

## Does the release of toxic metals due to subsurface CO<sub>2</sub> storage in basalts pose an environmental hazard?

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### ARTICLE INFO

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### ABSTRACT

Carbon dioxide storage through the carbonation of subsurface basaltic rocks is currently being explored to limit carbon emissions to the atmosphere. Basaltic rocks, however, contain trace and toxic metals that could potentially be mobilized by the carbonation process. This study reports the degree to which selected trace and toxic metals were mobilized during CarbFix1 and CarbFix2 projects. CarbFix1 injected 175 tons of CO<sub>2</sub>-charged water followed by 73 tons of CO<sub>2</sub>/H<sub>2</sub>S-charged water into basalts at 35 °C, whereas CarbFix2 continuously injected CO<sub>2</sub>/H<sub>2</sub>S-charged water into basalts at >250 °C. In most cases dissolved concentrations of Ba, Sr, Mo, Cu, Cr, Ni, Cd, and Pb in monitoring well fluids remained low. Although these fluids are not intended for human consumption, the aqueous trace element concentrations were generally below the WHO, EU, and Iceland drinking water standards, except for Fe and Mn in CarbFix1. Aluminum and As concentrations exceeded these standards during CarbFix2, but were elevated before injection. The low concentrations of most trace and toxic metals are consistent with their removal by secondary processes, particularly co-precipitation into carbonate and sulfide minerals formed during gas-water-basalt interaction. Solid precipitates recovered from CarbFix1 show strong enrichment of transition metals in calcite, consistent with natural and engineered analogues. As the two CarbFix injections bound the lower and upper temperature ranges of likely mineral carbon storage efforts, these results suggest limited risk of water contamination due to toxic and trace element release from subsurface basalts due to the injection of dissolved CO<sub>2</sub> and H<sub>2</sub>S.

### 1. Introduction

The CarbFix1 injection occurred during 2012 near the Hellisheiði geothermal power plant in Iceland with the goal to demonstrate an efficient subsurface carbon and sulfur storage technology. The Hellisheiði power plant is owned and operated by Reykjavík Energy. Water dissolved pure carbon dioxide (CO<sub>2</sub>) and then a water dissolved CO<sub>2</sub>-hydrogen sulfide (H<sub>2</sub>S) gas mixture was injected into 35 °C basaltic rocks (Matter et al., 2016; Snæbjörnsdóttir et al., 2017) for 10 weeks. The project was upscaled in 2014 as the CarbFix2 project, where a portion of the CO<sub>2</sub> and H<sub>2</sub>S emissions from the power plant were captured and injected into >250 °C geothermally altered basalts (Clark et al., 2020; Gunnarsson et al., 2018). The CarbFix2 injection continues at present. The CarbFix2 carbon and sulfur storage approach first captures the

soluble geothermal gases from power plant exhaust by their dissolution into water in a scrubbing tower adjacent to the gas source. The gas-charged water is then transported, at elevated pressure, to the injection well, where it is co-injected into the subsurface with separated geothermal brine, hereafter referred to as effluent water (Sigfússon et al., 2018). The injection of the acidic gas-charged water into subsurface basaltic rocks accelerates rock dissolution. This both releases divalent cations including Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Fe<sup>2+</sup> to the aqueous phase and increases the fluid pH. These two processes provoke the precipitation of stable carbonate and sulfide minerals leading to the long-term storage of the injected CO<sub>2</sub> and H<sub>2</sub>S (e.g., Gíslason and Oelkers, 2014; Oelkers and Gíslason, 2023; Snæbjörnsdóttir et al., 2020; Stefánsson et al., 2011). A similar approach to *in situ* carbon mineralization has also been tested outside of Iceland. In 2013, nearly 1000 tons of supercritical

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CO<sub>2</sub> was injected at the Wallula site in Washington, USA for 25 days targeting the Columbia River basalts (McGrail et al., 2017a; 2017b; White et al., 2020).

Co-injection of gases and water in basaltic rocks is an effective method for the secure storage of CO<sub>2</sub> and H<sub>2</sub>S through their mineralization. This process, however, may also lead to the mobilization of trace and toxic elements. Trace and potentially toxic elements in basaltic rocks (e.g., Wang et al., 2020; Wu et al., 2021; Linke et al., 2024) have been observed to be released by basaltic rock dissolution in meteoric water, especially during the early stages of gas-charged water-basalt interaction while the pH is low (Flaathen et al., 2009; Galezka et al., 2013; Romano et al., 2024). The concentration of trace elements in the liquid and vapor phases of geothermal fluids in basaltic terrains and their controlling processes have also been extensively studied in Iceland (Arnórsson and Andrédóttir, 1995; Arnórsson and Óskarsson, 2007; Kaasalainen and Stefánsson, 2012; Kaasalainen et al., 2015; Libbey and Williams-Jones, 2016; Markússon and Stefánsson, 2011; Olsen et al., 2010; Stefánsson and Arnórsson, 2005; Thomas et al., 2016), and elsewhere (Aiuppa et al., 2000a; 2000b; 2005; Christensen et al., 1983; Gurav et al., 2016; Karakaya et al., 2007; Migdisov and Bychkov, 1998). Other studies have examined natural analogues of trace metal mobility and scavenging during CO<sub>2</sub>-rich fluid-basalt interaction (Flaathen et al., 2009; Galezka et al., 2014, 2015; Gíslason et al., 2002; Olsson et al., 2014). Thomas et al. (2016) considered the potential implications of trace and toxic metal mobility for carbon mineralization in Icelandic geothermal reservoirs. Their study suggested that CO<sub>2</sub>-rich fluids could promote the dissolution of hydrothermal sulfide minerals, which are enriched in trace elements including arsenic (As). These elements could be transported in the aqueous phase potentially posing a hazard. In such systems, the mobility of trace metals would depend on the amount of dissolved inorganic carbon in the fluid, the fluid pH, and the presence of secondary Fe-oxyhydroxides and clays.

The CarbFix1 and CarbFix2 injections provide the opportunity to characterize the potential of acid gas-rich fluids to mobilize toxic and trace metals from basaltic rocks at moderate (20–50 °C) and elevated (250–280 °C) temperatures. In this study the toxic and trace element concentrations have been measured in fluid samples collected from the CarbFix1 monitoring well over a 2.5-year period spanning from before, during, and after the two test injections, and in samples collected from three monitoring wells at the CarbFix2 site over a 3.5-year period spanning from before to during the continuous injection of the CO<sub>2</sub>/H<sub>2</sub>S-charged water into the subsurface basalt storage reservoir. The purpose of this article is to report on the measured concentrations of these fluids, to better illuminate the fate of trace and potentially toxic metals during CO<sub>2</sub> injection into subsurface basalts, and to assess the degree to which the release of toxic metals may be an environmental hazard. This study also examines trace element uptake into calcite precipitates provoked by basalt-CO<sub>2</sub> interaction.

## 2. Background

### 2.1. CarbFix1 project

The CarbFix1 project performed two gas-charged water injections during 2012 into subsurface basaltic rocks via well HN-02, located three km southwest of the Hellisheiði geothermal power plant (Fig. 1). The injection site is located at the periphery of a geothermal reservoir. The first injection ran for 45 days from 24 January to 9 March 2012. In total, 175 t of pure CO<sub>2</sub> was injected. The second injection ran for 48 days from 15 June to 1 August 2012. This second injection added 73 t of 75 mol % CO<sub>2</sub>, 24 mol % H<sub>2</sub>S, and 1 mol % hydrogen (H<sub>2</sub>) to the subsurface through HN-02. Throughout the CarbFix1 injections, water was pumped at a rate of 7.2 m<sup>3</sup>/hr from well HN-01. This well is located about one km west of the HN-02 injection well. The HN-01 water was used to fully dissolve the gases within HN-02 via a sparger at a depth of 340 m. The gas and water mixtures were carried down a mixing pipe to a depth of

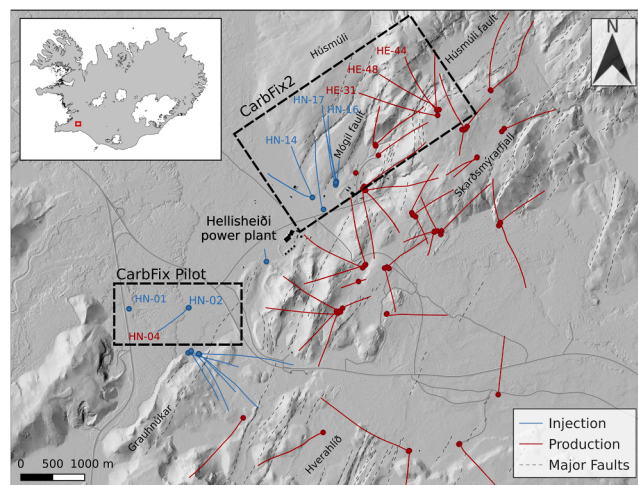


Fig. 1. Overview of the CarbFix injection sites near the Hellisheiði power plant. Injection wells (blue) and monitoring wells (red) are labelled, along with the surface expression of faults (dotted lines). The scrubbing towers were located adjacent to the power plant. Modified from Clark et al. (2020).

540 m to where the hydrostatic pressure was above 40 bar with temperatures of 20–50 °C (Sigfússon et al., 2015; 2024). Downhole camera observations and onsite high-pressure sampling and measurements were used to verify the complete dissolution of the injected gases into the downflowing water prior to their arrival into the basalts. Alfredsson et al. (2013) describes the surface geology of the site as olivine tholeiite basalts, including hyaloclastic formations consisting of glassy volcanic fragments.

Directionally drilled well HN-04 was used as the main monitoring well and is located about 10 m west of HN-02 at the surface but accesses a zone 125 m from this well at 520 m depth, where the target carbon storage aquifer is located. Water was pumped from this well at the rate of 3.5 m<sup>3</sup>/hr before and after the gas injection.

The major element concentrations of fluids collected from the HN-04 well were reported by Matter et al. (2016) and Snæbjörnsdóttir et al. (2017). They concluded that more than 95 % of the CO<sub>2</sub> injected was mineralized within two years of injection, and essentially all of the injected H<sub>2</sub>S was mineralized within four months of its injection. The Mg and Ca isotope compositions of these fluids were reported by Oelkers et al. (2019) and Pogge von Strandmann et al. (2019), respectively. These studies concluded that the Mg released from the basalt was largely incorporated into clay minerals, while the Ca was largely incorporated into carbonate minerals.

### 2.2. CarbFix2 project

The CarbFix2 project injected 23,200 t of CO<sub>2</sub> and 11,800 t of H<sub>2</sub>S captured in dissolved water at the Hellisheiði geothermal power plant into fractured, geothermally altered basalts from 2014 through the end of 2017. This gas mixture injection is still ongoing at this site. The injection site is located 1.5 km north of the power plant (see Fig. 1), where the gas is injected to a depth of 750 m into a basaltic reservoir having temperatures exceeding 250 °C. A description of the hydrology and the alteration of the rocks at this depth before the CarbFix2 injection is reported by Snæbjörnsdóttir et al. (2018b), who also noted that the subsurface is dominated by hyaloclastic formations that vary from crystalline pillow basalts to nearly pure volcanic glass tuffs.

Dissolved gas injection during CarbFix2 occurred in two distinct phases, as described by Clark et al. (2020) and Sigfússon et al. (2018). From 23 June 2014 to 15 July 2016, approximately 25 % of the exhaust gas from the Hellisheiði power plant was processed through a scrubbing tower. Approximately 56 % of the CO<sub>2</sub> and 97 % of the H<sub>2</sub>S of the

processed gas was dissolved into 20 °C condensate water (condensed steam from the power plant) at a pressure of 5 bar and a water flow rate of 30–36 L/s. The CO<sub>2</sub>/H<sub>2</sub>S-charged condensate waters were then transported by pipeline at 9 bar pressure to injection wells HN-16 or HN-14. This gas-charged condensate was co-injected together with effluent water into well HN-16, except from 14 July 2015 to 15 March 2016 when this fluid was injected into well HN-14. After 15 July 2016, the scrubbing tower gas capture facility capacity was doubled, and the resulting gas-charged condensate water was co-injected with effluent water into well HN-16. In all cases the gas-charged condensate water was injected separately into the well via a stainless-steel pipe located within the larger main carbon steel casing of the well with a mixing ratio of 30 % gas-charged condensate to 70 % effluent water (Clark et al., 2018).

Fluid flow rates into the injection wells are reported by Sigfússon et al. (2018) and the effluent and gas-charged condensate water compositions are reported in Clark et al. (2018). Three geothermal production wells, HE-31, HE-48, and HE-44 (Fig. 1), were used as monitoring wells. The major element concentrations of these fluids were published by Gunnarsson et al. (2018) and Clark et al. (2020). Clark et al. (2020) reported that the gas mixture injected into HN-14 from 15 July 2014 to 14 March 2015 flowed outside the CarbFix2 site and was not observed in wells HE-31, HE-48, and HE-44. Both studies concluded that the mineralization rates of the injected gases are accelerated by the high temperatures. Clark et al. (2020) noted that carbon and sulfur mineralization rates increased after the doubling of gas injection rates in July 2016. The dissolved CO<sub>2</sub> and H<sub>2</sub>S concentrations measured in the collected reservoir fluids from the monitoring wells (Clark et al., 2020; Gunnarsson et al., 2018) are comparable to the dissolved gas contents measured in production wells prior to brine reinjection (Stefánsson et al., 2009).

### 3. Methods

#### 3.1. Sampling and analysis

A total of 104 water samples were collected during 2011–2013 from well HN-04 at the CarbFix1 site and 76 fluid samples were collected during 2014–2017 from the three CarbFix2 monitoring wells, HE-31, HE-48, and HE-44. All samples were collected and analyzed according to methods described by Alfredsson et al. (2013), Snæbjörnsdóttir et al. (2017), and Clark et al. (2020), and are briefly reviewed here. The CarbFix1 samples are single-phase liquid samples. These were collected from a dedicated sampling valve located inside an on-site field laboratory. Owing to the high temperature of the fluids, the CarbFix2 samples were two-phase vapor and liquid samples at ambient pressure. These samples were first separated into two phases using a stainless steel Webre separator connected to the well head. To prevent boiling during sample collection, the separator was connected to a stainless-steel cooling coil placed in a cooling bath, which brought the temperature of the sample down to below 100 °C (Arnórsson et al., 2006).

