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Reservoir Tracer Test in the Krafla Geothermal Field using Conservative and Potentially Degrading Liquid-phase Tracers

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ABSTRACT

A reservoir tracer test was conducted in the Krafla geothermal field, NE Iceland, in summer 2016 as a part of the EU-FP7 funded project IMAGE (Integrated Methods for Advanced Geothermal Exploration). Three liquid-phase tracer compounds were injected into well K-39; two naphthalene sulphonate molecules (2,6-NDS and 2,7-NDS) which are reported to be thermally stable at temperatures exceeding 300°C but degrade at higher temperatures, and potassium iodide (KI) from which the iodide ion is presumed to be conservative. Tracer recovery was only observed in one out of five monitoring wells; well K-19. The first tracer breakthrough was observed within 26 hours of injection and the recovery peak about 15 days after injection. The fast tracer recovery shows that there is a strong connection between the two wells. One-dimensional convection-diffusion models were fitted to the measured concentration data, resulting in a good fit for all tracer types. The excellent correspondence of the calibrated parameters for all three tracers suggests that no thermal breakdown of two NDS compounds has occurred.

1. INTRODUCTION

Tracer tests are routinely conducted in geothermal systems to map flow paths in the subsurface and the structure of the geothermal system. In such tests an easily identifiable material is injected into the reinjection wells and the returns are monitored in the production wells over a period of several months. The results can be used to enhance the efficiency of energy extraction from the geothermal system and, thus, improve the economy of utilisation of the resource and sustainability. In general, the tracer returns can give information about connectivity patterns that may add to the understanding of the geological and hydrological structure of the geothermal reservoir. Such information can be used to locate new injection or production wells and refine reservoir modelling for a geothermal reservoir. Thus, the tracer test would in general have much practical value for future production plans and cost analysis for the geothermal areas.

The Krafla geothermal field in NE Iceland has been studied extensively since the early 1970s, with drilling of exploration wells starting in 1974 (Ármannsson at al., 1987). In 2008–2009, Landsvirkjun (National Power Company of Iceland) drilled the first of three deep wells proposed by the Iceland Deep Drilling Project (IDDP), well IDDP-1, into magma (Elders et al., 2014). In 2012 the well reached a temperature of 450°C during discharge. Super-hot conditions were also met in well K-39 in Krafla, where a temperature of 385°C was recorded in 2008 (Júlíusson et al., 2015). However, the IDDP-1 well has been cemented and well K-39 is presently used for reinjection. The currently producing part of the Krafla reservoir is expected to have sub-critical temperatures, i.e. not exceeding 374°C. Liquid phase tracing remains of major importance at Krafla and although several tracer tests have been performed there (e.g. Júlíusson et al., 2015), the combined use of a conservative tracer and potentially decomposing liquid tracers, i.e. the injection into the same well and at the same time of a mixture of both types of tracer, was never attempted.

In this contribution, a comparison is made of two different types of tracers; potassium iodide (KI), which does not thermally degrade and is assumed to be conservative, and two naphthalene sulphonate molecules (2,6-NDS and 2,7-NDS) which are reported to be thermally stable at temperatures exceeding 300°C but degrade at higher temperatures. The tracers were injected into the Krafla reservoir in summer 2016 as part of the EU-FP7 funded project IMAGE. A more comprehensive description of the execution of the tracer test as well as a discussion on the results after the initial 8 weeks of sampling are given by Gadalia et al. (2016).

2. SELECTION OF TRACERS

Among the required properties for tracers in high-temperature geothermal systems are that they are: environmentally safe, thermally stable, conservative (non-reactant, non-adsorptive in the field conditions), low cost (tracers and their analyses), easily soluble in hot water (or in another solvent that is, itself, soluble in water), detectable at very low concentrations (preferably in the low ppb or sub-ppb range), and either absent from or at very low concentrations in the investigated geothermal fluids.

2.1 Naphtalene Sulphonates

Largely based on the work of Peter Rose, polyaromatic sulphonic acids, are now classically implemented in geothermal fields (e.g. Rose et al., 2001; Rose et al., 2009; Mountain and Winick, 2012; Júlíusson et al., 2015; Kristjánsson et al., 2016). As liquid phase tracers, they will remain in the liquid but be absent from the vapour phase. The thermal resistance of 2,6- and 2,7-naphthalene disulphonic acids (Fig. 1) was tested (Mountain and Winick, 2012) up to a temperature of 340°C in Rotakawa (New Zealand). Due to the earlier use of NDS compounds in Krafla, their background concentrations in the reservoir were measured, as was done before the 2013-2014 tracer test (Júlíusson et al., 2015). Thermal degradation of NDS molecules in the Krafla geothermal reservoir may be inferred from the test carried out in 2009 (Ásmundsson et al., 2014) and justifies the use of an additional reference tracer.

