et al., 2008; Flaathen et al., 2009; Ambrosio et al., 2010; Floor et al., 2011). Some of these studies confirm that the input of magmatic gases, including CO_2, may promote host rock dissolution increasing significantly dissolved metal concentrations (e.g. Federico et al., 2002, 2004; Flaathen et al., 2009; Oskarsdottir et al., 2011). Increased host rock dissolution may, however, have a positive impact on the biota due to the addition of limiting elements to the fluid, potentially leading to short lived net flux of CO_2 from the atmosphere (Gislason et al., 2002). If water–rock interaction is sufficient, the water can be neutralised leading to the precipitation of metal scavenging (oxy)hydroxides and other secondary phases (Aiuppa et al., 2000a,b, 2005; Flaathen and Gislason, 2007; Flaathen et al., 2009; Kaasalainen and Stefánsson, 2012).

An improved understanding of glacial floods is of wide interest for several reasons. Firstly, the heat source origin is critical to the potential environmental impact of the flood. If the heat was sourced by volcanic eruption, acid gas input can lead to acidic flood waters and toxic metal release from the host rock. If the heat source origin was geothermal activity, extensive, long-term fluid–rock interaction would lead to higher pH and less toxic flood waters (Sigvaldason, 1963, 1965; Arnórsson et al., 1983; Steinthórsson and Óskarsson, 1983; Kaasalainen and Stefánsson, 2012). Secondly, the chemical composition of the flood waters is often one of the few, if not the only, indicator of the flood triggering mechanism. As such monitoring of river water chemistry might prove to be an effective method for alerting the public of the possible volcanic eruption in the potential inundated area. Thirdly, glacial floods may play an important role in global cycle of elements. Large number of studies have shown that particulate transport in rivers contribute significantly into the global cycle of elements (e.g. Oelkers et al., 2004, Stefánsdóttir and Gíslason, 2005, Oelkers et al., 2011; Jones et al., 2012a,b; Oelkers et al., 2012). Glacial floods are heavily loaded with suspended material having large surface areas, making it especially reactive once it settles in estuaries. Moreover, suspended particulate flux is far more dependent on runoff than is the dissolved element flux; glacial floods can thus increase dramatically particulate fluxes to the ocean (Gislason et al., 2006). The term ‘flux’ in this case corresponds to the mass of material transported by water towards the oceans. This particulate material can influence greatly primary productivity along the coast and in lakes (Gislason and Eiriksdottir, 2004).

In this study we focus on the chemical composition of two small Icelandic glacial floods which emerged in July 2011 from the Mýrdalsjökull and the Vatnajökull glaciers. This study was motivated to better understand the origin of the heat source that caused the melting of the glacier and its effect on the flood water chemistry. This study also helps illuminate the potential significance of glacial floods on suspended particulate material transport on a local scale.

2. General description of the study area

2.1. The Mýrdalsjökull glacier and Katla volcanic system

The Mýrdalsjökull glacier is located in southern Iceland within the Eastern Volcanic Zone (Fig. 1a). It covers almost 600 km^2 with a maximum ice thickness of ~740 m in the northern part of the caldera (Björnsson et al., 2000). There is an active central volcano beneath the glacier with a large caldera, which bottom elevation is approximately 650 m above sea level. The caldera, together with an 80 km long northeast-trending fissure swarm, comprises the Katla volcanic system. The circular volcano base is about 30 km in diameter and the highest peaks reach 1380 m above sea level (Björnsson et al., 2000). The caldera is oval shaped with its longest axis trending 14 km NW–SE. The area and volume of ice inside the caldera is 100 km^2 and 45 km^3, respectively. On the caldera rim, the ice cap thickness ranges from 150 to 200 m (Björnsson et al., 2000). Ablation in summer lowers the glacier surface elevation by 4–8 m from spring to autumn. Snow accumulation restores this elevation during the winter. The central volcano is one of the most seismically active in Iceland. The epicentres are usually located within the caldera and beneath the western rim at Goðabunga. Katla erupts roughly twice a century (Larsen, 2000; Óladóttir et al., 2008). It produces high Fe–Ti basalts of the transitional-alkaline magma suite (e.g. Jakobsson, 1979). Katla activity is dominated by explosive subglacial eruptions producing numerous and widespread tephra layers with volumes from ~0.01 to ~1 km^3 (Lacasse et al., 1995; Thordarson and Larsen, 2007; Óladóttir et al., 2008).

The last major glacial flood from Katla occurred in 1918 and was triggered by a volcanic eruption within the caldera with total volume of tephra fallout of 0.7 km^3 (Eggertsson, 1919; Sturkell et al., 2008) and the volume of water-transported material of 0.7–1.6 km^3 (Larsen, 2000). The dense-rock equivalent may have been as high as 1 km^3 (Sturkell et al., 2008). Most of the flood water flowed during an eight-hour period at the initial stages of the eruption. The total flood water volume was estimated to be 8 km^3 (Tómasson, 1996). The majority of the water came from beneath the glacier, breaking the glacial tail. Witnesses reported that large blocks of ice were carried with the flood water. The flood was estimated to have peaked at 300,000 m^3/s and inundated an area of 600–800 km^2 to the east of the volcano (Tómasson, 1996; Larsen, 2000). The coastline moved 4 km towards the sea as the sediments carried by the flood water were deposited. Other smaller glacial floods from Katla, each with a peak discharge of about 2000 m^3/s, occurred in 1955, 1999, and 2011 (Gudmundsson et al., 2013).

2.2. The Vatnajökull glacier and Hamarinn central volcano

The Vatnajökull glacier is the largest in Iceland and covers 8100 km^2. It is situated in the Eastern Volcanic Zone (Fig. 1b). The ice thickness is generally 600–800 m with a maximum thickness of 950 m (Björnsson and Pálsson, 2008). There are several central volcanoes beneath the glacier including the Grímsvötn, Bárðarbunga, Gjálp, and Hamarinn (Gudmundsson and Högnadóttir, 2007). Hamarinn is a central volcano (Fig. 1b) and belongs to the Bárðarbunga–Veidivötn tholeitic volcanic system. This volcanic system is 190 km long and 28 km wide, and it covers an area of 2500 km^2 (Thordarson and Larsen, 2007). Most of the historical eruptions, which account for 14% of the verified eruptions in Iceland, took place on the ice-covered part of the system, forming