It is anticipated that the addition of metals, such as cobalt (Co), chromium (Cr), manganese (Mn), nickel (Ni), vanadium (V), and iron (Fe), to the sampled fluids from the well materials is negligible. At the CarbFix1 site, water was continuously pumped from the monitoring well HN-04 during the entire monitoring period, resulting in thorough flushing of pipes and casings. At the CarbFix2 monitoring wells, high temperature water rapidly creates a protective coating between the fluid and the steel well casings limiting metal release (Arnórsson et al., 2006). Moreover, each monitoring well at the CarbFix2 site has its own cooling coil and approximately 4–5 liters of geothermal fluid was flushed through the Webre separator and cooling coil before the collection of samples for major and trace element analysis (Clark et al. 2020).

Liquid samples collected for trace element analysis were filtered and acidified with 1.0 vol % concentrated suprapure HNO<sub>3</sub>. Samples collected during CarbFix1 were analyzed using a Thermo Scientific

ELEMENT XR Inductively Coupled Plasma-Sector Field Mass Spectrometry (ICP-SFMS) at ALS Scandinavia. Samples collected during CarbFix2 were analyzed using a Thermo Scientific iCAPQc ICP-MS at Leeds University. Analytical uncertainties on all measurements were on the order of ≤ 5 % and the detection limits are listed in the Supplementary Material.

Rock samples were selected from drill cuttings of wells HN-04 and HE-31 at different depths. Samples of calcite precipitates from the CarbFix1 site were also recovered from the HN-04 pump in July 2013. The HN-04 drill cuttings were analyzed using X-ray fluorescence at the University of Edinburgh. The HE-31 drill cuttings and HN-04 pump precipitates were sent to ALS Scandinavia, where subsamples were pulverized and prepared using three different digestion methods: (a) HNO<sub>3</sub> + HF microwave digestion, (b) HNO<sub>3</sub> + HCl + HF microwave digestion, and (c) lithium borate fusion followed by dissolution in tartaric acid/HNO<sub>3</sub> solution. The resulting solutions were analyzed by High-Resolution (HR)-ICP-MS.

#### 3.2. Calculation of the CarbFix2 sample fluid compositions

The three CarbFix2 monitoring wells used in this study are wet-steam wells sometimes referred to as liquid enthalpy wells (Gunnarsson et al., 2018). The calculation of the *in situ* water chemistry, therefore, requires accounting for phase separation as the samples rose to the surface. This was done by first determining the vapor fraction of the fluid at the sample collection pressure. The vapor fraction of the fluid was calculated assuming adiabatic boiling of the fluid from the reservoir to the sampling pressure using the WATCH aqueous geochemistry speciation program (Arnórsson et al., 1982; Bjarnason and Arnórsson, 2010). The reservoir temperature was calculated using a quartz geothermometer equation (Gunnarsson and Arnórsson, 2000), and its pH was determined with charge balance constraints in accord with Bjarnason and Arnórsson (2010).

Taking into account of the fraction of vapor in the fluid sample, the reservoir fluid compositions were then calculated using

$$C_{i,fluid} = C_{i,liquid} \cdot (1 - X) + C_{i,vapor} \cdot X \quad (1)$$

where  $C_i$  designates the concentration of the  $i$ th element in the indicated phase, and  $X$  stands for the mass fraction of the vapor phase at the sampling pressure. Boiling and phase segregation may lead to the partitioning of some trace elements such as boron (B), As, copper (Cu), mercury (Hg), molybdenum (Mo), and antimony (Sb) into the vapor phase (Giroud, 2008; Glover, 1988; Heinrich, 2007; Kaasalainen and Stefánsson, 2012; Neely et al., 2018). Nevertheless, studies indicate that most metals preferentially partition in the liquid phase under typical geothermal conditions (Heinrich, 2007; Pokrovski et al., 2013). The CarbFix2 wells discharge fluids at relatively low pressures ( $5.7 \pm 0.3$  bar-g), making adiabatic boiling a reasonable assumption. Under these conditions, metals are expected to partition predominantly into the liquid phase. Thus  $C_{i,vapor}$  was assumed to be negligible in Eq. (1). Note, however, that this assumption may slightly underestimate reservoir dissolved element concentrations if some metals partitioned into the vapor phase.

#### 3.3. Rock dissolution and scavenging calculations

The amount of basalt dissolved into each collected water sample was determined assuming stoichiometric rock dissolution. Assuming sodium (Na) is not consumed by secondary phases after its addition to the fluid phase, the mass of basalt dissolved into each collected water sample can be estimated from

$$m_{basalt} = \frac{C_{Na,fluid} - C_{Na,background}}{v_{Na}} \quad (2)$$

where  $m_{basalt}$  refers to the number of moles of basalt dissolved in each kg of sampled fluid,  $C_{Na,background}$  stands for the average Na concentration of

the subsurface fluid samples collected prior to injection, and  $\nu_{Na}$  designates the stoichiometric number of moles of Na element in the relevant basaltic rock.

For this calculation it was assumed that one mole of basalt contains one mole of silica (Si). For CarbFix1, the basaltic rock composition used in the calculation was taken to be equal to the bulk chemical composition of drill cuttings collected from well HN-04 taken at 500 m depth (Alfredsson et al., 2013). For CarbFix2, this composition was taken to be equal to those of drill cuttings collected from well HE-31 taken at 1786 m depth. These depths correspond to the main feed zones identified at these sites (Níelsson et al., 2007). Some trace elements (e.g., As, Co) in the HN-04 drill cuttings were not measured; in the absence of these values, they were assumed to be equal to those of HE-31 drill cuttings collected from a depth of 1138 m. This was the shallowest depth for which concentrations are available for well HE-31 drill cuttings. The amount of each trace element expected to have dissolved from the basalt into the fluids at both sites was thus computed.

The concentration of the  $i$ th element in the fluid phase due to stoichiometric basalt dissolution,  $C_{i,stoichiometric}$ , would then be equal to

$$C_{i,stoichiometric} = \nu_i m_{basalt} \quad (3)$$

where  $\nu_i$  signifies the stoichiometric number of moles of the  $i$ th element in the basalt. Note this assumes that the elemental release is proportional to that in the basaltic rock, rather than due to a preferential dissolution of specific minerals.

The ratio between the concentration of an element measured in each fluid sample divided by  $C_{i,stoichiometric}$  is assumed to be due to scavenging by secondary minerals. These ratios, given as a percentage, were calculated using

$$Scavenged (\%) = \left(1 - \frac{C_{i,fluid} - C_{i,background}}{C_{i,stoichiometric}}\right) \times 100 \quad (4)$$

### 3.4. Partition coefficient calculations

The trace element uptake by calcite from the CarbFix1 fluids can be quantified using a partition coefficient,  $P_{Me}$ , calculated following that of Olsson et al. (2014):

$$P_{Me} = \frac{X_{Me,s} / C_{Ca,s}}{X_{Me,l} / C_{Ca,l}} \quad (5)$$

where  $X_{Me,s}$  and  $X_{Ca,s}$  represent the mole fraction of the scavenged metal and of Ca in the solid phase and  $C_{Me,l}$  and  $C_{Ca,l}$  represent the molar concentration of the metal and of Ca in the liquid phase. The values of  $C_{Me}$  used in this calculation was the average concentration of the five water samples collected during June–July 2013.

A value of  $P_{Me} > 1$  indicates the preferential incorporation of the metal into calcite, while values  $< 1$  indicate its preferential exclusion. Three data sets of partition coefficients are compared: (a) CarbFix1 calcite from pump precipitates recovered from the HN-04 in July 2013, (b) natural travertines precipitated in Hvanná river (Olsson et al., 2014), and (c) calcite scales sampled from the district heating network in Selfoss, Iceland (Galczka et al., 2021).

## 4. Results

### 4.1. Trace element concentrations of the CarbFix1 monitoring well fluids

The aqueous trace element concentrations of the fluids collected from the HN-04 monitoring well before, during, and after the CarbFix1 injections are reported in Table S-1 and also archived in Zenodo. The temporal evolution of selected trace element concentrations of the sample fluids collected are shown in Fig. 2. Sampling began on 21 January 2011, prior to the pure CO<sub>2</sub> injection on 24 January 2012. The pure CO<sub>2</sub>-charged water injection occurred from 24 January 2012 until 9 March

2012. A discontinuous mixed gas injection occurred from 15 June 2012 to 1 August 2012. Note that pH, Al, and Fe values were previously reported in Snæbjörnsdóttir et al. (2017) and reproduced here.

An increase in the fluid concentrations of barium (Ba), Co, Fe, Mn, Ni, strontium (Sr), and zinc (Zn) is evident during both the initial pure CO<sub>2</sub> injection and the subsequent discontinuous CO<sub>2</sub>/H<sub>2</sub>S injection. The transition metals Co, Ni, and Zn show a similar trend, while Fe exhibits a prominent peak during the pure CO<sub>2</sub> injection and a less prominent peak during the mixed gas injection. During both gas injections, the aqueous Fe concentrations of the sampled fluids are observed to be higher than the European Union's (EU) and Iceland's drinking water health-based guidelines (EU, 2020; Umhverfisstofnuneyti, 2018) as well as the World Health Organization's (WHO) Maximum Ideal Tasting Value for Fe (WHO, 2023).

The elements Ba, Sr, and Mn exhibit similar temporal patterns with concentrations peaking concurrently with the lowest measured pH values (Fig. 2). Although the concentration of these elements decrease after the arrival of the decrease in pH, after the second injection they remain elevated compared to their pre-injection concentrations during early 2013. Other trace elements analyzed do not exhibit a significant response to the second breakthrough.

The Al and As concentrations and pH are observed to decrease during the pure CO<sub>2</sub> injection, although changes in these concentrations are not as prominent during the latter discontinuous mixed gas injection. The concentrations of Cd, Hg, Pb, Ti and V, reported in Table S-1, were all below the EU/Iceland drinking water health-based guidelines when above the detection limit of the analytical methods.

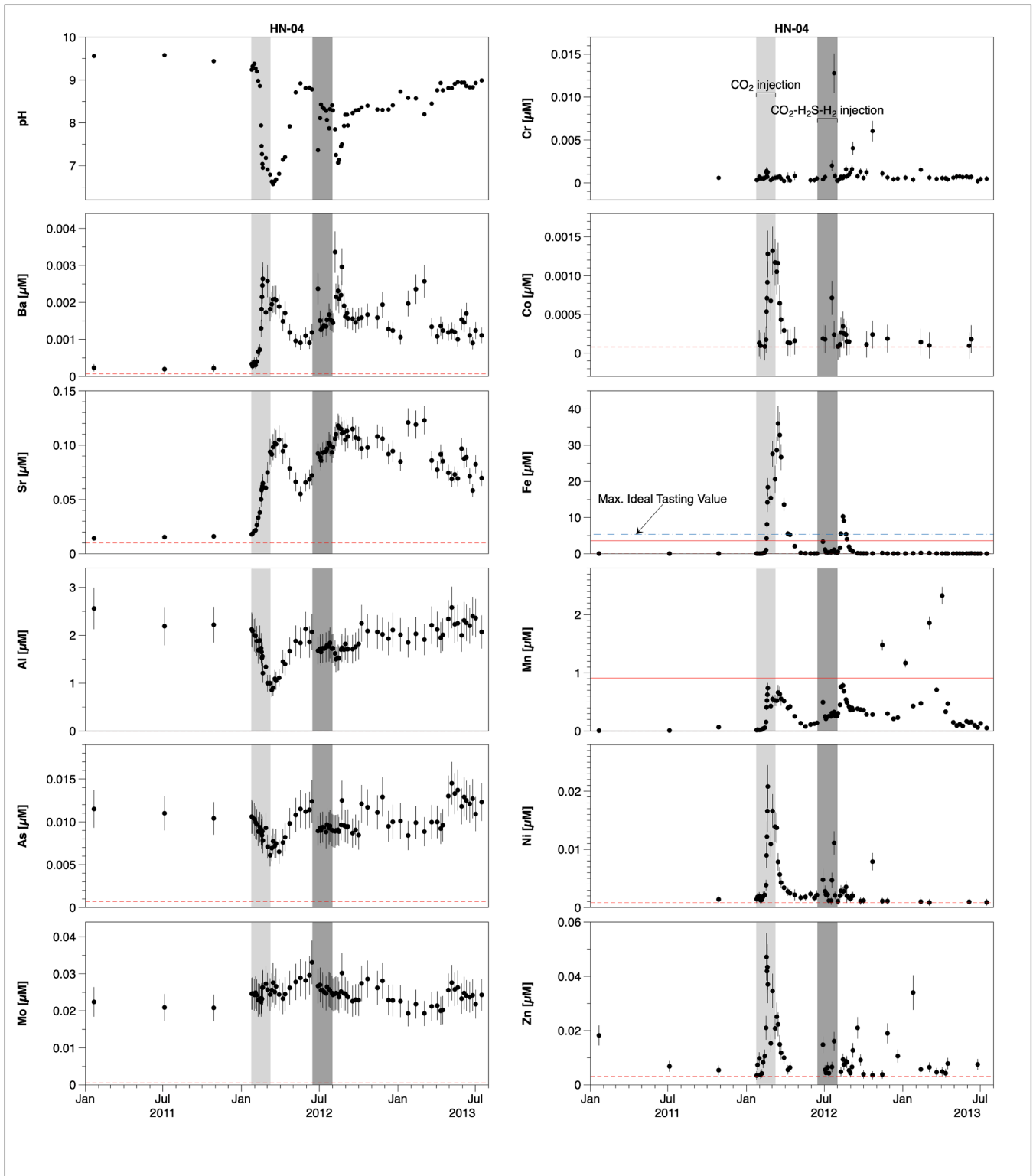
### 4.2. Trace element concentrations of the CarbFix2 monitoring well fluids

The trace element concentrations of the fluids collected from the three CarbFix2 monitoring wells, HE-31, HE-48, and HE-44, are reported in Tables S-2 to S-4, respectively, with the full dataset deposited in Zenodo. The temporal evolution of selected trace element concentrations of the sample fluids collected from 2014 to 2017 are shown in Figs. 3–7. Fluid sampling began on 29 April 2014, prior to the start of gas-charged water injection on 23 June 2014, with the amount of dissolved gas injected increased on 15 July 2016 (Clark et al., 2020).