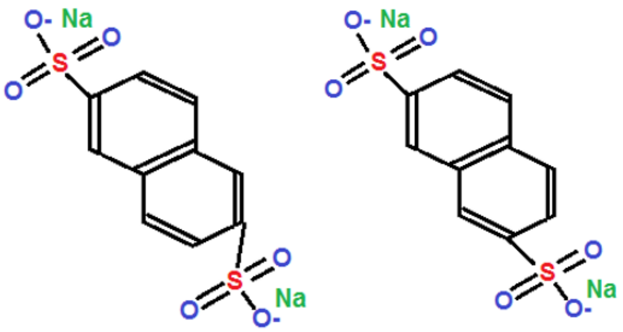

Figure 1: Structural formulae of 2,6-NDS (left) and 2,7-NDS (right).

2.2 Potassium Iodide

As the Krafla field may reach very high temperatures and impact the NDS molecules, potassium iodide, as a supposed conservative tracer, was added. Here also, attention will be paid to the background concentrations as (i) the reservoir is known to be heterogeneous and (ii) it has already been used twice at Krafla within the last 20 years. The limited returns from the 2005-2007 tracer test, suggest that the background levels should not be very high. According to the previous tracer test which used potassium iodide the background concentrations ranged between 5 and 15 µg/L (Ármannsson et al., 2009) but higher variable values were obtained for wells K-33 and K-21 (Fig. 2). Another advantage of using iodide would be the possibility to estimate its concentration on site just after the sampling, using an electrochemical device (ionometer and associated specific iodide electrode). The ionometer was supposed to estimate the potential signal, but could hardly give absolute values for samples having concentrations lower than 10 ppb (likely baselines of several parts of the Krafla reservoir (Fig. 2; Ármannsson et al., 2009). However, due to interference from high sulphide concentrations in the samples, no reliable results were obtained from the field measurements.

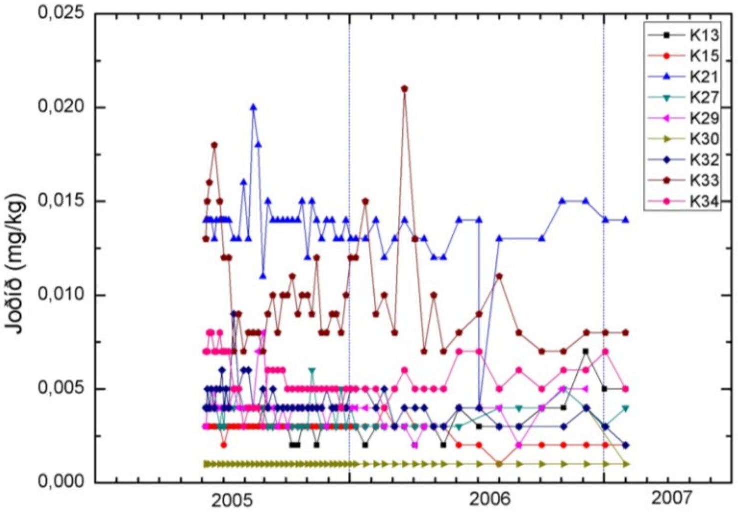

Figure 2: Iodide concentration monitored during the 2005–2007 tracer test (from Ármannsson et al., 2009).

3. SELECTION OF INJECTION AND MONITORING WELLS

Well K-39 was selected as the injection well. It was drilled in 2008 from Leirbotnar to the ESE and the bottom of the well reaches the Suðurhlíðar area basement (Fig. 3). Its initial depth was 2848 m, but a 240 m cement plug was placed in the bottom as it was believed to have hit a magma body. The initial temperature of the well, before plugging, exceeded 350°C but now the temperature of the well has significantly decreased as water at 126°C has been injected into the well since 2013. Well K-39 intersects 3 feed zones: at approximately 800 m, 1000 m and 1320 m below sea level.

