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The effect of the 2014-15 Bárðarbunga volcanic eruption on chemical denudation rates and the CO_2 budget

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Abstract

Chemical denudation rates during the 2014–15 Bárðarbunga eruption, calculated using river chemical fluxes, increased substantially confirming that volcanic activity and its products such as fresh lava, and acidic volatiles accelerates these rates. Although the long-term net effect of the combined input of volcanic gases and basalt from the eruption appears to be the overall net drawdown of CO_2, it is found that the rapid release of acid gases to surface waters once the basaltic lava comes in contact with surface waters will lead to a short-term release of CO_2 from these waters.

Keywords: Denudation rate; dissolved flux; CO_2; volcanic eruption; Bárðarbunga

1. Introduction

The 2014–15 Bárðarbunga volcanic eruption, which lasted from August 31, 2014 until February 27, 2015, was the largest eruption in Iceland in terms of volume of erupted material for more than 200 years. This eruption released to the atmosphere an average of 60 kt/day of SO_2, 30 kt/day of CO_2, 500 t/day of HCl and 280 t/day of HF [1, 2]. The emission of such volcanic gases can alter the composition of the atmosphere and thus can affect climate. The climatic effect of volcanic SO_2 depends on chemical composition of the magma and the mass of sulphur-rich gases released into atmosphere. If released SO_2 transforms into sulphate aerosols, this product will cool the lower troposphere [3]. In contrast, unoxidized SO_2 is a short-lived greenhouse gas in the atmosphere as it absorbs ultraviolet radiation, and

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warms the climate. The relationship between released SO_2 and the magnitude of its transformation into sulphate aerosols is highly nonlinear [e.g. 4, 5]. Another feedback between volcanic gas release and global temperature stems from CO_2. Although this greenhouse gas will tend to increase global temperature, it is eventually consumed by silicate weathering [e.g. 6].

The long-term negative feedback between atmospheric CO_2 and silicate weathering stems from the increase of silicate weathering rates with increasing temperature [6, 7]. As modeled by [8], the basaltic Deccan traps emplacement increased global surface temperature rapidly by 4 °C as a result of volcanic CO_2 emissions. Due to enhanced silicate weathering rates stemming from this temperature increase, climate cooled and the global temperature was 1.5 °C lower than it was prior to the emplacement 1.5 million years later [8]. Weathering rates are not only enhanced by increased temperature but also by the addition of acidic volatiles, aerosols and salts during volcanic eruptions. After their interaction with rain and surface waters they can decrease fluid pH, resulting in accelerated basaltic mineral and glass dissolution. Ligands such as F^- and SO_4^{2-} are also known to accelerate basalt dissolution rates at neutral pH [9, 10]. A number of studies have also suggested that weathering rates depend on rock age, such that fresh basalts will weather faster than older basalts [e.g. 11-15]. The top and bottoms of newly formed lava consists of basaltic glass, which is more reactive than crystalline basalt [e.g. 15-19]. The degree to which fresh basaltic lava exhibits accelerated weathering rates and thus accelerated carbon drawdown from the atmosphere can be assessed by comparing catchment denudation rates before and during the 2014–15 Bárðarbunga volcanic eruption.

This study expands the discussion previously presented in [20] on the weathering rates in the Jökulsá á Fjöllum catchment affected by the 2014–15 Bárðarbunga volcanic eruption. The flux of dissolved material transported from the continents to the oceans is attributed to chemical denudation. Denudation rates based on river fluxes provide an integrated average of denudation rates over a large area and take account the large number of processes that contribute to denudation. Chemical denudation draws down CO_2 from the atmosphere as carbonic acid dissolves minerals and releases alkalinity to surface waters. In this study we use measured chemical denudation rates before and during the 2014–15 Bárðarbunga volcanic eruption to determine how much faster the fresh lava reacts compared to the older pre-existing bedrock in the Jökulsá á Fjöllum catchment. This catchment trapped the bulk of the lava originating from the eruption. We then compare the enhanced weathering rate (e.g. the denudation rate before and during the eruption) with the mass of CO_2 released during the eruption. Finally, we use this comparison to estimate how long it would take for this additional weathering to consume this mass of CO_2. Although this may give a minimum estimate of the time required for this drawdown, as denudation rates are likely faster during than after the eruption, it provides some insight into the longer-term fate of CO_2 injected into the atmosphere during volcanic eruptions.