The temporal evolution of the concentrations of the alkali metals lithium (Li), rubidium (Rb), and cesium (Cs) are shown in Fig. 3. There was a decrease in dissolved Li concentrations during 2017, about a year after the gas injection rate was doubled. In contrast, the Rb concentrations increased slightly over time, whereas dissolved Cs concentrations show no significant change throughout the study period. The Sr concentrations of the fluids collected from all three sampled wells, shown in Fig. 4, increased significantly during the time that Li decreased, following the doubling of the gas injection rate. The Ba concentrations in the sampled fluids collected from wells HE-31 and HE-48 decreased slowly over time during the study period.

The concentrations of As, Mo, and Sb in the CarbFix2 fluids decreased significantly one year after the start of gas injection as shown in Fig. 5. The concentrations of As and Mo are largely close to or at their respective detection limits after this time. This trend is less clear for Sb. The Sb concentrations were below the detection limits during much of 2015 and 2016. There was a significant improvement in the analytical detection limit for Sb mid-2016. Nevertheless, these data show a continuous decrease in Sb concentration over time during the injections. The As concentrations of the sampled fluids were higher than the WHO guideline value for safe drinking water (WHO, 2023) before the injections and briefly increased in all three monitoring wells when the gas-charged mixture was injected into well HN-14 (Clark et al., 2020). From 2015, As was at or below the WHO guideline value.

The Al concentrations of the fluid samples, originally reported in Clark et al. (2020), are also plotted in Fig. 4, and show a decrease in concentration over time during the study period, particularly in the HE-31 monitoring well. The concentrations of this element showed little



**Fig. 2.** Concentrations of Ba, Sr, Al, As, Mo, Co, Fe, Mn, Ni, and Zn in fluids from the HN-04 monitoring well prior to, during, and after the CarbFix1 injections. Light and dark gray bars denote the  $\text{CO}_2$  and  $\text{CO}_2/\text{H}_2\text{S}$  injection periods, respectively. Red solid lines indicate the EU/Iceland drinking water health-based guideline for Fe and Mn and blue dashed line the WHO Maximum Ideal Tasting Value for Fe, while red dashed lines indicate the analytical detection limit of the measurements. Error bars are sometimes smaller than the symbol size.

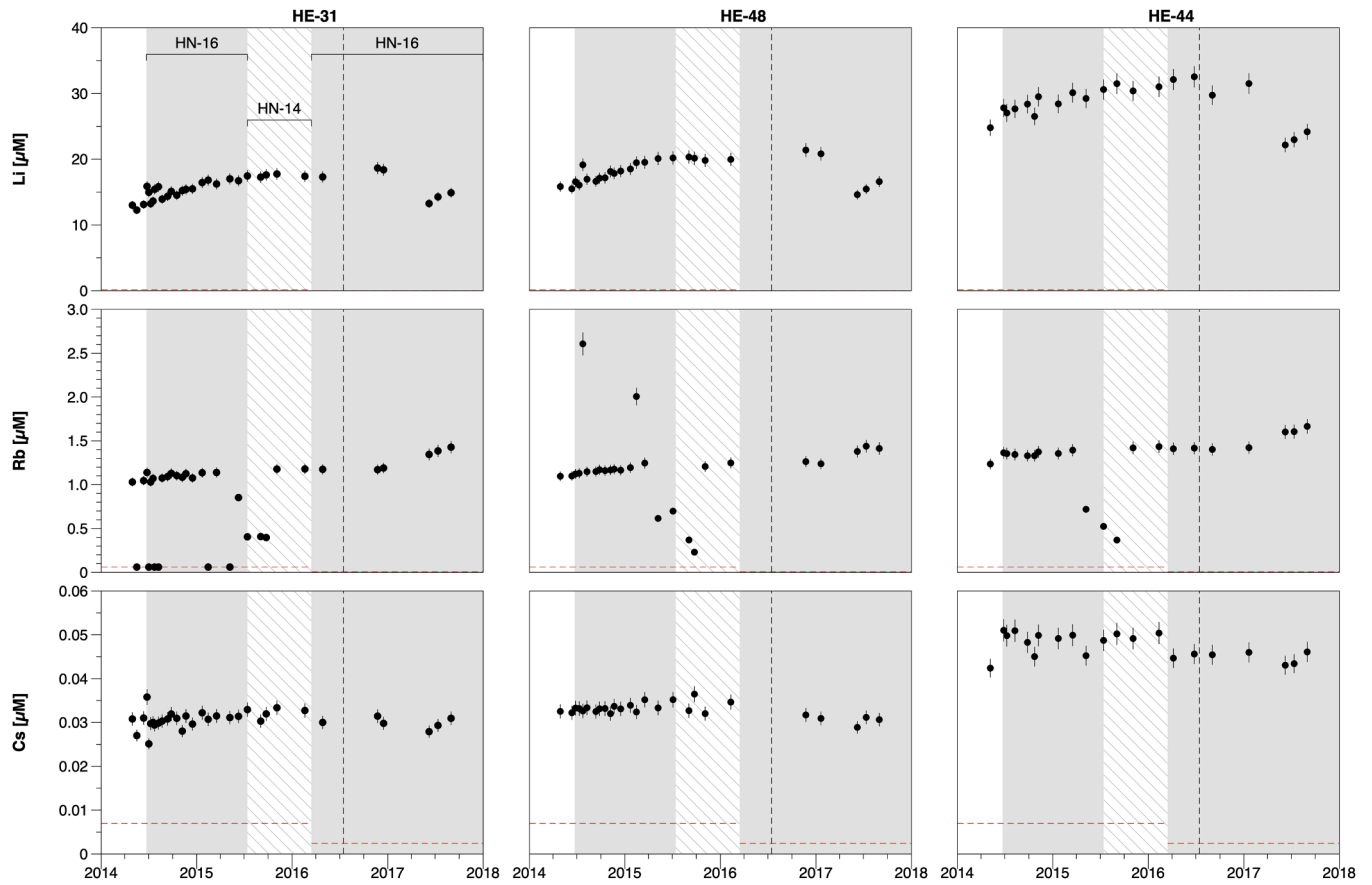


Fig. 3. Concentrations of Li, Rb, and Cs in fluids from the HE-31, HE-48, and HE-44 monitoring wells before and during the CarbFix2 injections. Gray shading and the diagonal lines denote injection periods into wells HN-16 and HN-14, respectively. The vertical dashed line signifies when the gas injection rate doubled, and red dashed lines indicate the analytical detection limits. Error bars are sometimes smaller than the symbol size.

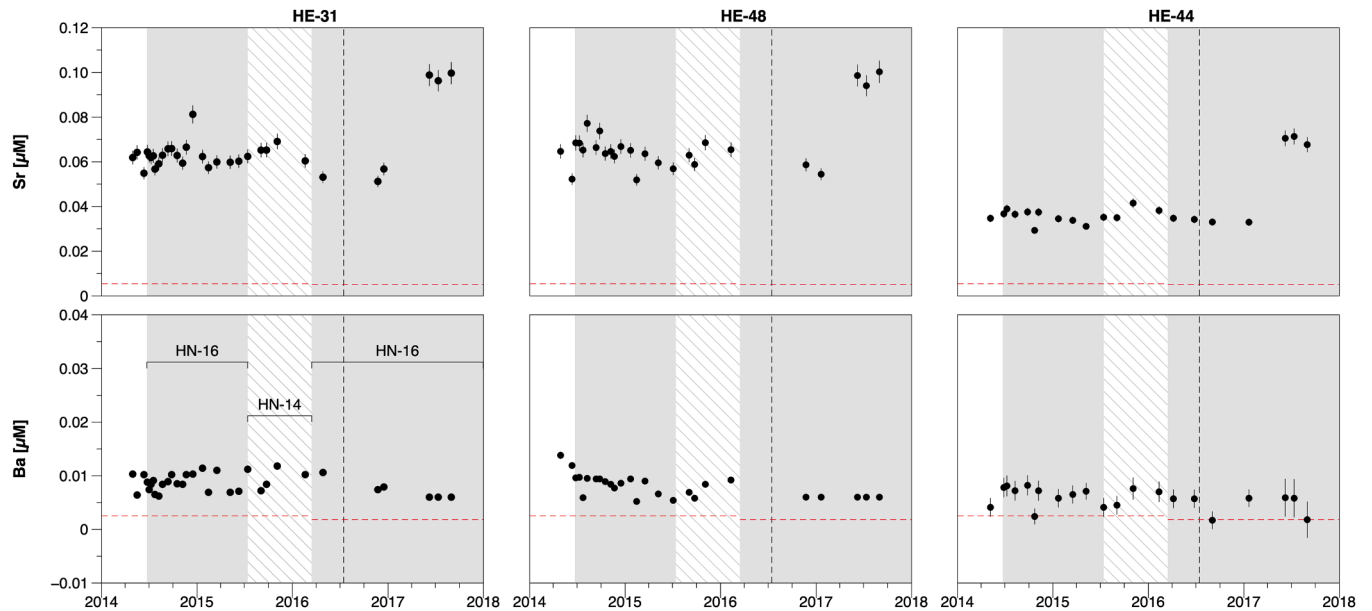
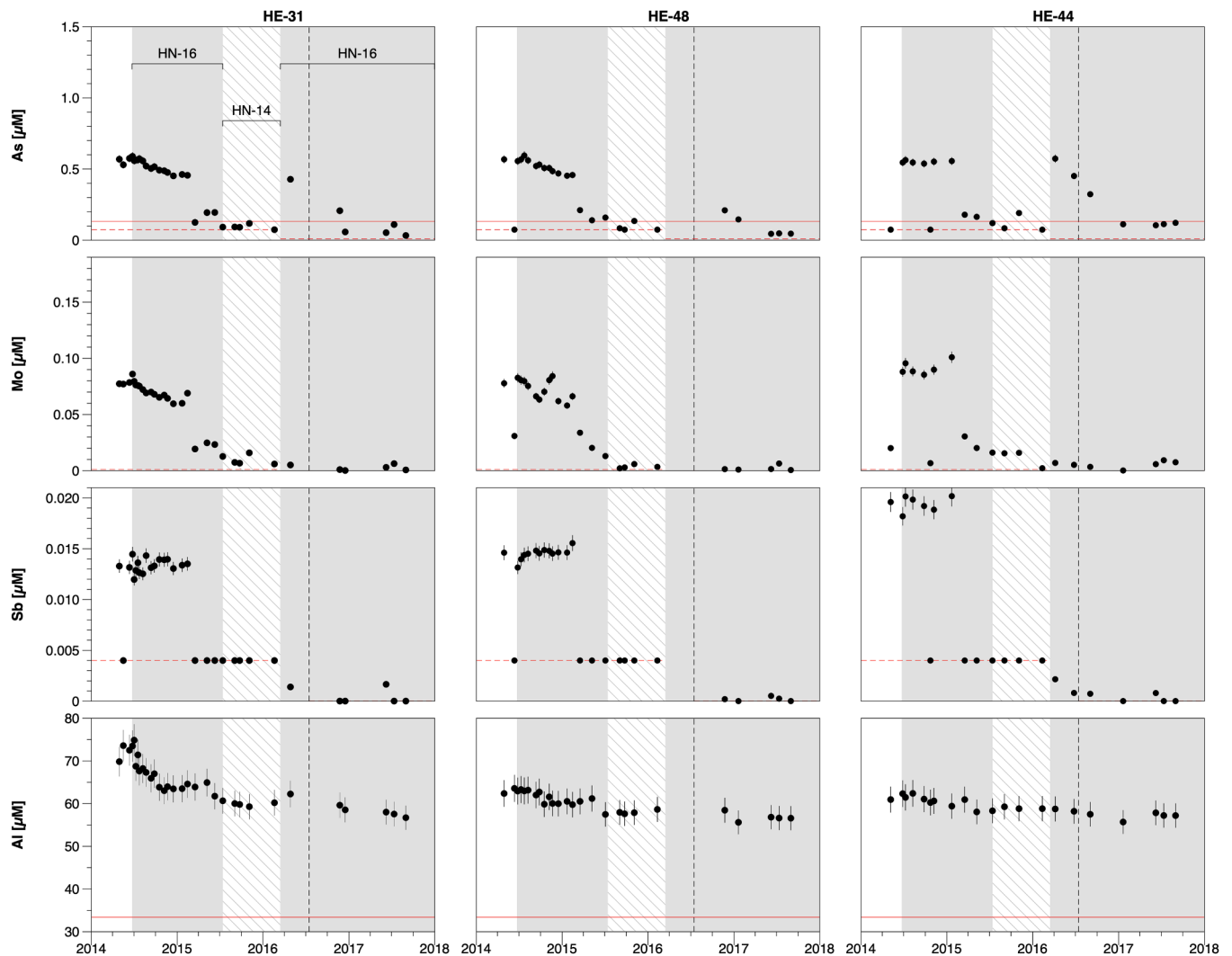


Fig. 4. Concentrations of Sr and Ba in fluids from the HE-31, HE-48, and HE-44 monitoring wells before and during the CarbFix2 injections. Gray shading and the diagonal lines denote injection periods in wells HN-16 and HN-14, respectively. The vertical dashed line signifies the time when the gas injection doubled, and red dashed lines indicate the analytical detection limits. Error bars are sometimes smaller than the symbol size.