The wells to be monitored were selected according to two main criteria: (i) the specific enthalpy (h) must be low enough to get a liquid phase as only liquid tracers are monitored, (ii) a wide geographical distribution within the field to obtain as much information as possible on the paths followed by the tracers.

The monitoring wells selected: K-06 (h ~ 1300 kJ/kg), K-17 (h ~ 2400 kJ/kg), K-19 (h ~ 1700 kJ/kg), K-33 (h ~ 2300 kJ/kg), and K-34 (h ~ 2500 kJ/kg). Four out of the five selected wells (K-17, K-19, K-33 and K-34) have excess enthalpy, i.e. higher enthalpy than corresponds to the saturated liquid enthalpy at the reservoir temperature and produce vapour-rich fluids (vapour fraction at sampling > 50%). For this reason, the liquid phase is easily contaminated by condensed vapour in the separator and great care is needed when sampling liquid from the wells.

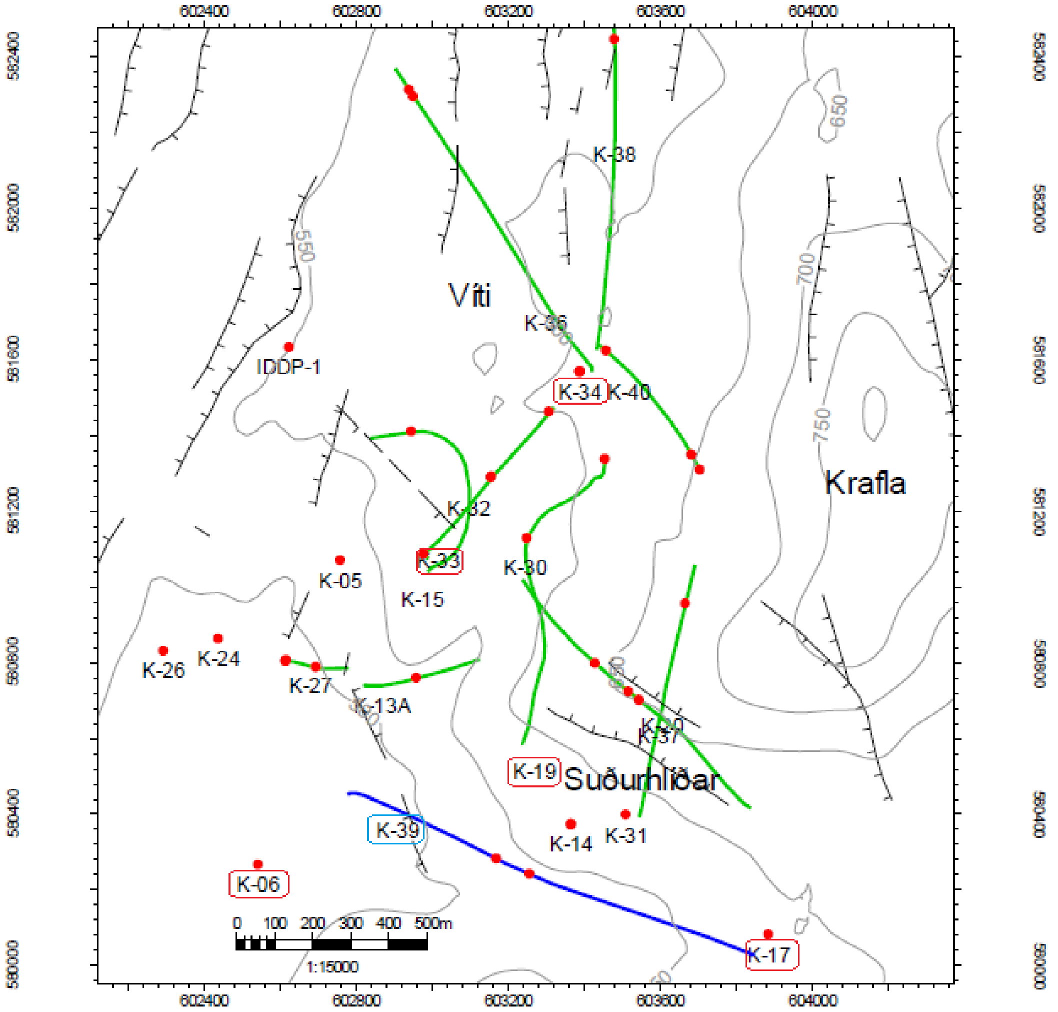

Figure 3: Map of Krafla showing well locations and tracks of directional wells (K-39 in blue, other wells in green). The main feed zones of each well are identified with red dots (modified from Júlíusson et al., 2015). The names of selected injection and monitoring wells are surrounded in light blue and red, respectively.

