

Chemical changes in groundwater before and after earthquakes in northern Iceland

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Since October 2008, groundwater samples have been collected on a weekly basis from a bore hole (HA-01), which is situated near Hafralækur, approximately 30 km south of Húsavík. This bore hole taps a series of aquifers, which are at approximate depths ranging from 65 to 100 m. The water has a low content of dissolved solids (240 ppm), which is typical of low-temperature geothermal waters on the flanks of active rift zones in Iceland. Hydrogen isotope values indicate mixing of modern day (Holocene) meteoric water ($\delta^2\text{H} \sim -70$ ‰ at Hafralækur) and pre-Holocene meteoric water ($\delta^2\text{H} < -106$ ‰). Water-rock interaction can be inferred from oxygen isotope values, which are less negative than the Global Meteoric Water Line (GMWL).

Groundwater samples from this site have been analyzed for concentrations of dissolved Na, Ca, Mg, K, Si, Al, Fe, Ti, Cl, F and SO_4 , and for stable isotope ratios of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$). The pH, temperature, alkalinity and conductivity have also been measured. To our knowledge, this 8-year time series together with a 14-year time series from an aquifer at an approximate depth of 1.2 km near Húsavík town (HU-01) represents the longest time series collected for the purpose of studying coupling between groundwater chemistry and earthquakes.

During our study, $M > 5$ earthquakes occurred on 21 October 2012 (M 5.6) and 2 April 2013 (M 5.3). These earthquakes coincided with $\delta^2\text{H}$ and Na maxima (Fig. 1).