**Fig. 5.** Concentrations of As, Mo, Sb, and Al in fluids from the HE-31, HE-48, and HE-44 monitoring wells before and during the CarbFix2 injection. Gray shading and diagonal lines denote periods when the gas was injected into wells HN-16 and HN-14, respectively. The vertical dashed line signifies when the gas injection rate was doubled. Red dashed lines indicate the analytical detection limits, and the solid red line indicates the drinking water guideline value. Error bars are sometimes smaller than the symbol size.

change in response to the doubling of the gas injection rate in 2016. Note that levels of Al before and throughout the entire injection period are much higher than the health-based WHO drinking water limit (WHO, 2023).

The concentrations of the transition metals Cu, Ni, Mn, and Cr in the sampled fluids throughout the study period are shown in Fig. 6. Small fluctuations in measured Mn concentrations are evident. Measured Cu concentrations are low and scattered but tend to decrease following the increase in the gas injection rate, where the concentrations are close to or below the detection limit. There was no clear trend in measured Ni and Cr concentrations, although there was greater variation in these concentrations after 2015. Fig. 6 shows that V concentrations slowly decreased over time in fluids collected from HE-31, the monitoring well closest to the injection wells, while the concentrations of this element remained close to constant in the fluids collected from HE-48 and HE-44.

## 5. Discussion

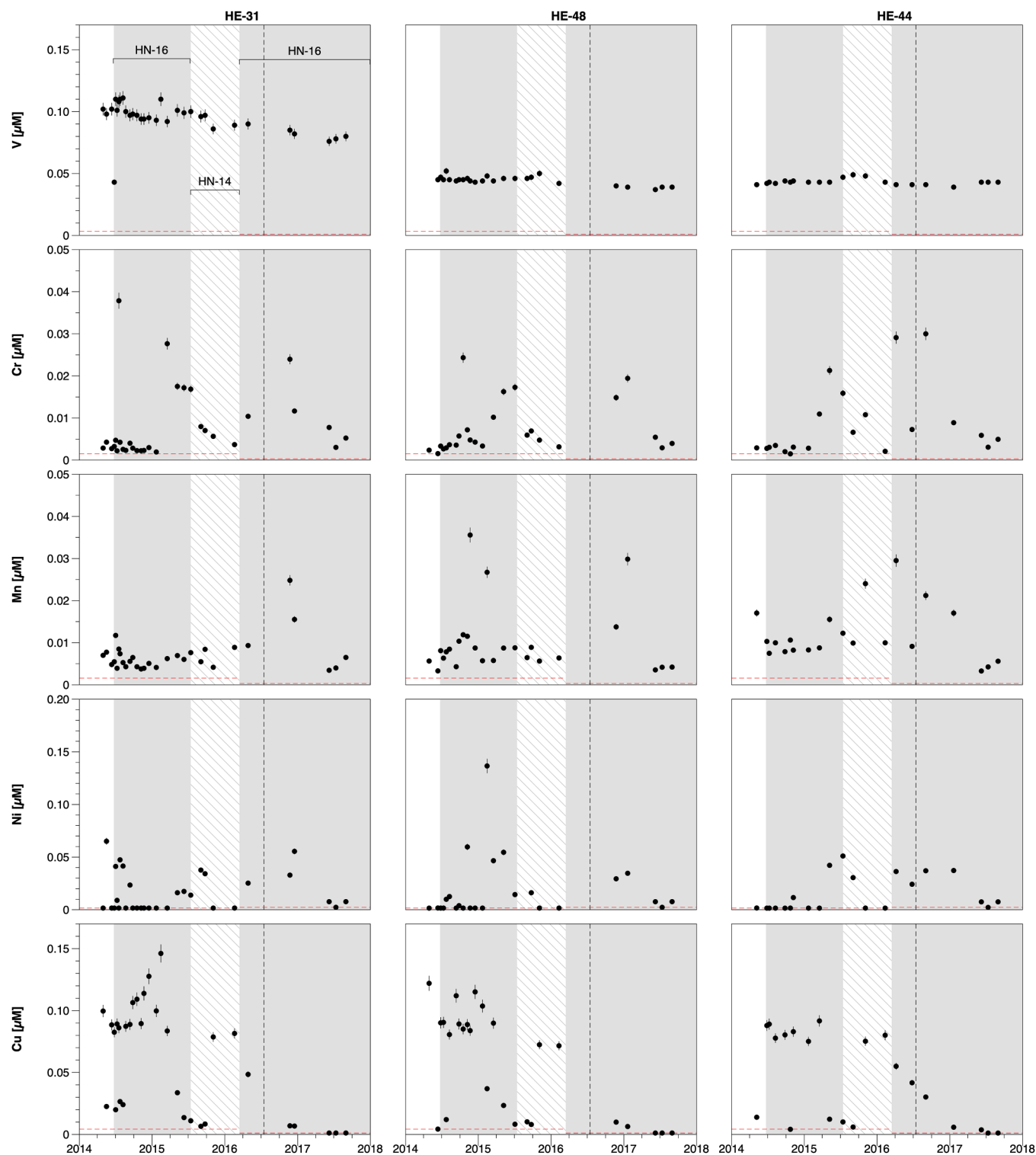
### 5.1. Environmental impact of gas injections

Numerous dissolved trace metals, including As, Mo, Mn, and Al, are considered toxic if present at elevated concentrations (World Health

Organization, 2023; European Union, 2020; Umhverfisstofnun, 2018). Maximum concentrations of these metals considered to be safe in drinking water according to these guidelines are shown in Table 1. Although the Hellisheiði fluids from both injection sites are not meant for human consumption, a comparison of measured sampled fluid concentrations with the guidelines presented in Table 1 provides insight into the potential environmental risks of the injection of  $\text{CO}_2 \pm \text{H}_2\text{S}$  into basaltic rocks.

During the CarbFix1 injection at 35 °C, Fe concentration levels spiked above both the WHO's ideal taste threshold and the health-based limits set by the EU and Iceland shortly after the arrival of the  $\text{CO}_2$ -charged water (see Fig. 2). These peaks, while short-lived, suggest the potential for risks induced by the addition of  $\text{CO}_2$  to this system. Additionally, three outlier Mn concentrations (Table S-1) surpassed the WHO, the EU, and Iceland health-based limits. However, none of the measured As and Cr concentrations surpassed the drinking water standards set by WHO, the EU, and Iceland. The same applies for the concentrations of cadmium (Cd), Cu, mercury (Hg), lead (Pb), and titanium (Ti) reported in Table S-1. The concentrations of each of these elements were all below the guidelines when above the detection limit of the respective analytic methods.

At the CarbFix2 site at >250 °C, Mn concentrations remained below



**Fig. 6.** Concentrations of V, Cr, Mn, Ni, and Cu in fluids from the HE-31, HE-48, and HE-44 monitoring wells before and during the CarbFix2 injections. Gray shading and diagonal lines denote periods when gas was injected into wells HN-16 and HN-14, respectively. The vertical dashed line signifies when the gas injection rate doubled, and red dashed lines indicate the analytical detection limits. Error bars are sometimes smaller than the symbol size.

**Table 1**

Summary of maximum concentrations of various elements considered to be safe for human drinking water.

| Element    | World Health Organization <sup>a</sup><br>[μM] | European Union <sup>b</sup><br>[μM] | Icelandic <sup>c</sup><br>[μM] |
|------------|------------------------------------------------|-------------------------------------|--------------------------------|
| Aluminum   | 3.71–7.41 <sup>d</sup>                         | 7.41 <sup>d</sup>                   | 7.41 <sup>d</sup>              |
| Antimony   | 0.164                                          | 0.082                               | 0.041                          |
| Arsenic    | 0.133                                          | 0.133                               | 0.133                          |
| Barium     | 9.47                                           | -                                   | -                              |
| Beryllium  | 1.33 <sup>d</sup>                              | -                                   | -                              |
| Boron      | 222                                            | 139                                 | 92.5                           |
| Cadmium    | 0.027                                          | 0.044                               | 0.044                          |
| Chloride   | 7050 <sup>f</sup>                              | 7050 <sup>d</sup>                   | 7050 <sup>d</sup>              |
| Chromium   | 0.962                                          | 0.481                               | 0.962                          |
| Copper     | 31.5                                           | 31.5                                | 31.5                           |
| Fluoride   | 79.0                                           | 79.0                                | 79.0                           |
| Hydrogen   | 1.47–2.94 <sup>f</sup>                         | -                                   | -                              |
| Sulfide    | 5.37 <sup>f</sup>                              | 3.58 <sup>d</sup>                   | 3.58 <sup>d</sup>              |
| Iron       | 0.048                                          | 0.024                               | 0.048                          |
| Lead       | 1.46 <sup>e</sup>                              | 0.910 <sup>d</sup>                  | 0.910 <sup>d</sup>             |
| Manganese  | 0.030                                          | 0.005                               | 0.005                          |
| Mercury    | 0.730                                          | -                                   | -                              |
| Molybdenum | 1.19                                           | 0.341                               | 0.341                          |
| Nickel     | 0.633 <sup>e</sup>                             | 0.253                               | 0.127                          |
| Selenium   | 8700 <sup>f</sup>                              | 8700 <sup>d</sup>                   | 8700 <sup>d</sup>              |
| Sodium     | 2080 <sup>f</sup>                              | 2600 <sup>d</sup>                   | 2600 <sup>d</sup>              |
| Sulfate    | 0.126                                          | 0.126                               | -                              |
| Uranium    | 45.9 <sup>f</sup>                              | -                                   | -                              |
| Zinc       | -                                              | -                                   | -                              |

<sup>a</sup> WHO, 2023.

<sup>b</sup> EU, 2020.

<sup>c</sup> Umhverfisstofnuneyti, 2018.

<sup>d</sup> Health-based limit.

<sup>e</sup> Provisional Limit.

<sup>f</sup> There is no health-based guideline currently proposed. The value shown is the tasting threshold for consumers, concentrations above may affect acceptability of drinking water (WHO, 2023).

the WHO guideline limit throughout the study. In contrast, As concentrations were above these guidelines before and during the first months of the injection. Afterwards they remained mostly close to the WHO guideline limit (Fig. 5). The Al concentrations were above health-based concentration limits before and during the injection, but the concentrations decreased over time in all three monitoring wells (see Fig. 5). Two of the elements, Cr and Ni, were observed to surpass WHO, EU, and Icelandic guideline limits in a single outlier sample (15–5132 in Table S-2a not shown in Fig. 6) but otherwise remained well below guidelines (Fig. 6).

Overall, despite some transient exceptions, no metal concentrations were observed to surpass the drinking water limits over the long-term except for Al concentrations, which were already above drinking water limits prior to the gas injection. These results suggest that while CO<sub>2</sub> injection into basaltic formations is unlikely to cause sustained water contamination, continued monitoring may be necessary to assure groundwater quality. The differences in the measured trace element concentrations between CarbFix1 and CarbFix2 indicate that temperature and pH strongly influence trace metal mobility.

## 5.2. Mass of dissolved basalt and scavenging potential of subsurface reactions

In this study, Na concentrations was used as a baseline to assess the fate of trace elements released during the injection of water dissolved pure CO<sub>2</sub> and CO<sub>2</sub>/H<sub>2</sub>S mixtures into basalts. The mobilization of Na occurs primarily due to the dissolution of Na-bearing silicate minerals and glasses, and it is negligibly incorporated into secondary phases. Na is thereby a useful proxy to estimate water-rock interaction due to its high mobility (Gíslason et al., 1996).

The mass of basalt dissolved into each water sample, expressed as

moles of basalt dissolved per kg of fluid sample, was calculated assuming stoichiometric basalt dissolution. This was calculated according to Eq. (2) using the measured Na concentrations for CarbFix1 reported in Matter et al. (2016) and Snæbjörnsdóttir et al. (2017) and for CarbFix2 reported by Gunnarsson et al. (2018) and Clark et al. (2020). The results of these calculations are shown in Figs. 7 and 8 for CarbFix1 and CarbFix2, respectively. These values were used to calculate the percentage scavenged using Eqs. (3) and (4) together with the concentrations of each element in the measured water samples. The results of this calculation are shown in Figs. 9 and 10.

Basalt dissolution varied continuously over time at the CarbFix1 monitoring well HN-04 (Fig. 7). A noticeable increase is evident shortly after the first pure CO<sub>2</sub> injection started. This early increase coincides with increasing concentrations of the sulfur hexafluoride (SF<sub>6</sub>) tracer, consistent with the arrival of the gas-charged water after enhanced water-rock interaction. Dissolution peaked early 2013, indicating continued basalt dissolution even after the injections ceased. The mass of basalt dissolved correlates well with the SF<sub>6</sub> tracer concentrations, which peaked in January – February 2013 (Matter et al., 2016), and with the maximum calcite precipitation rates, estimated to have occurred in October – November 2012 (Pogge van Strandmann et al., 2019).

Basalt dissolution at the CarbFix2 site (Fig. 8), generally increased over time when the gas-charged fluid was continuously injected into well HN-16, then declined when the gas-charged fluid was diverted away from these wells by the HN-14 injection, as shown in Fig. 8. The calculated mass of basalt dissolved increased again during the second phase of injection of CarbFix2 in wells HE-31 and HE-48, when the amount of CO<sub>2</sub> and H<sub>2</sub>S injected was doubled. The calculated mass of basalt dissolved differs among the three monitoring wells, reflecting the distinct distances between the injection and monitoring wells and the relative concentration of the gas-charged water, with HE-44 showing the lowest basalt mass dissolved. These trends reflect the carbon and sulfur mineralization rates calculated by Clark et al. (2020).