2. Methods

The effect of the presence of fresh basalt on chemical denudation rates is characterized in this study by comparing selected constituents' fluxes in the Jökulsá á Fjöllum catchment before and during the 2014–15 Bárðarbunga volcanic eruption. The term 'flux' in this case corresponds to the mass of material transported in dissolved form by the river water towards the oceans. The calculated 2014 annual fluxes are shown in Table 1. These fluxes were calculated by first creating correlation curves between fluxes and discharge at the time of sampling such as shown in Fig. 1. The baseline curves for chosen components, in the absence of volcanic activity are based on discharge and river samples collected at Grímsstaðir during 1998–2001 (diamonds in Fig. 1). Corresponding correlation curves were also generated from these constituents' fluxes as obtained using an osmotic sampler and discharge from August, 23 until September, 21, 2014, when the osmotic sampler was deployed (triangles and squares in in Fig. 1). As described in [20] the osmotic sampler collects the river water samples continuously and therefore records rapid chemical changes in river composition. The osmotic sampler was deployed in this Jökuslá several days before the eruption to monitor chemical changes caused by seismicity. The eruption began on 31 August. On September, 9 lava flowed into the Jökulsá á Fjöllum river channel. After that time the river concentration of DIC (dissolved inorganic carbon), SO_4 and some trace metals changed noticeably, therefore we divided the samples collected before and after this time into two periods [20]. These two time periods are referred to as 'Grímsstaðir before' and 'Grímsstaðir after' in Table 1 and Fig. 1. Note, however, that the gas emission rates were the highest near the beginning of volcanic activity [1]. Using these three correlation curves and the 2014 daily discharge measured at Grímsstaðir the hypothetical total chemical fluxes for each day of the year for each of these three correlation curves was calculated. These values were summed together to generate the 2014 annual fluxes based on each of the three distinct flux/discharge curves – the non-eruption 1998-2001 regime, during the volcanic activity but before the lava flowed into the channel (Grímsstaðir before), and after the lava arrived in the river channel (Grímsstaðir after - see Table 1). Comparison of these hypothetical annual fluxes was used to quantify the effect of the presence of fresh lava and volcanic gases on catchment chemical denudation rates.

Table 1. Comparison of the 2014 annual fluxes in tonnes calculated using the correlation between flux and discharge measured during the background period of 1998-2001, and the same relation obtained before ('Grímsstaðir before'), and after ('Grímsstaðir after') lava flowed into the Jökulsá á Fjöllum channel.

Component	SiO_2	Na	Ca	Mg	Al	Fe	K	DIC	SO_4	F	Cl
1998-2001 Grímsstaðir	72,000	57,400	34,600	11,800	157	46	2,490	212,000	31,600	761	11,700
Grímsstaðir before	95,300	86,200	49,600	22,300	431	516	2,990	233,000	34,800	774	15,500
Grímsstaðir after	87,300	77,300	43,300	19,000	480	513	2,600	173,000	33,100	506	12,000

3. Results

As can be seen in Fig. 1, fluxes obtained during the eruption are higher than the background fluxes for the corresponding constituents' discharges. Lava flow into the river channel did not change substantially the correlation between flux of SiO_2, Na, Ca, Mg, and K (see 'Grímsstaðir before' and 'Grímsstaðir after') and discharge. The Al, Fe, SO_4, and F fluxes are higher after the lava flowed into the Jökulsá channel in contrast to the DIC flux, which is lower after the lava inflow.

The calculated annual dissolved fluxes during the Bárðarbunga activity before lava flowed into the Jökulsá á Fjöllum channel increased by 32% for SiO_2, 50% for Na, 43% for Ca, 20% for K, 89% for Mg, 1012% for Fe, and 176% for Al compared to the background fluxes (Table 1). The anion fluxes increased to a lower extent; 10% for DIC and for SO_4, and 2% for F compared to the earlier measurements. Although the trace metal fluxes were in general higher during the activity (Fig. 1), the Al and Fe fluxes in Table 1 might be inaccurate due to the low detection limit of the analytical method used for trace metals determination in samples collected by osmotic sampler as described in [20].