4. TRACER MIXING AND INJECTION

Based on results from previous tracer tests and solubility experiments, it was decided to use 200 kg of each tracer, and dissolve all in 5000 L of hot water. The tracer compounds were purchased from Yick-Vic Chemical and Pharmaceuticals, Hong-Kong, Ltd., which reported the level of purity of the selected tracers as higher than 96% for 2,6-NDS and higher than 98% for 2,7-NDS and KI.

To minimise contamination risk, the people who carried out the tracer mixing and injection were not involved in sampling and/or analysis of the tracers. Contact between the mixing/injection people and sampling/analysing people was also avoided for several days after tracer injection.

The mixing and injection operation were performed by ÍSOR staff on 21st June 2016, in the nearby Bjarnarflag facilities (several km from Krafla). The process is described in more detail by Hersir and Vilhjálmsson (2016). The operators used disposable suits and gloves, boots being carefully cleaned after injection. Drums of tracer salts (NDS and KI) were carefully opened above both the mixing tanks. First, 100 kg of 2,6-NDS and 100 kg of 2,7-NDS were dissolved in each 2500 L tank containing hot tap water (>70°C). Then 100 kg of potassium iodide were dissolved into each of the same 2500 L tanks. An electric stirrer was used to facilitate the mixing. The mixing, as a whole, lasted from 15:00 to 18:00. All the waste (disposal suits and gloves, drums) was packed into plastic waste bags. The trailer and the outside of the tanks were thoroughly cleaned with water before leaving the mixing site. Then both the 2500 L tracer mixture tanks were moved to the well pad of K-39 together with two other 1000 L tanks of tap water: one for a first injection volume to check if everything worked well, another to clean the facilities which were used for the injection (tanks, pipes, pumps, valves) and to rinse down possible remaining tracer solids.

The same injection skid as in the 2013 tracer test (Júlíusson et al., 2015) was used, albeit restricted to liquid tracers: they were injected from both the 2500 L tanks through a centrifugal pump. Injection of the tracer mixture started at 19:18 after an injection of 1000 L of tap water. It ended at 20:22, after injecting 5085 L of tracer mixture. The cleaning of the tanks, pipes, pumps, valves, was followed by 1500 L of tap water that were injected into well K-39. The operation was completed at 21:30.

5. SAMPLE COLLECTION AND ANALYSIS

Sampling was carried out by staff from BRGM, ÍSOR, CNR and Landsvirkjun. Liquid samples were collected from the five monitoring wells, initially four times a day in week 1 and then with decreasing frequency down to one sample a day in week 3, and three samples per week until week 8. Additionally, well K-19 was sampled 1-2 times a month for six more months, until February 2017. The two-phase fluid was collected at wellhead pressures from 10.3 to 10.8 bar-g (depending on the well) and separated using portable Webre separators connected to sampling valves at the wellhead. The liquid and the vapour phases can then be sampled separately. A cooling system was installed downstream of the separator made of a ¼" steel cooling spiral which was immersed in a barrel of water. A 1" exhaust hose was added to rapidly evacuate the vapour phase from the separator and to prevent H_2S accumulation in the wellhead hut. One separator was used for each well in order to minimise contamination between wells.

The samples were collected into two 60 mL HDPE bottles according to standard geothermal sampling methods, without any treatment besides cooling. One bottle was sent to each laboratory for analysis (2,6-NDS and 2,7-NDS to the ÍSOR lab and KI to BRGM). Prior to the injection of tracers, background samples were collected in order to estimate the baseline level of each tracer in the geothermal fluid, including a sample of the fluid injected into K-39 after passing through the power plant process.