To evaluate the robustness of the stoichiometric basalt dissolution calculations, these calculations were repeated using Cl concentrations in the place of sodium in Eq. (2) (see Figs. S-1 and S-2 in the Supplementary Materials). Unlike Na, Cl is not a major constituent of basalt but behaves conservatively in geothermal fluids (Arnórsson, 2000). The Cl-based results yield the same temporal patterns as the Na-based results, particularly in CarbFix1, although the absolute magnitudes differ and some negative values occur. These variations likely reflect fluid mixing and injection-related dilution rather than mineral dissolution, thus the results of the Cl-based calculation support using Na to estimate the mass of basalt dissolved in the CarbFix systems.

The maximum calculated basalt mass dissolved in the sampled CarbFix1 and CarbFix2 fluids was similar and approximately 9 mmol per kg water. This result may be somewhat surprising as the temperature of the CarbFix1 basalts was approximately 35 °C whereas that of CarbFix2 was >250 °C. The similarity in the maximum basalt mass dissolved suggests that Na may not have been fully mobile in the higher temperature system. Notably plagioclase is altered to albite and wairakite at temperatures >280 ° (Snæbjörnsdóttir et al., 2018a). This possibility is also consistent with the saturation states of albite and wairakite reported by Clark et al. (2018).

The calculated scavenging percentage of selected trace and toxic elements in the collected CarbFix1 and CarbFix2 (well HE-31) fluids are presented in Figs. 9 and 10, respectively. Note the results of the HE-48 and HE-44 CarbFix2 wells are presented in Figs. S-3 and S-4 in the Supplementary Materials. In these figures a 100 % scavenging indicates that all of the element released to the fluid phase by basalt dissolution has been removed from the fluid phase and retained in the subsurface. A high scavenging percent is found for all measured elements. A scavenging percentage greater than 100 % indicates that the injection of the gas-charged water lowered the concentration to below its background reinjection value. The large scavenging percentages observed for most studied elements demonstrate the effectiveness of subsurface processes

to remove these elements from the fluid phase over time. This high degree of scavenging is also supported by experiments conducted by Galeczka et al. (2013) and Romano et al. (2024). Note that these scavenging magnitudes are sensitive to the chosen pre-injection baseline, which was taken to be the average of fluids sampled before the gas injections reached the monitoring wells.

The behavior of the measured trace elements in the CarbFix2 samples from well HE-31 contrasts somewhat with those of the CarbFix1 fluids from well HN-04. The transition metals Fe, Mn, Cu, and Ni, as well as Al are nearly completely scavenged from the subsurface fluids as was the case for CarbFix1. The As exhibits substantial scavenging in the CarbFix2 system, with many values exceeding 200 %. Similar to Mo and Sr, As concentrations tend to decrease after injection in all three wells (Fig. 5). This indicates that As was efficiently removed under high-temperature conditions. A few lower As concentration values appear in the dataset, which may reflect sensitivity to the chosen pre-injection baseline and/or the solubility of arsenopyrite at  $>250$  °C (Pokrovsky et al., 2002), despite the likely precipitation of pyrite in the system (Clark et al., 2020). The monovalent cations Li, Rb, and Cs, together with the divalent cations Sr and Ba, were scavenged to a lesser extent compared to most other elements, although their median scavenging values remain close to 100 % (Table S-6). These elements are also typically present in high concentrations in geothermal fluids (e.g., Liu et al., 2025).

Despite the extensive studies on the mobility and scavenging of trace elements, particularly in Iceland (Flaathen et al., 2009; Galeczka et al., 2014; 2015; Gíslason et al., 2002; Olsson et al., 2014; Thomas et al., 2016), there is still limited thermodynamic data available to quantify the fate of most trace elements released to subsurface waters.

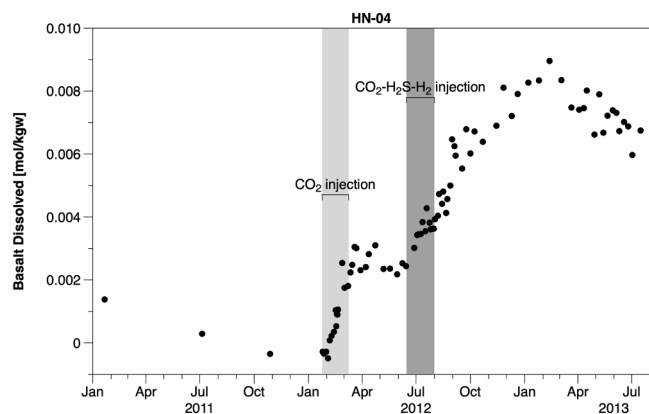


Fig. 7. Temporal evolution of calculated basalt dissolved mass per kilogram of water at well HN-04 (CarbFix1 site) based on Na concentrations. Shaded regions denote periods of gas-charged water injection.

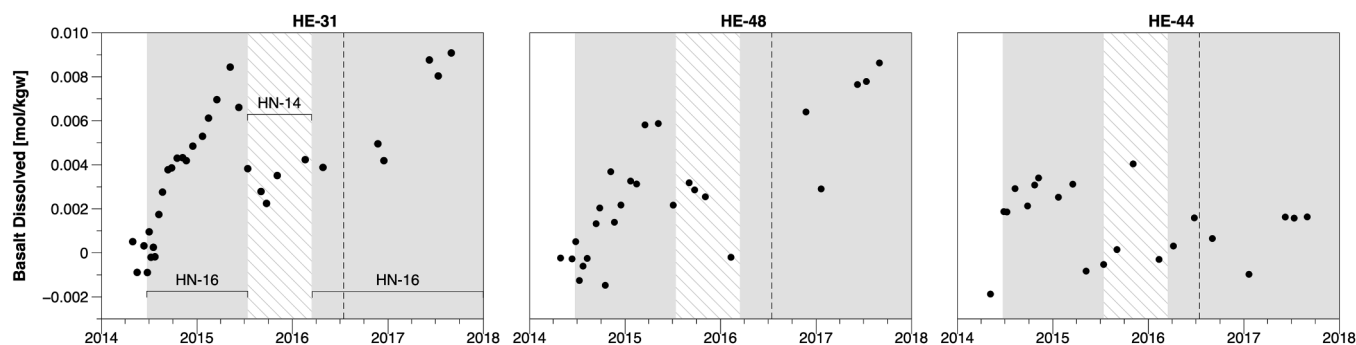


Fig. 8. Temporal evolution of calculated basalt dissolved mass in the CarbFix2 HE-31, HE-48, and HE-44 well fluids, based on measured Na concentrations. Shaded regions denote periods of gas injection into well HN-16, diagonal lines mark gas injection into well HN-14, and the vertical dashed line signifies when the gas injection rate doubled.

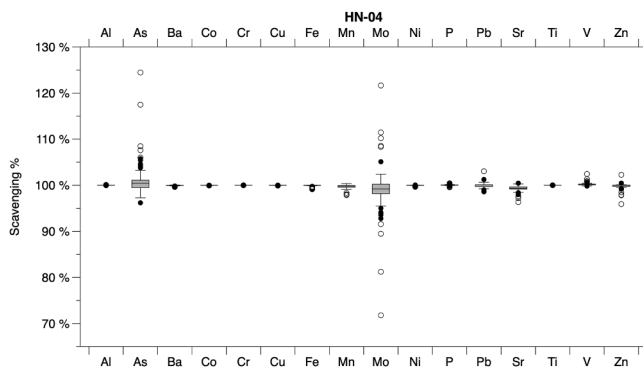
Nevertheless, there are a large number of observations of the behavior of these trace elements in natural systems. A summary of the minerals observed to take up various elements is provided in Table 2; a similar review was provided by Kassalainen et al. (2015). This review suggests that most trace elements are taken up as impurities in carbonate, sulfide, or clay minerals. In addition, adsorption onto mineral surfaces and cation exchange processes are known to influence the mobility of both anions and cations in groundwater and soil water. The observed decreases in elements like As, Mo, and Al in the CarbFix2 fluids are consistent with adsorption playing a role alongside mineral precipitation (Appelo and Postma, 2005).

According to Kassalainen et al. (2015), the divalent cations Ba and Sr are likely largely taken up by Ca carbonates and the elements As, Mo, Sb, Cu, Cr, and Ni could be taken up by sulfides, such as pyrite (Abraitis et al., 2004; Thomas et al., 2016). Such incorporation has also been documented in numerous natural and experimental systems, for example, the uptake of trace metals into calcite in Hvanná, a river near Eyjafjallajökull (Olsson et al., 2014), and the enrichment of transition metals in Icelandic pyrite (Libbey and William-Jones, 2016). The systematic decrease and high scavenging percentages observed for many of these elements in the CarbFix2 fluids are consistent with their removal by their co-precipitation into these mineral phases.

In contrast, the monovalent cations Li, Rb, and Cs are commonly taken up by clay minerals such as smectite at low-temperature conditions. The results of the present study, however, suggest that these clays are not effective scavengers in the high-temperature CarbFix2 system. At these temperature conditions, chlorite formation is favored over smectite (Kristmannsdóttir, 1979), and the chlorite mineral structure apparently does not readily incorporate large monovalent cations.

The CarbFix1 and CarbFix2 results also show that trace element behaviour differs between lower temperature (35 °C) and higher temperature ( $>250$  °C) systems. Both systems are characterized by ongoing water-rock interaction where the arrival of  $\text{CO}_2$ - and  $\text{CO}_2/\text{H}_2\text{S}$ -charged water shifted fluid pH and mineral equilibria, leading to distinct changes in element concentrations. In CarbFix1, where the gases were injected only for limited periods, several elements, notably Ba, Sr, Mn, Fe, Co, Ni, Zn, increased in concentration during injection, coinciding with lower pH values, even though they were subsequently somewhat scavenged. In CarbFix2, where the gas injection has been largely continuous, elements including As, Mo, Sb, Al, Cu, and V generally decreased in concentration after injection, while Li, Rb, Cs, and in some cases Sr and Ba, showed little change. These differences suggest that both temperature and gas injection mode influences trace element mobility, but the present dataset does not allow these effects to be separated.

Similar patterns of trace element mobilization have been reported in other  $\text{CO}_2$ -water-rock systems. Aiuppa et al. (2000a) documented enhanced metal release in basaltic aquifers at Mt. Etna (Italy) due to volcanic  $\text{CO}_2$  input, with concentrations largely controlled by pH and secondary mineral equilibria. Romano et al. (2024) showed that basalt

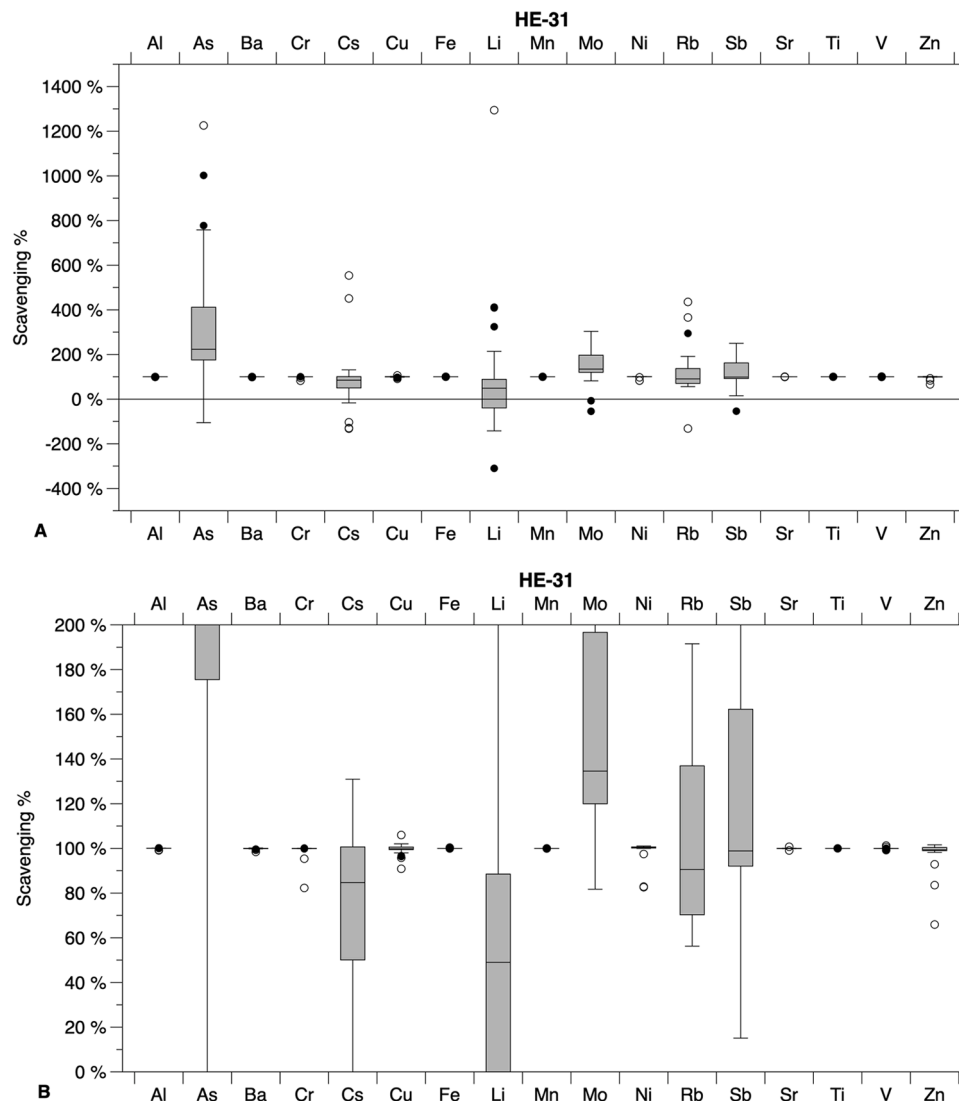


**Fig. 9.** Scavenging percentage of selected elements in the CarbFix1 fluids based on 104 samples collected from monitoring well HN-04. The boxes show the median, quartiles, whiskers, and outliers. Values >100 % suggest that gas injection reduced concentrations of the indicated metal in the sampled fluids.

dissolution under CO<sub>2</sub>-rich conditions leads to transient increases in Al, Fe, and transition metal concentrations, followed by a decrease as secondary phases precipitate. Experiments simulating CO<sub>2</sub> leakage into sub-seafloor sediments also indicate significant increases in Fe, Co, Pb, Zn, and Cu concentrations driven by acidification and reductive dissolution of Fe–Mn oxides (Dolores Basallote et al., 2020). Likewise, CO<sub>2</sub>-brine-sandstone experiments demonstrate that trace metals such as Cd, Pb, and Mn can be mobilized above drinking-water standards, particularly under saline conditions, before being partially immobilized as alkalinity increases (Jean et al., 2019). These results, together with those of the present study, suggest the risks of trace and potentially toxic metal mobility stemming from subsurface CO<sub>2</sub> injection are likely limited.