4. Discussion

There are a number of processes that increase chemical denudation rates during and following a volcanic eruption, making it difficult to identify their relative significance. The increased denudation rates during volcanic events not only stem from the accelerated dissolution rate of the newly erupted lava, but also from acidic gases such as SO_2, CO_2, HCl, and HF emitted during the eruption. Dissolution of these gases and aerosols lowers the pH of rain and surface waters and therefore increases the dissolution rates of basalt and its mineralogical and glass constituents [9, 10, 17, 18]. Galeczka et al. [20] estimated, using the Na flux in Jökulsá a Fjöllum river, that the annual chemical denudation rate in 2014 was 24% higher than the background flux. Note that in this previous estimation, the background annual flux for 1998-2001 was calculated using the chemical and discharge data obtained during that period. This observation is noteworthy as less than 1% percent of the catchment was covered by fresh lava at the end of September 2014. Note, that seismic activity related to this event might have also enhanced the rates as it opens new fractures and expose fresh surfaces for the contact with percolating fluid [20].

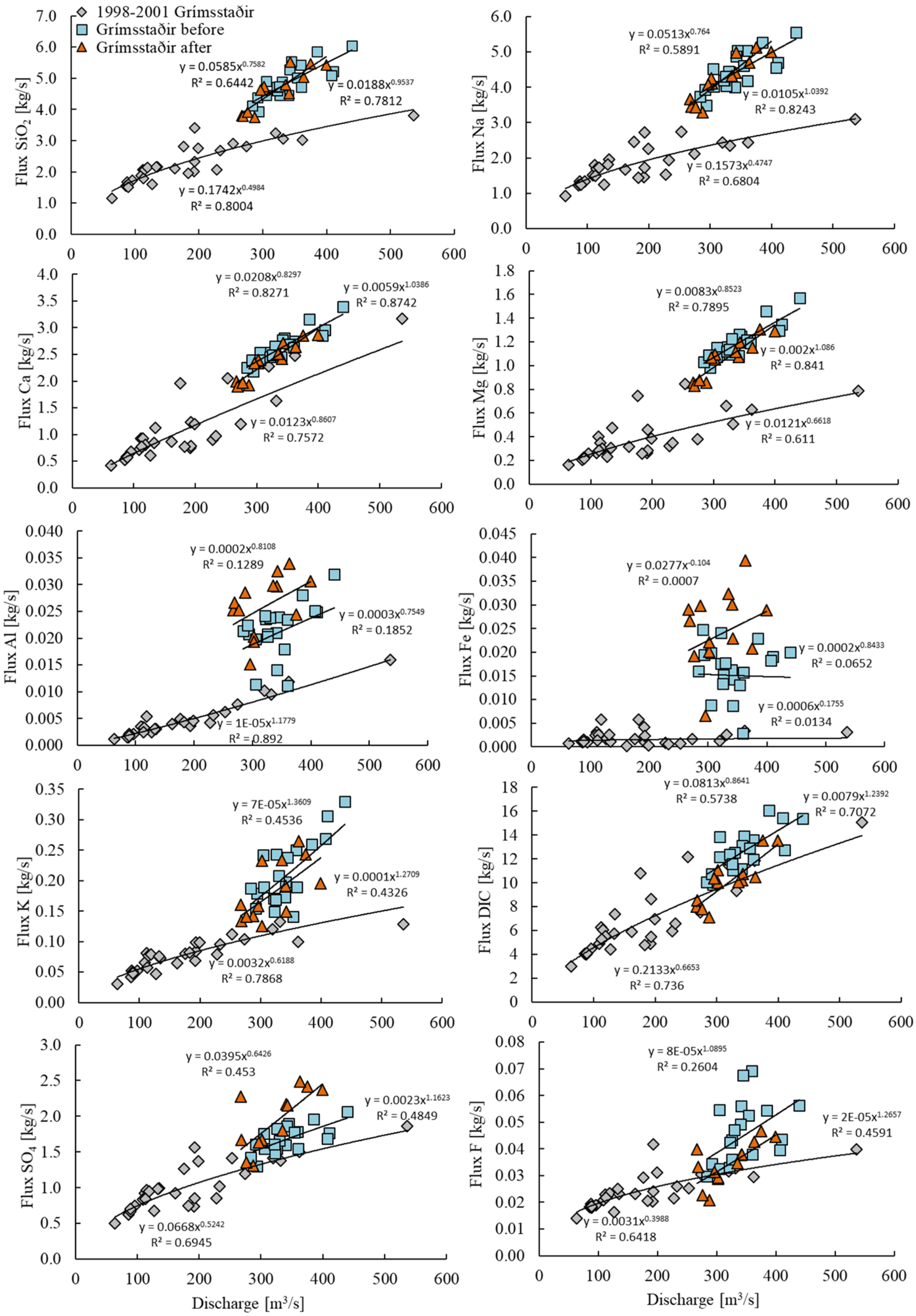

Fig. 1. Selected dissolved fluxes calculated at the Grímsstaðir monitoring station during the 1998–2001 (diamonds) and during the 2014 Bárðarbunga activity before (squares) and after (triangles) lava flowed into the Jökulsá á Fjöllum channel (modified from [20]).