For the initial 8 week sampling period, analysis for total iodine concentration was carried out at the BRGM laboratory using ICP-MS. The ICP method has a detection limit for iodine of about 1 µg/L. For the samples collected from K-19 later than 8 weeks after injection, iodide ion (I^-) concentration was determined by suppressed ion chromatography at the ÍSOR laboratory. The detection limit of the method is about 10 µg/L. The naphthalene sulphonate isomers were analysed at the ÍSOR laboratory using HPLC with a fluorescence detector and a detection limit of 0.1 µg/L (method modified from Rose et al., 2001). As many of the samples were mixed to some extent with condensed vapour, the chloride concentration of each sample was determined by ion chromatography at the ÍSOR laboratory and used to assign a correction factor for each sample based on the established Cl concentration of the uncontaminated liquid phase from the well, at the sampling pressure. This correction factor was used to calculate the tracer concentration in uncontaminated liquid phase.

6. RESULTS

6.1 Chemical Analysis

As previously noted, wells K-06, K-17, K-33 and K-34 were sampled according to the predefined schedule for 8 weeks only. During that time no naphthalene sulphonate tracers were observed in the wells and the measured iodine concentrations did not change from the background levels, which were quite different for different parts of the field; ranging from 1 to 2 µg/L in wells K-06 and K-17, and from 4 to 6 µg/L in wells K-33 and K-34.

Well K-19 was also sampled according to the schedule for 8 weeks, but as all three tracers had been observed in the well fluid by that time, it was decided to carry on sampling the well for another 6 months, first twice and later once per month. Due to difficulties encountered with sampling, the first samples collected from the well are strongly contaminated by condensate (up to 90%) and therefore the exact breakthrough time is somewhat uncertain. However, it is clear that all three tracers were observed in samples collected from the well about 26 hours after injection (at 22:12 on 22nd June). The condensate-corrected tracer concentration in samples from well K-19 are shown in Figure 4. The concentrations are reported as mass of the Na-salts of the sulphonic acids and as KI, although the analyses are carried out for the sulphonic acid molecules and iodine/iodide only.

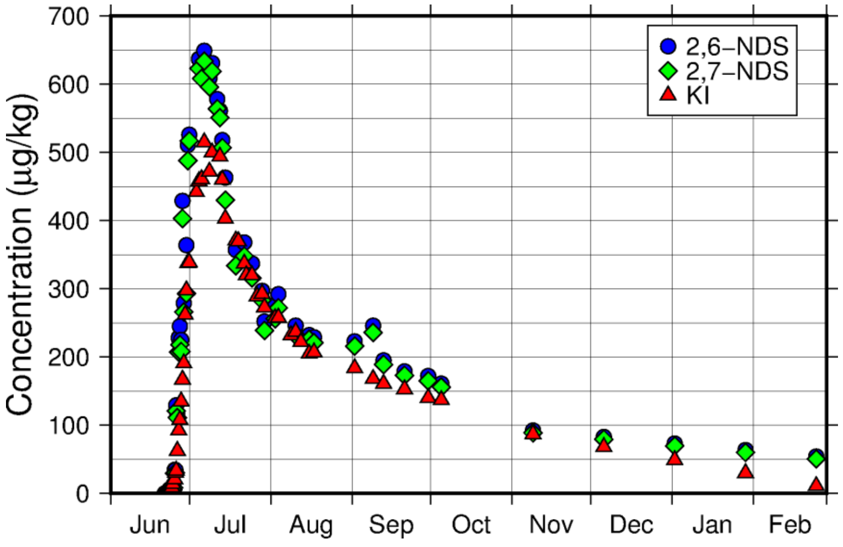

Figure 4: Corrected tracer concentration in liquid samples from well K-19 in 2016-2017, collected at about 10.8 bar-g.

The figure shows that the recovery curves are quite similar but not identical for all three tracers. The peak shapes are not very sharp, especially for KI. The NDS peak can be identified within the frame between 5th and 9th July, about 14-18 days after the injection time (Fig. 4). The KI peak is of somewhat lower amplitude (520 vs. 650 µg/L) and is reached between 6th and 11th July, i.e. about 15-20 days after the injection time (Fig. 4). Also, the NDS tail concentrations are higher than for KI, which approaches zero faster.