### 5.3. Partition coefficients in calcite precipitates

While scavenging calculations indicate that trace elements are efficiently removed from the aqueous phase, partition coefficients provide direct evidence of their incorporation into calcite precipitates. Trace



**Fig. 10.** Scavenging percentage of selected elements in the CarbFix2 fluids based on 32 samples collected from monitoring well HE-31. The boxes show the median, quartiles, whiskers and outliers. Values >100 % suggests that gas injection reduced concentrations of the indicated metals in the sampled fluids.

**Table 2**  
Mineral types hosting trace elements<sup>a</sup>.

| Element | Carbonate | Sulfide | Sulfate | (Hydr)oxides | Clay/Si-minerals |
|---------|-----------|---------|---------|--------------|------------------|
| As      |           | X       |         | X?           |                  |
| Ba      | X         |         | X       |              | X?               |
| Cd      |           | X       |         |              |                  |
| Co      |           | X       |         |              |                  |
| Cr      |           |         |         | X            |                  |
| Cs      |           |         |         |              | X                |
| Cu      | X         | X       | X       | X            |                  |
| Fe      |           | X       |         | X?           | X                |
| Li      |           |         |         |              | X                |
| Mo      |           | X       |         | X?           | X                |
| Mn      | X         | X       |         | X?           | X                |
| Ni      |           | X       |         | X            | X                |
| Pb      | X         | X       |         | X?           |                  |
| Rb      |           |         |         |              | X                |
| Sb      |           | X       |         | X            |                  |
| Sr      | X         |         | X       |              | X                |
| V       |           | X       |         | X            |                  |
| W       |           | X       |         |              |                  |
| Zn      |           | X       |         | X            | X?               |

<sup>a</sup> Based on: Abraitis et al. (2004), Arnórsson and Ivarsson (1985), Ballantyne and Moore (1988), Berget al. (1988), Christensen al. (1983), Exley (1982), Fridriksson et al. (2009), Galois et al. (1995), Goguel (1983), Gurav et al. (2016), Harðardóttir et al. (2010), Kassalainen and Stefánsson (2012), Kassalainen et al. (2015), Kendall et al. (2017), Libbey and William-Jones (2016), Marks et al. (2010), Neely et al. (2018), O'Day (2006), Olsson et al. (2014), Thomas et al. (2016).

**Table 3**

Partition coefficients ( $P_{Me}$ ) for trace and major elements in calcite, calculated using Eq. (5) (after Olsson et al., 2014). Values are shown for HN-04 pump precipitations from CarbFix1, natural travertines from the Hvanná river, and calcite scales from the Selfoss district heating network.  $P_{Me} > 1$  indicates preferential incorporation into calcite, while values  $< 1$  indicate exclusion relative to Ca.

|                  | Carbfix1 Pump Samples |          | Hvanná travertine <sup>a</sup> |       | Selfoss              |
|------------------|-----------------------|----------|--------------------------------|-------|----------------------|
|                  | CC01                  | CC02     | Min.                           | Max.  | Calcite <sup>b</sup> |
| Al               | 0.185                 | 0.118    | 1                              | 12.4  | 0.429                |
| As               | 0.000091              | 0.000161 |                                |       | 0.0890               |
| B                | 0.00668               | 0.00206  |                                |       | 0.00208              |
| Ba               | 1.67                  | 0.775    | 0.63                           | 1.2   | 0.350                |
| Ca               |                       |          |                                |       |                      |
| Cd               | 6.12                  | 8.50     | 4.5                            | 51    | 0.547                |
| Co               | 5.47                  | 2.30     | 1.4                            | 2.8   | 9.49                 |
| Cr               | 74.5                  | 13.8     |                                |       | 54.2                 |
| Cu               |                       |          | 7.8                            | 50    | 14.3                 |
| Fe               | 96.7                  | 61.6     | 0.93                           | 50    | 13.1                 |
| Hg               | 0.0454                | 0.0420   |                                |       | 2.05                 |
| K                | 0.000708              | 0.000320 |                                |       | 0.00120              |
| Mg               | 0.0667                | 0.0562   | 0.012                          | 0.018 | 0.526                |
| Mn               | 8.72                  | 11.0     | 3.4                            | 13.1  | 15.4                 |
| Mo               | 0.0341                | 0.0183   |                                |       | 0.0159               |
| Na               | 0.000087              | 0.000062 | 0.00069                        | 0.004 | 0.000064             |
| Ni               | 15.2                  | 2.21     | 0.15                           | 0.44  | 1.70                 |
| Pb               | 9.27                  | 3.90     |                                |       | 51.2                 |
| SiO <sub>2</sub> | 0.00711               | 0.00608  |                                |       | 0.00305              |
| Sr               | 0.129                 | 0.135    | 0.26                           | 0.37  | 0.068                |
| Ti               | 4.25                  | 2.76     | 1.9                            | 11    | 0.674                |
| V                | 0.145                 | 0.0584   |                                |       | 1.12                 |
| Zn               | 55.9                  | 14.6     | 0.9                            | 16    | 0.915                |

<sup>a</sup> Olsson et al. (2014)

<sup>b</sup> Galciczka et al. (2021).

element concentrations of the HN-04 pump precipitates collected during CarbFix1 are presented in Table S-7 in the Supplementary Material. Partition coefficients calculated from these data are shown in Table 3 and Fig. 11, together with corresponding values for natural travertines (Olsson et al., 2014) and Selfoss calcite scales (Galciczka et al., 2021).

The HN-04 pump calcite shows enrichment for several chalcophile

and transition elements when normalized to the HN-04 fluid from June–July 2013 (Cr, Fe, Mn, Ni, Zn, Pb, Co;  $P_{Me} > 1$ ). In contrast, the partition coefficients for Sr remains  $< 1$  and Ba straddles unity, while As, Na, K, and Mg are consistently  $< 1$ . Nevertheless, these results show that CO<sub>2</sub> mineralization as calcite can immobilize a number of trace and toxic metals liberated by basalt dissolution.

The Selfoss calcite scales are similar to those of the CarbFix1 carbonates, with  $P_{Me} > 1$  for Cr, Cu, Fe, Mn, Ni, Pb, and Zn (Galciczka et al., 2021). That study concluded that much of the metal uptake occurs within the calcite matrix via fine sulfide inclusions, rather than by lattice substitution alone. The similarity in enrichment patterns between Selfoss and HN-04 suggests that analogous processes may operate during the CarbFix1 injections. The calcite in travertines is formed due to the natural degassing of CO<sub>2</sub> (Olsson et al., 2014). This might explain the significant differences in the partition coefficients retrieved from the travertine deposits compared to those of the CarbFix1 system for elements such as for Fe, Ni, and Zn.

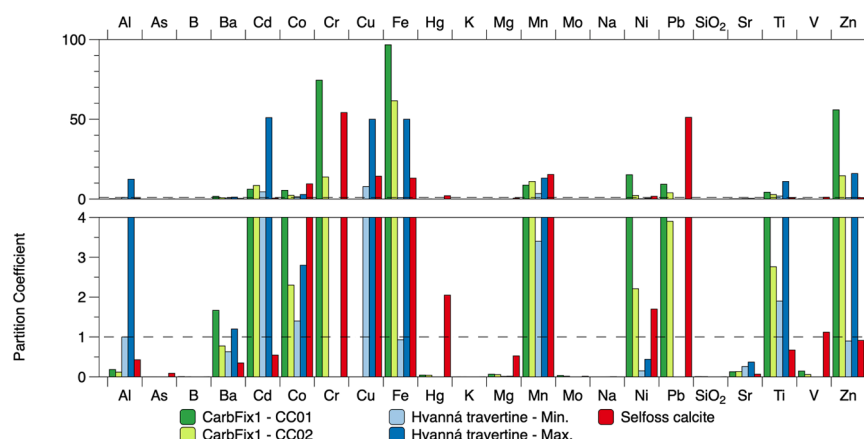
## 6. Uncertainties

The major source of uncertainty in the scavenging calculations presented above originates from the heterogeneity of the subsurface basalts. Table S-5 provides the measured compositions of basalt cuttings collected from the HN-04 well at a depth of 500 m, well HE-31 at a depth of 1789 m, and Stapafell basaltic glass. This latter Icelandic glass has been widely used in laboratory experiments and is close to Mid-Ocean Ridge Basalt (MORB) composition (e.g., GERM, 2000, Oelkers and Gislason, 2001, Gislason and Oelkers, 2003). The trace element compositions of these three Icelandic basalts vary substantially; for example, the Ni concentrations range from 58 to 237 ppm, the As concentrations range from 0.126 to 2.5 ppm, and the Cr concentrations range from 120 to 752 ppm. In contrast, despite varying injection and production rates of the CarbFix2 wells (Ratouis et al., 2022), the collected fluid samples are likely well mixed in the subsurface and are relatively homogeneous, as evidenced by their systematic behavior. The adoption of a single trace element composition of the subsurface basalts and the assumption of stoichiometric basalt dissolution, makes the dissolution rates and scavenging percentages calculated in this study to be qualitative rather than quantitative. Nevertheless, this limitation does not invalidate the conclusions of this study that (a) the large percentage of numerous trace and potentially toxic metals are retained in the subsurface during CO<sub>2</sub>/H<sub>2</sub>S-water-basalt interaction and (b) that the concentrations of trace elements and potentially toxic waters resulting from this interaction are largely below recommended drinking water limits over the timeframe of the experiments.

## 7. Conclusions

The results and discussion presented above indicate that most trace and potentially toxic elements are efficiently scavenged during the injection of CO<sub>2</sub> and CO<sub>2</sub>/H<sub>2</sub>S-charged water into basaltic reservoirs. Secondary processes, likely dominated by mineral precipitation but with possible contributions from adsorption and cation exchange, lead to the efficient removal of many dissolved elements, even under strongly perturbed pH conditions. The observed concentration decreases and high scavenging percentages for divalent cations and transition metals are consistent with their co-precipitation into secondary carbonates and sulfides, which are known to incorporate these elements in past studies. Partition coefficient calculations also confirm that calcite is one of the main sinks, at least during CarbFix1, with preferential incorporation of transition metals consistent with both natural and geothermal analogues.

Nevertheless, some elements displayed short-lived concentration increases during injection. In the 35 °C CarbFix1 system, where the gases were injected for a limited time, several metals increased in concentration before later decreasing. In contrast, in the  $> 250$  °C CarbFix2



**Fig. 11.** Partition coefficients ( $P_{Me}$ ) of calcite precipitates from solids collected from the CarbFix1 injection well pump, Selfoss district heating scales (Galeczka et al., 2021), and Hvanná river travertines (Olsson et al., 2014). The dashed line marks  $P_{Me} = 1$ , above which elements are preferentially incorporated into calcite compared to Ca. For clarity, the values are shown with two distinct vertical scales.

system, where gases were injected continuously, the concentration of most dissolved elements are altered. Notably, in this latter system, Al concentrations remained elevated and As showed strong scavenging throughout the study period.

The findings in this study demonstrate that trace element mobility during carbon storage in basalts depends on both temperature and mode of gas injection. While the long-term risk of contamination appears limited, the concentration of many increases, at least temporally, in response to dissolved  $\text{CO}_2$  injection. This suggests that the monitoring of potentially toxic elements should be included in best practice monitoring strategies for future mineral storage projects.

#### CRediT authorship contribution statement

**Deirdre E. Clark:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Iwona M. Galeczka:** Writing – review & editing, Validation. **Sigurður R. Gíslason:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Sandra Ó. Snæbjörnsdóttir:** Writing – review & editing, Resources, Investigation, Data curation. **Ingvi Gunnarsson:** Resources, Project administration. **Eric H. Oelkers:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.ijggc.2025.104526](https://doi.org/10.1016/j.ijggc.2025.104526).

#### Data availability

The data is available in Supplementary Materials and Data Repositories.