The increase in DIC flux during the eruption but before lava flowed into the Jökulsá channel (Fig. 1 and Table 1) indicates increased consumption of CO_2 due to enhanced water-rock interaction. The increase in the flux of basalt forming constituents including SiO_2, Na, Ca, K, and Mg confirms that the observed carbon alkalinity increase resulted from basalt dissolution. In addition, there is a strong correlation between SiO_2 and DIC, Ca and DIC, and Ca and SiO_2 fluxes confirming that dissolution of carbonates contributed negligibly to the observed alkalinity increase. This result, which stems directly from river water composition measurements, differs from that of [21] who speculated, based on calcium isotope measurements, that calcite dissolution dominated dissolved Ca fluxes from Iceland to the ocean.

After lava flowed into the Jökulsá, the DIC flux decreased whereas the SO_4 flux increased suggesting that volcanic gases such as SO_2 and aerosols such as H_2SO_4 dissolve in water, dissociate, and "titrate" out the dissolved carbon alkalinity. Similarly, water samples collected upstream from the lava front had higher DIC concentrations compared to the samples collected downstream the lava front confirming that the alkalinity removal was caused by water-lava-gas interaction [20]. The small SO_4 flux increase (Table 1) during the eruption indicates that the deposition and scavenging potential of this gas within the catchment was minor compared to the mass of this gas emitted during the eruption. This suggests that the residence time of SO_2 gases and aerosols in the atmosphere was long enough to be transported out of the catchment [1, 2].

Assuming that all the dissolved DIC in the river water stems from CO_2 consumption due to weathering, and using the difference between the hypothetical 2014 annual DIC flux before lava flowed into Jökulsá channel (based on 'Grímsstaðir before' and the hypothetical 2014 annual DIC flux based on the pre-eruption flux-discharge curve, the annual net increase in CO_2 fixation was 21,000 tonnes/year. Based on these calculations, and assuming this increase in weathering flux remains constant after the eruption, it would take 284 years for this additional chemical weathering to consume all the CO_2 emitted to the atmosphere during the eruption [1, 2]. Note that this is a crude estimate as it is based solely on the discharge of the 2014 calendar year. Changing weather patterns can readily change the daily water discharges in this catchment. Note also that the annual DIC flux after the lava flowed into the Jökulsá channel is lower than the background flux, resulting in a net CO_2 release of 39,300 tonnes on an annual basis based on 2014 discharge. This indicates that this volcanic eruption not only emitted magmatic CO_2 but it also contributed to CO_2 release indirectly by its removal from surface waters where it was already present as DIC. The volume of lava erupted during the eruption was 84.1 km^3. If this volume of lava completely dissolves, it has a potential to fix about 605,000 Mt of CO_2 through water-rock interaction. For comparison, 5.96 Mt of CO_2 were emitted during the Bárðarbunga eruption and 1-2 Mt/yr of magmatic CO_2 are on average released from volcanoes and geothermal systems in Iceland [22]. Taking into account the mass of erupted lava and the annual Na flux calculated during the background period, it would take 65,000 years to completely dissolve the lava erupted from the Bárðarbunga eruption in the Jökulsá a Fjöllum catchment.

There are a number of processes that may enhance chemical denudation rates including fresh lava supply, seismic activity, volcanic gas emissions, aerosols formation and their subsequent dissolution, and addition of ligands enhancing dissolution of basaltic minerals such as F and SO_4. The increased major constituents' fluxes accompanied by increased DIC flux before lava flowed into Jökulsá channel indicate that carbon alkalinity increases largely through basalt dissolution. Taking into account the overall mass of basalt compared to that of CO_2 emitted during the eruption, the long-term net CO_2 input to the atmosphere will be strongly negative. However, the addition of acidic volcanic gases at the Earth's surface by water-lava interaction results in an additional short term net addition of CO_2 to the atmosphere by removing the DIC already present in the surface water.

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