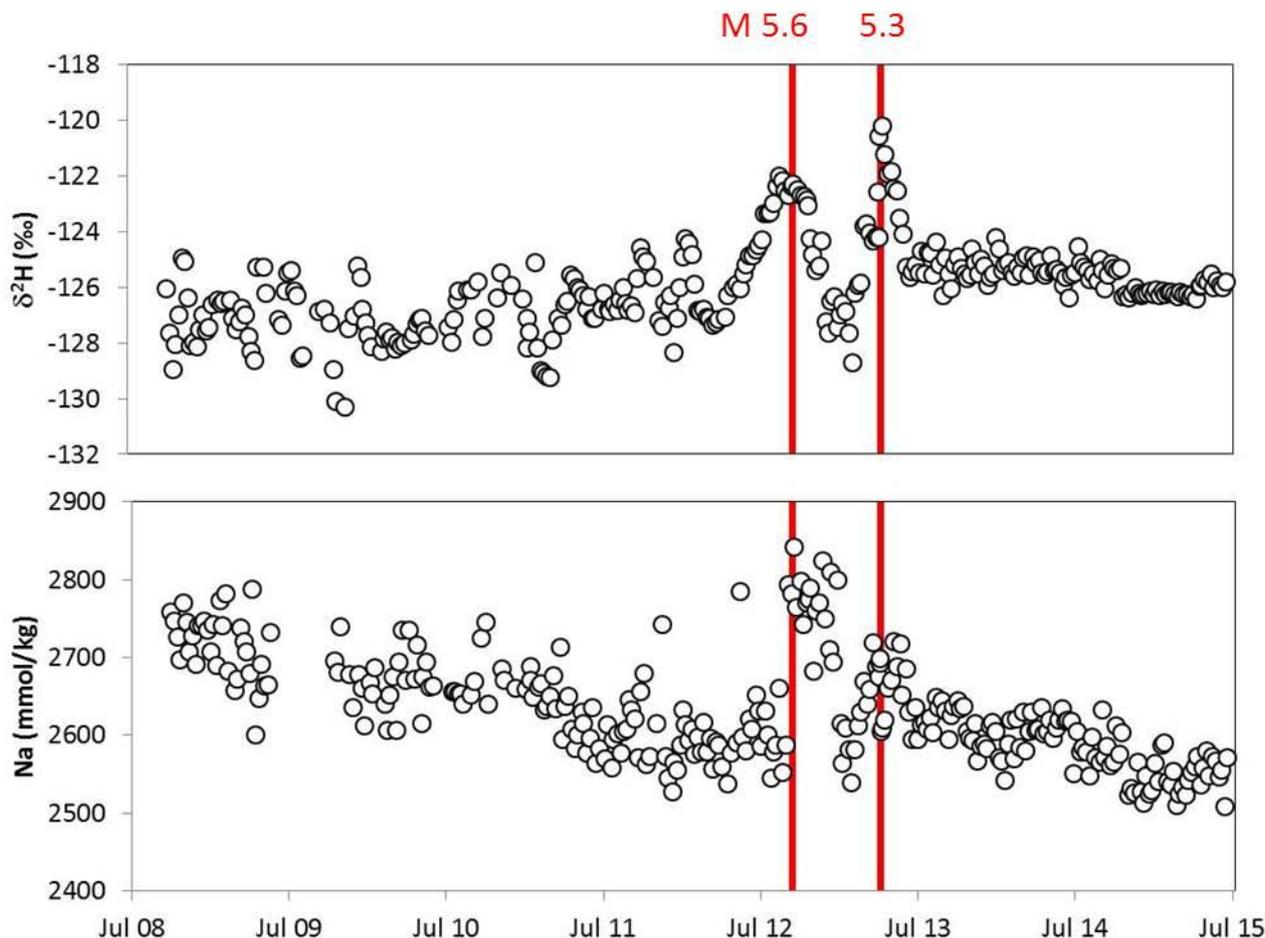


Fig. 1. Time series for $\delta^2\text{H}$ and Na concentration at Hafralækur from September 2008 to July 2015. 2σ errors are better than 1 ‰ for $\delta^2\text{H}$ and better than 50 mmol/kg for Na concentration.

The $\delta^2\text{H}$ maxima began six months before each earthquake and the Na maxima began two months before each earthquake. Skelton et al. (2014) used a Shapiro-Wilk normality test to show that these maxima are not part of a normal distribution (p-value < 10^{-6}) and a binomial test to show that these maxima did not occur randomly (p-value = 10^{-5}).

These maxima followed a four-year period during which 1) concentrations of Na, Si and Ca (Si and Ca are not shown) decreased, 2) K concentration (not shown) increased, 3) $\delta^{18}\text{O}$ values (not shown) decreased in a stepwise manner, with steps that sometimes correlated with smaller earthquakes, and 4) $\delta^2\text{H}$ values oscillated. The concentrations of Na, Si and Ca continued to decrease, whereas K concentration as well as $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values have been fairly constant since the earthquakes.

X-ray diffraction analysis of drill cuttings, recovered from borehole HA-04, which is adjacent to the borehole from which groundwater samples are taken (HA-01), revealed an inverse correlation between wt. % feldspar and wt. % zeolite, pointing to replacement of feldspars by zeolites at Hafralækur (Andrén et al., *in press*).

Petrographic analysis of these drill cuttings revealed evidence for constant volume replacement of labradorite by analcime (Fig. 2). This reaction, coupled with precipitation of zeolites in vesicles and

along fractures, is shown to be able to explain the observed decrease in the concentrations of Na, Si and Ca (Andrén et al., *in press*).

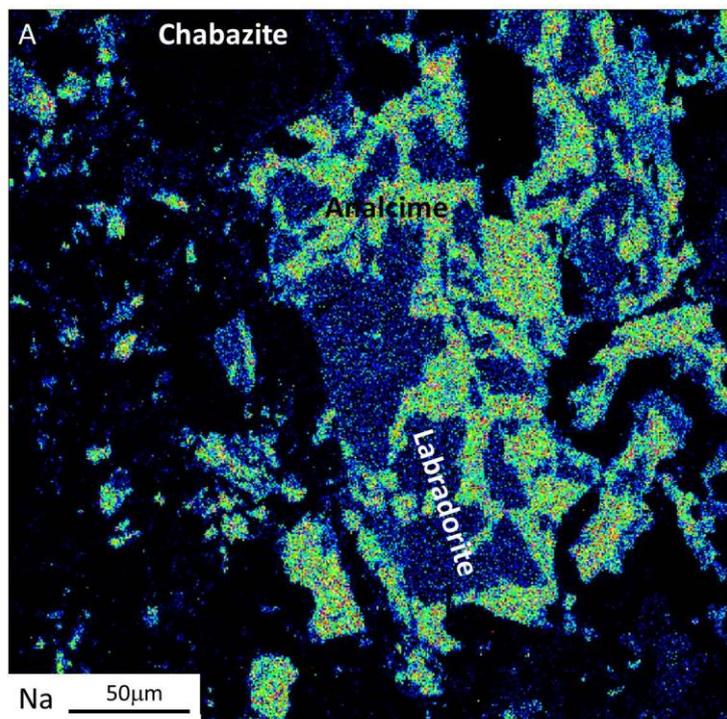


Fig. 2: Element map (for Na) showing evidence of patchy, constant volume replacement of labradorite (blue) by analcime (green) as well as precipitation of zeolites (e.g. chabazite, black).