[Geothermal fluid composition of liquid and gas samples collected from wells HE-31, HE-48, and HE-44 from CarbFix2  \$\text{CO}\_2\$ -H<sub>2</sub>S injection \(2014–2017\) \(Original data\) \(Zenodo\)](#)

[Trace element concentrations of water samples collected from well HN-04 from the CarbFix1  \$\text{CO}\_2\$  injection \(2011–2013\) \(Original data\) \(Zenodo\)](#)

#### References

- Abratis, P.K., Patrick, R.A.D., Vaughan, D.J., 2004. Variations in the compositional, textural and electrical properties of natural pyrite: a review. *Int. J. Mine. Process.* 74, 41–59. <https://doi.org/10.1016/j.minpro.2003.09.002>.
- Aiuppa, A., Allard, P., D'Alessandro, W., Michel, A., Parello, F., Treuil, M., Valenza, M., 2000a. Mobility and fluxes of major, minor and trace metals during basalt weathering and groundwater transport at Mt. Etna volcano (Sicily). *Geochim. Cosmochim. Acta.* 64, 1827–1841. [https://doi.org/10.1016/S0016-7037\(00\)00345-8](https://doi.org/10.1016/S0016-7037(00)00345-8).
- Aiuppa, A., Dongarra, G., Capasso, G., Allard, P., 2000b. Trace elements in the thermal groundwaters of Vulcano Island (Sicily). *J. Volcanol. Geotherm. Res.* 98, 189–207. [https://doi.org/10.1016/S0377-0273\(99\)00156-0](https://doi.org/10.1016/S0377-0273(99)00156-0).
- Aiuppa, A., Federico, C., Allard, P., Gurrieri, S., Valenza, M., 2005. Trace metal modeling of groundwater–gas–rock interactions in a volcanic aquifer: mount Vesuvius, Southern Italy. *Chem. Geol.* 216, 289–311. <https://doi.org/10.1016/j.chemgeo.2004.11.017>.
- Alfredsson, H.A., Oelkers, E.H., Harðarsson, B.S., Franzson, H., Gunnlaugsson, E., Gíslason, S.R., 2013. The geology and water chemistry of the Hellisheidi, SW-Iceland carbon storage site. *Int. J. Greenh. Gas Con.* 12, 399–418. <https://doi.org/10.1016/j.ijggc.2012.11.019>.
- Appelo, C.A.J., Postma, D., 2005. *Geochemistry, Groundwater and Pollution*. CRC Press/Balkema, Leiden, The Netherlands, p. 649. Second ed.
- Arnórsen, S., 2000. *Isotopic and Chemical Techniques in Geothermal Exploration, Development and Use: Sampling Methods, Data Handling, Interpretation*. IAEA, Vienna, p. 351.

- Arnórsson, S., Bjarnason, J.O., Giroud, N., Gunnarsson, I., Stefánsson, A., 2006. Sampling and analysis of geothermal fluids. *Geofluids* 6, 203–216. <https://doi.org/10.1111/j.1468-8123.2006.00147.x>.
- Arnórsson, S., Sigurdsson, S., Svararsson, H., 1982. The chemistry of geothermal waters in Iceland. I. Calculation of aqueous speciation from 0 °C to 370 °C. *Geochim. Cosmochim. Acta* 46, 1513–1532. [https://doi.org/10.1016/0016-7037\(82\)90311-8](https://doi.org/10.1016/0016-7037(82)90311-8).
- Arnórsson, S., Andrésdóttir, A., 1995. Processes controlling the distribution of boron and chlorine in natural waters in Iceland. *Geochim. Cosmochim. Acta* 59, 4125–4146. [https://doi.org/10.1016/0016-7037\(95\)00278-8](https://doi.org/10.1016/0016-7037(95)00278-8).
- Arnórsson, S., Ivarsson, G., 1985. Molybdenum in Icelandic geothermal waters. *Contrib. Mineral. Petrol.* 90, 179–189. <https://doi.org/10.1007/BF00378259>.
- Arnórsson, S., Óskarsson, N., 2007. Molybdenum and tungsten in volcanic rocks and in surface and <100 °C ground waters in Iceland. *Geochim. Cosmochim. Acta* 71, 284–304. <https://doi.org/10.1016/j.gca.2006.09.030>.
- Ballantyne, J.M., Moore, J.N., 1988. Arsenic geochemistry in geothermal systems. *Geochim. Cosmochim. Acta* 52, 475–483. <https://doi.org/10.1016/j.gca.2006.09.030>.
- Berger, G., Schott, J., Guy, C., 1988. Behavior of Li, Rb and Cs during basalt glass and olivine dissolution and chlorite, smectite and zeolite precipitation from seawater: experimental investigations and modelization between 50 ° and 300 °C. *Chem. Geol.* 71, 297–312. [https://doi.org/10.1016/0009-2541\(88\)90056-3](https://doi.org/10.1016/0009-2541(88)90056-3).
- Bjarnason, J.O., Arnórsson, S., 2010. The chemical speciation program WATCH.
- Christensen, O.D., Capuano, R.A., Moore, J.N., 1983. Trace-element distribution in an active hydrothermal system, Rosevelt hot springs thermal area, Utah. *J. Volcanol. Geotherm. Res.* 16, 99–129. [https://doi.org/10.1016/0377-0273\(83\)90086-0](https://doi.org/10.1016/0377-0273(83)90086-0).
- Clark, D.E., Gunnarsson, I., Aradóttir, E.S., Arnarsson, M.P., Sigurðardóttir, S.S., Sigfússon, B., Snæbjörnsdóttir, S.O., Oelkers, E.H., Gíslason, S.R., 2018. The chemistry and potential reactivity of the CO<sub>2</sub>-H<sub>2</sub>S charged injected waters at the basaltic CarbFix2 site, Iceland. *Energy Procedia* 146, 121–128. <https://doi.org/10.1016/j.egypro.2018.07.016>.
- Clark, D.E., Oelkers, E.H., Gunnarsson, I., Sigfússon, B., Snæbjörnsdóttir, S.O., Aradóttir, E.S., Gíslason, S.R., 2020. CarbFix2: CO<sub>2</sub> and H<sub>2</sub>S mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. *Geochim. Cosmochim. Acta* 279, 45–66. <https://doi.org/10.1016/j.gca.2020.03.039>.
- Dolores Basallote, M., Borrero-Santiago, A.R., Cánovas, C.R., Hammer, K.M., Olsen, A.J., Ardelan, M.V., 2020. Trace metal mobility in sub-seabed sediments by CO<sub>2</sub> seepage under high-pressure conditions. *Sci. Total Environ.* 700, 134761. <https://doi.org/10.1016/j.scitotenv.2019.134761>.
- EU, 2020. Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 On the Quality of Water Intended For Human Consumption. European Union.
- Exley, R.A., 1982. Electron microprobe studies of Iceland Research Drilling Project high-temperature hydrothermal mineral geochemistry. *J. Geophys. Res.: Solid Earth* 87, 6547–6557. <https://doi.org/10.1029/JB087iB08p06547>.
- Flaathen, T.K., Gíslason, S.R., Oelkers, E.H., Sveinbjörnsdóttir, Á.E., 2009. Chemical evolution of the Mt. Hekla, Iceland, groundwaters: a natural analogue for CO<sub>2</sub> sequestration in basaltic rocks. *Appl. Geochem.* 24, 463–474. <https://doi.org/10.1016/j.apgeochem.2008.12.031>.
- Fridriksson, T., Arnórsson, S., Bird, D.K., 2009. Processes controlling Sr in surface and ground waters of tertiary tholeiitic flood basalts in Northern Iceland. *Geochim. Cosmochim. Acta* 73, 6727–6746. <https://doi.org/10.1016/j.gca.2009.08.025>.
- Galeczka, I., Eiríksdóttir, E.S., Harðardóttir, J., Oelkers, E.H., Torssander, P., Gíslason, S.R., 2015. The effect of the 2020 glacial flood on dissolved and suspended chemical fluxes in the Skaftá river. Iceland. *J. Volcanol. Geotherm. Res.* 301, 253–276. <https://doi.org/10.1016/j.jvolgeores.2015.05.008>.
- Galeczka, I., Harðardóttir, V., Haraldsson, S.P., 2021. The metal scavenging by calcite scaling formed during utilization of the low temperature geothermal waters. A case study in Selfoss geothermal area, Sw Iceland. In *Proceedings World Geothermal Congress 2020* +1.
- Galeczka, I., Oelkers, E.H., Gíslason, S.R., 2014. The chemistry and element fluxes of the July 2011 Múlavísl and Kaldavísl glacial floods, Iceland. *J. Volcanol. Geotherm. Res.* 273, 41–57. <https://doi.org/10.1016/j.jvolgeores.2013.12.004>.
- Galeczka, I., Wolff-Boenisch, D., Gíslason, S., 2013. Experimental studies of basalt-H<sub>2</sub>O-CO<sub>2</sub> interaction with a high pressure column flow reactor: the mobility of metals. *Energy Procedia* 37, 5823–5833. <https://doi.org/10.1016/j.egypro.2013.06.505>.
- Galoisy, L., Calada, G., Brown Jr., G.E., 1995. Intracrystalline distribution of Ni in San Carlos olivine: an EXAFS study. *Amer. Miner.* 80, 1089–1092. <https://doi.org/10.2138/am-1995-9-1028>.
- GERM (2000). The Geochemical Earth Reference Model, <http://EarthRef.org> (accessed 4 April 2025).
- Giroud, N., 2008. A Chemical Study of arsenic, Boron and Gases in High-Temperature Geothermal Fluids in Iceland. University of Iceland, Reykjavik, p. 128 pp.
- Gíslason, S.R., Arnórsson, S., Armannsson, H., 1996. Chemical weathering of basalt in southwest Iceland: effects of runoff, age of rocks and negative/glacial cover. *Am. J. Science* 296, 837–907. <https://doi.org/10.2475/ajs.296.8.837>.
- Gíslason, S.R., Oelkers, E.H., 2003. Mechanism, rates, and consequences of basaltic glass dissolution: II. An experimental study of the dissolution rates of basaltic glass as a function of pH and temperature. *Geochim. Cosmochim. Acta* 67, 3817–3832. [https://doi.org/10.1016/S0016-7037\(03\)00176-5](https://doi.org/10.1016/S0016-7037(03)00176-5).
- Gíslason, S.R., Oelkers, E.H., 2014. Carbon storage in Basalt. *Science* 344, 373–374. <https://doi.org/10.1126/science.1250828>.
- Gíslason, S.R., Snorrason, Á., Kristmannsdóttir, H.K., Sveinbjörnsdóttir, Á.E., Torssander, P., Ólafsson, J., Castet, S., Durpé, B., 2002. Effects of volcanic eruptions on the CO<sub>2</sub> content of the atmosphere and the oceans: the 1996 eruption and flood within the Vatnajökull Glacier. Iceland. *Chem. Geol.* 190, 181–205. [https://doi.org/10.1016/S0009-2541\(02\)00116-X](https://doi.org/10.1016/S0009-2541(02)00116-X).
- Glover, R.B., 1988. Boron Distribution Between Liquid and Vapour in Geothermal Fluids. 10th New Zealand Geothermal Workshop, New Zealand.
- Goguel, R., 1983. The rare alkalis in hydrothermal alteration at Wairakei and Broadlands, geothermal fields, N.Z. *Geochim. Cosmochim. Acta* 47, 429–437. [https://doi.org/10.1016/0016-7037\(83\)90265-X](https://doi.org/10.1016/0016-7037(83)90265-X).
- Gunnarsson, I., Aradóttir, E.S., Oelkers, E.H., Clark, D.E., Arnarsson, M.P., Sigfússon, B., Snæbjörnsdóttir, S.O., Matter, J.M., Stute, M., Júlíusson, B.M., Gíslason, S.R., 2018. The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. *Int. J. Greenh. Gas Con.* 79, 117–126. <https://doi.org/10.1016/j.ijggc.2018.08.014>.
- Gunnarsson, I., Arnórsson, S., 2000. Amorphous silica solubility and the thermodynamic properties of H<sub>4</sub>SiO<sub>4</sub> in the range of 0 to 350 °C at p. amt. *Geochim. Cosmochim. Acta* 64, 2295–2307. [https://doi.org/10.1016/S0016-7037\(99\)00426-3](https://doi.org/10.1016/S0016-7037(99)00426-3).
- Gurav, T., Singh, H.K., Chandrasekharan, D., 2016. Major and trace element concentrations in the geothermal springs along the west coast of Maharashtra, India. *Arab. J. Geosci.* 9. <https://doi.org/10.1007/s12517-015-2139-2>.
- Harðardóttir, V., Hannington, M., Hedenquist, J., Kjarsgaard, I., Hoal, K., 2010. Cu-rich scales in the Reykjanes geothermal system. Iceland. *Econ. Geol.* 105, 1143–1155. <https://doi.org/10.2113/econgeo.105.6.1143>.
- Heinrich, C.A., 2007. Fluid-Fluid interactions in magmatic-hydrothermal ore formation. *Rev. Mineral. Geochem.* 65, 363–387. <https://doi.org/10.2138/rmg.2007.65.11>.
- Jean, J.S., Lin, H.W., Li, Z., Yang, H.J., Hsiang, H.I., Yang, K.M., Wang, C.L., Shen, Y.H., Kuo, C.C., Kuo, W.C., 2019. Salinity-enhanced release of trace metals from sandstone and variations in mineral compositions after water-rock interactions in the presence of supercritical CO<sub>2</sub>. *Aerosol Air Qual. Res.* 19, 639–648. <https://doi.org/10.4209/aaqr.2018.03.0088>.
- Kaasalainen, H., Stefánsson, A., 2012. The chemistry of trace elements in surface geothermal waters and steam, Iceland. *Chem. Geol.* 330–331, 60–85. <https://doi.org/10.1016/j.chemgeo.2012.08.019>.
- Kaasalainen, H., Stefánsson, A., Giroud, N., Arnórsson, S., 2015. The geochemistry of trace elements in geothermal fluids. Iceland. *Appl. Geochem.* 62, 207–223. <https://doi.org/10.1016/j.apgeochem.2015.02.003>.
- Karakaya, N., Karakaya, M.C., Nalbantçılar, M.T., Yavuz, F., 2007. Relation between spring-water chemistry and hydrothermal alteration in the Şaplıca volcanic rocks, Şebinkarahisar (Giresun, Turkey). *J. Geochem. Explor.* 93, 35–46. <https://doi.org/10.1016/j.gexplo.2006.08.012>.
- Kendall, B., Dahl, T.W., Anbar, A.D., 2017. The stable isotope geochemistry of molybdenum. *Rev. Mineral. Geochem.* 82, 683–732. <https://doi.org/10.2138/rmg.2017.82.16>.
- Kristmannsdóttir, H., 1979. Alteration of basaltic rocks by hydrothermal activity at 100–300 °C. *Dev. Sedimentology* 27, 359–367. [https://doi.org/10.1016/S0070-4571\(08\)70732-5](https://doi.org/10.1016/S0070-4571(08)70732-5).
- Libbey, R.B., Williams-Jones, A.E., 2016. Relating sulfide mineral zonation and trace element chemistry to subsurface processes in the Reykjanes geothermal system, Iceland. *J. Volcanol. Geotherm. Res.* 310, 225–241. <https://doi.org/10.1016/j.jvolgeores.2015.12.011>.
- Linke, T., Oelkers, E.H., Dideriksen, K., Möckel, S., Nilabh, S., Grandia, F., Gíslason, S.R., 2024. The geochemical evolution of basalt enhanced Rock weathering systems quantified from a natural analogue. *Geochim. Cosmochim. Acta* 270, 66–77. <https://doi.org/10.1016/j.gca.2024.02.005>.
- Liu, M., Kong, Y., Guo, Q., 2025. Sources and enrichment mechanisms of lithium, rubidium, and cesium in waters of magmatic-hydrothermal systems. *Earth-Sci. Rev.* 270, 105241. <https://doi.org/10.1016/j.earscirev.2025.105241>.
- Matter, J.M., Stute, M., Snæbjörnsdóttir, S.O., Oelkers, E.H., Gíslason, S.R., Aradóttir, E.S., Sigfússon, B., Gunnarsson, I., Sigurðardóttir, H., Gunnlaugsson, E., Axelsson, Guðni, Alfredsson, H.A., Wolff-Boenisch, D., Mesfin, K., Taya, D.F., Hall, J., Dideriksen, K., Broecker, W.S., 2016. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science* 352 (6291), 1312–1314. <https://doi.org/10.1126/science.aad8132>.
- Marks, N., Schiffman, P., Zierenberg, R., Elders, W.A., Fridleifsson, G.O., Franzson, H., 2010. Isotopic Evidence of Hydrothermal Exchange and Seawater Ingress from Alteration Minerals in the Reykjanes geothermal system: Results from the IDDP. *World Geothermal Congresses*, Bali, Indonesia.
- Markússon, S.H., Stefánsson, A., 2011. Geothermal surface alteration of basalts, Krýsuvík Iceland—Alteration mineralogy, water chemistry and the effects of acid supply on the alteration process. *J. Volcanol. Geotherm. Res.* 206, 46–59. <https://doi.org/10.1016/j.jvolgeores.2011.05.007>.
- McGrail, B.P., Schaefer, H.T., Spaine, F.A., Cliff, J.B., Qafoku, O., Horner, J.A., Thompson, C.J., Owen, A.T., Sullivan, C.E., 2017a. Field validation of supercritical CO<sub>2</sub> reactivity with basalts. *Environ. Sci. Tech. Lett.* 4, 6–10. <https://doi.org/10.1021/acs.estlett.6b00387>.
- McGrail, B.P., Schaefer, H.T., Spaine, F.A., Horner, J.A., Owen, A.T., Cliff, J.B., Qafoku, O., Thompson, C.J., Sullivan, C.E., 2017b. Wallula basalt pilot demonstration project: postinjection results and conclusions. *Energy Procedia* 114, 57835790. <https://doi.org/10.1016/j.egypro.2017.03.1716>.
- Migdisov, A.A., Bychkov, A.Y., 1998. The behaviour of metals and sulphur during the formation of hydrothermal mercury–antimony–arsenic mineralization, Uzon caldera, Kamchatka, Russia. *J. Volcanol. Geotherm. Res.* 84, 153–171. [https://doi.org/10.1016/S0377-0273\(98\)00038-9](https://doi.org/10.1016/S0377-0273(98)00038-9).
- Neely, R.A., Gíslason, S.R., Ólafsson, M., McCoy-West, A.J., Pearce, C.R., Burton, K.W., 2018. Molybdenum isotope behaviour in groundwaters and terrestrial hydrothermal systems. Iceland. *Earth Planet. Sci. Lett.* 486, 108–118. <https://doi.org/10.1016/j.epsl.2017.11.053>.

- Níelsson, S., Haraldsdóttir, S.H., Snæbjörnsdóttir, S.Ó., Blischke, A., Guðbrandsson, S., Feucht, C., Einarsson, G.M., Helgadóttir, H.M., Franzson Júlísson, E., 2007. Skarðsmýrarfjall – Hóla HE-31. Iceland GeoSurvey, Report No. ISOR-2007/050.
- O'Day, P.A., 2006. Chemistry and mineralogy of Arsenic. *Elements* 2, 77–83. <https://doi.org/10.2113/gselements.2.2.77>.
- Oelkers, E.H., Butcher, R., Pogge von Strandmann, P.A.E., Schuessler, J.A., Von Blanckenburg, F., Snæbjörnsdóttir, S.Ó., Mesfin, K., Aradóttir, E.S., Gunnarsson, I., Sigfússon, B., Gunnlaugsson, E., Matter, J.M., Stute, M., Gislason, S.R., 2019. Using stable Mg isotope signatures to assess the fate of magnesium during the in situ mineralisation of CO<sub>2</sub> and H<sub>2</sub>S at the CarbFix site in SW-Iceland. *Geochim. Cosmochim. Acta* 245, 542–555. <https://doi.org/10.1016/j.gca.2018.11.011>.
- Oelkers, E.H., Gislason, S.R., 2001. The mechanism, rates and consequences of basaltic glass dissolution: I. An experimental study of the dissolution rates of basaltic glass as a function of aqueous Al, Si and oxalic acid concentration at 25 °C and pH = 3 and 11. *Geochim. Cosmochim. Acta* 65, 3671–3681. [https://doi.org/10.1016/S0016-7037\(01\)00664-0](https://doi.org/10.1016/S0016-7037(01)00664-0).
- Oelkers, E.H., Gislason, S.R., 2023. Carbon capture and storage: from global cycles to global solutions. *Geochem. Perspect.* 12, 179–349. <https://doi.org/10.7185/geochempersp.12.2>.
- Olsen, N.J., Bird, D.K., Arnórsson, S., Fridriksson, S., Fridriksson, P., Fridleifsson, G.Ó., Elders, W.A., 2010. Iceland Deep Drilling Project (IDDP): Arsenic distribution and Mobility in Active and Fossil Geothermal Systems in Iceland. *World Geothermal Congress, Bali, Indonesia*.
- Olsson, J., Stipp, S.L.S., Makovicky, E., Gislason, S.R., 2014. Metal scavenging by calcium carbonate at the Eyjafjallajökull volcano: a carbon capture and storage analogue. *Chem. Geol.* 384, 135–148. <https://doi.org/10.1016/j.chemgeo.2014.06.025>.
- Pogge von Strandmann, P.A.E., Burton, K.W., Snæbjörnsdóttir, S.Ó., Sigfússon, B., Aradóttir, E.S., Gunnarsson, I., Alfredsson, H.A., Mesfin, K.G., Oelkers, E.H., Gislason, S.R., 2019. Rapid CO<sub>2</sub> mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes. *Nat. Commun.* 10, 1983. <https://doi.org/10.1038/s41467-019-10003-8>.
- Pokrovski, G.S., Kara, S., Roux, J., 2002. Stability and solubility of arsenopyrite, FeAsS, in crustal fluids. *Geochim. Cosmochim. Acta* 66, 2361–2378. [https://doi.org/10.1016/S0016-7037\(02\)00836-0](https://doi.org/10.1016/S0016-7037(02)00836-0).
- Pokrovski, G.S., Borisova, A.Y., Bychkov, A.Y., 2013. Speciation and transport of metals and metalloids in geological vapors. *Rev. Mineral. Geochem.* 76, 165–218. <https://doi.org/10.2138/rmg.2013.76.6>.
- Ratouis, T.M.P., Snæbjörnsdóttir, S.Ó., Voigt, M.J., Sigfússon, B., Gunnarsson, G., Aradóttir, E.S., Hjörleifsdóttir, V., 2022. Carbfix 2: A transport model of long-term CO<sub>2</sub> and H<sub>2</sub>S injection into basaltic rocks at Hellisheidi, SW-Iceland. *Int. J. Greenh. Gas Con.* 114, 103586. <https://doi.org/10.1016/j.ijggc.2022.103586>.
- Romano, P., Brusca, L., Liotta, M., 2024. Element mobility during Basalt-water-CO<sub>2</sub> interaction: observations in natural systems vs. Laboratory experiments and implication for carbon storage. *Geochem. Trans.* 25 (4). <https://doi.org/10.1186/s12932-024-00087-7>.
- Sigfússon, B., Aradóttir, E.S.P., Gunnarsson, I., Arnarson, M.P., Gunnlaugsson, E., Sigurðardóttir, H., Sighvatsson, H., Gislason, S.R., Oelkers, E.H., Mesfin, K.G., Snæbjörnsdóttir, S.Ó., Galeczka, I., Wolff-Boenisch, D., Alfredsson, H.A., Jónsson, P., Stefánsson, A., Matter, J., Stute, M., Clark, D.E., Voigt, M., 2024. Method of Abating Carbon Dioxide and Hydrogen Sulfide. United States Patent Office. US0375041A1.
- Sigfússon, B., Gislason, S.R., Matter, J.M., Stute, M., Gunnlaugsson, E., Gunnarsson, I., Aradóttir, E.S., Sigurðardóttir, H., Mesfin, K., Alfredsson, H.A., Wolff-Boenisch, D., Anarsson, M.P., 2015. Solving the carbon-dioxide buoyancy challenge: the design and field testing of a dissolved CO<sub>2</sub> injection system. *Int. J. Greenh. Gas Con.* 37, 213–219. <https://doi.org/10.1016/j.ijggc.2015.02.022>.
- Sigfússon, B., Arnarsson, M.P., Snæbjörnsdóttir, S.Ó., Karlsdóttir, M.R., Aradóttir, E.S., Gunnarsson, I., 2018. Reducing emissions of carbon dioxide and hydrogen sulfide at Hellisheidi power plant in 2014–2017 and the role of CarbFix in achieving the 2040 Iceland climate goals. *Energy Procedia* 146, 135–145. <https://doi.org/10.1016/j.egypro.2018.07.018>.
- Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Mesfin, K., Aradóttir, E.S., Dideriksen, K., Gunnarsson, I., Gunnlaugsson, E., Matter, J.M., Stute, M., Gislason, S.R., 2017. The chemistry and saturation states of subsurface fluids during the in situ mineralisation of CO<sub>2</sub> and H<sub>2</sub>S at the CarbFix site in SW-Iceland. *Int. J. Greenh. Gas Con.* 58, 87–102. <https://doi.org/10.1016/j.ijggc.2017.01.007>.
- Snæbjörnsdóttir, S.Ó., Gislason, S.R., Galeczka, I.M., Oelkers, E.H., 2018a. Reaction path modelling of in-situ mineralisation of CO<sub>2</sub> at the CarbFix site at Hellisheidi, SW-Iceland. *Geochim. Cosmochim. Acta* 220, 348–366. <https://doi.org/10.1016/j.gca.2017.09.053>.
- Snæbjörnsdóttir, S.Ó., Tómasdóttir, S., Sigfússon, B., Aradóttir, E.S., Gunnarsson, G., Niemi, A., Basirat, F., Dessirier, B., Gislason, S.R., Oelkers, E.H., Franzson, H., 2018b. The geology and hydrology of the CarbFix2 site, SW-Iceland. *Energy Procedia* 146, 146–157. <https://doi.org/10.1016/j.egypro.2018.07.019>.
- Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S.R., Oelkers, E. H., 2020. Carbon dioxide storage through mineral carbonation. *Nat. Rev. Earth Environ.* 1, 90–102. <https://doi.org/10.1038/s43017-019-0011-8>.
- Stefánsson, A., Arnórsson, S., 2005. The geochemistry of As, Mo, Sb, and W in natural geothermal waters, Iceland, *Proceedings World Geothermal Congress, Antalya, Turkey*.
- Stefánsson, A., Arnórsson, S., Gunnarsson, I., Kaasalainen, H., 2009. Förgun brennisteins frá Hellisheiðarvirkjun Jarðefnafræðileg athugun, Orkuveita Reykjavíkur (Reykjavik Energy).
- Stefánsson, A., Arnórsson, S., Gunnarsson, I., Kaasalainen, H., Gunnlaugsson, E., 2011. The geochemistry and sequestration of H<sub>2</sub>S into the geothermal system at Hellisheidi, Iceland. *J. Volcanol. Geotherm. Res.* 202, 179–188. <https://doi.org/10.1016/j.jvolgeores.2010.12.014>.
- Thomas, D.L., Bird, D.K., Arnórsson, S., Maher, K., 2016. Geochemistry of CO<sub>2</sub>-rich waters in Iceland. *Chem. Geol.* 444, 158–179. <https://doi.org/10.1016/j.chemgeo.2016.09.002>.
- Umhverfisstofnun, 2018. Reglugerð 536/2001 um neysluvatn. Stjórnarráð Íslands.
- Wang, H., Li, X., Chen, T., Li, Z., Hedding, D.W., Nel, W., Ji, J., Chen, J., 2020. Geochemical behavior and potential health risk of heavy metals in basalt-derived agricultural soil and crops: a case study from Xuyi County, Eastern China. *Sci. Total Environ.* 729, 139058. <https://doi.org/10.1016/j.scitotenv.2020.139058>.
- White, S.K., Spane, F.A., Schaefer, H.T., Miller, Q.R., White, M.D., Horner, J.A., McGrail, B. P., 2020. Quantification of CO<sub>2</sub> mineralization at the Wallula basalt pilot project. *Environ. Sci. Tech.* 54, 14609–14616. <https://doi.org/10.1021/acs.est.0c05142>.
- Wu, W., Qu, S., Nel, W., Ji, J., 2021. The influence of natural weathering on the behavior of heavy metals in small basaltic watersheds: a comparative study from different regions in China. *Chemosphere* 262, 127897. <https://doi.org/10.1016/j.chemosphere.2020.127897>.
- WHO, 2023. Guidelines For Drinking-Water quality: Fourth Edition Incorporating the First and Second Addenda. World Health Organization.