Element mapping and profiling using an electron microprobe revealed evidence of non-stoichiometric Na loss from analcime alongside fractures (Figs. 2 and 3). This mechanism, which has been shown to occur experimentally (Savage et al., 2001), could explain Na maxima observed before earthquakes. Also, geochemical modelling using PHREEQCI confirms that analcime was close to saturation at most times in groundwater from Hafralækur (Andrén et al., *in press*).

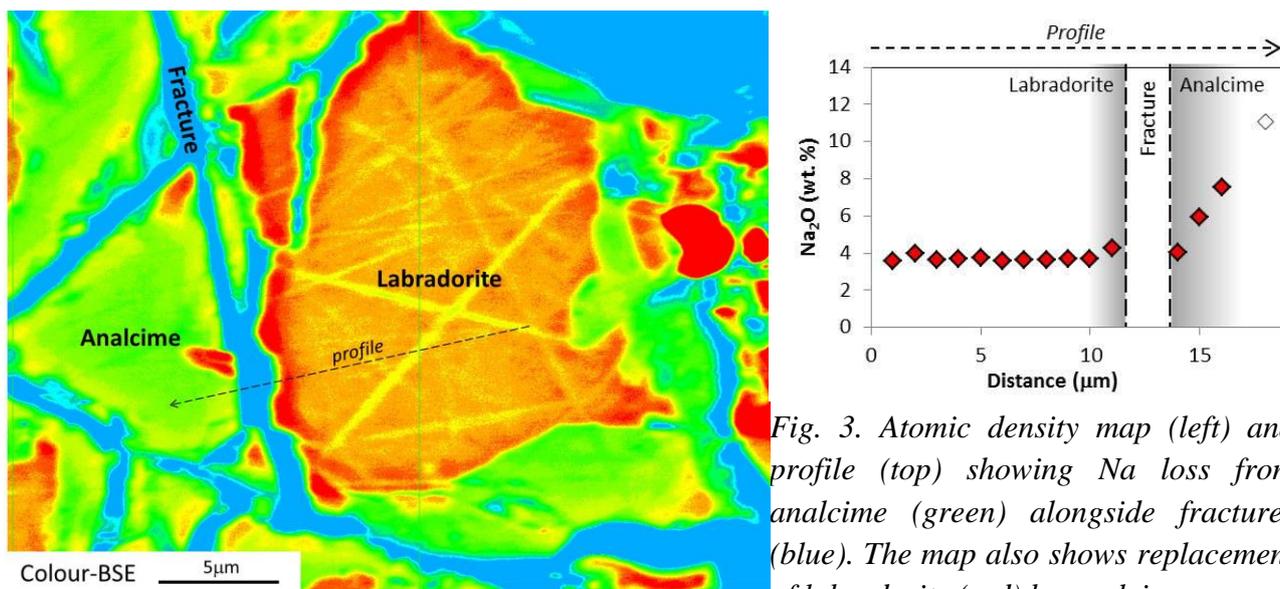


Fig. 3. Atomic density map (left) and profile (top) showing Na loss from analcime (green) alongside fractures (blue). The map also shows replacement of labradorite (red) by analcime.

The white marker shows the centre of the analcime crystal which contains less Na₂O than stoichiometric analcime (which contains 14 wt. % Na₂O).

In conclusion, we propose coupling between 1) non-stoichiometric loss of Na from analcime

alongside fractures, and 2) Na maxima in groundwater that are statistically associated with earthquakes. Based on the spatial association with fractures (Fig. 3), we infer that Na loss from analcime was in response to dilation. Based on the temporal association of Na maxima in groundwater with both earthquakes and that these maxima began two months before each earthquake (Fig. 1), we infer that dilation was associated with and began before each earthquake. This association could reflect a common cause unrelated to earthquakes (e.g. magma movement) or that dilation was a response to the build-up of stress before each earthquake. However, a plausible mechanism whereby pre-seismic dilation can occur so far from the focus of an earthquake remains to be discovered.

References

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