6.2 Flowpath Analysis

We simulate the flow of the tracers between well K-39 and well K-19 with the following 1D convection-dispersion model

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{C}{t}. \tag{1}$$

Here C (kg/m^3) is the concentration of the tracer in the flow channel, x (m) the length along the channel, t (s) time, u (m/s) the average flow velocity through the channel and D the dispersion coefficient. The average flow velocity through the channel can be written as

$$u = \frac{q}{\rho A\phi} \tag{2}$$

where ρ=799 kg/m^3 is the density of the fluid in the channel, A (m^2) the cross-sectional area of the channel, ϕ the porosity, and q=72.6 kg/s is the injection rate. Note that only a portion of the reinjection fluid finds its way to each of the flow channels. The rest is assumed to flow to other parts of the geothermal system, or even out of the system. We assume that molecular diffusion is negligible and the dispersion coefficient can therefore be written as $D = \alpha_L u$, where α_L (m) is the diffusivity.

The tracer concentration is measured in the production wells at the end of the flow channels. We are therefore interested in the solution of Equation (1) at x = L, where L is the length of the channel. To simplify, we assume that the tracers are not lost or destroyed within the flow channels. This is equivalent to $cQ = Cq$, where Q=1.9 kg/s is the flow rate from the production well and c (kg/m^3) is the measured concentration of the tracers at the production wells. We also assume that the tracer mass m (kg) enters immediately into the flow channel at time t = 0 s. Note that m is always less than M=200 kg, the total mass of the tracer material of each tracer type injected into the injection well. This corresponds to a Dirac-delta initial condition at x=0 for which Equation (1) has the following solution

$$c(t) = \frac{um\rho}{Q}\frac{1}{2\sqrt{\pi D t}}e^{-\frac{(L-ut)^2}{4Dt}}. \tag{3}$$

There may be more than one channel between a reinjection well and a production well. In the current case, well K-39 has 3 identified feed zones at depths 800 m b.s.l., 1000 m b.s.l., and 1340 m b.s.l., which the tracers can enter into the flow channels and well K-19 has one identified feed zone at 980 m b.s.l. which the tracers can exit out of the flow channel. By assuming the channels are straight structures that connect the feed zones of the injection well to the feed zone of the production well, we have three channels with lengths L=338 m, L=313 m, and L=533 m. As two of these channels have very similar length we make the simplification that there are effectively only two channels. We refer to these channels as channel 1 with length L=326 m and channel 2 with length L=533 m. The coefficients D, u, m are estimated by a nonlinear regression analysis from the corrected tracer concentration values at the production wells. For this we used the TR program that is found in the inhouse software package ICEBOX at ÍSOR.

We can estimate the representative volume of each channel by

$$V_x = L(A\phi), \tag{4}$$

where the representative cross sectional area of the flow through the channel, $A\phi$, is calculated from Equation (2). We can get an estimate of how dispersive the flow is through the channels via the Péclet number. The Péclet number is defined as the ratio of advective transport rates against dispersive transport rates, which for mass transfer is

$$Pe = \frac{Lu}{D} = \frac{L}{\alpha_L}. \tag{5}$$

The numerical values of the parameters produced by the calibration can be found in Table 1. The calibrated parameters are in good agreement between different tracer flow models; with only a slight discrepancy between the KI tracer and the 2,6-NDS and 2,7 NDS tracers. This demonstrates that effectively the same flow path results are achieved for all the three tracers.

Table 2. Numerical values of the calibrated parameters for the flow models of the KI, 2,6-NDS and 2,7-NDS tracers.

	KI		**2,6-NDS**		**2,7-NDS**	
	Channel 1	**Channel 2**	**Channel 1**	**Channel 2**	**Channel 1**	**Channel 2**
u [10^{-4} m/s]	0.45 ± 0.03	3.3 ± 0.2	0.42 ± 0.04	3.6 ± 0.2	0.42 ± 0.04	3.6 ± 0.2
α_L [m]	70 ± 20	110 ± 10	60 ± 20	110 ± 10	60 ± 20	110 ± 10
m [kg]	4.5 ± 0.5	2.9 ± 0.3	5.7 ± 0.9	3.5 ± 0.4	5.4 ± 0.9	3.3 ± 0.3
F [%]	2.3	1.5	2.9	1.8	2.7	1.7
Aϕ [m^2]	45.9	4.03	61.9	4.38	57.8	4.16
t_{max} [days]	72.3	15.0	72.3	14.0	72.3	14.0
V_x [m^3]	15000	2150	20200	2330	18800	2220
Pe [-]	4.7	5.0	5.0	4.8	5.4	5.1

The concentration curve for each tracer as predicted by the calibrated models can be seen in Figure 5 plotted with the corrected measured concentration values. The model closely reproduces the corrected measured values. Also, in Figure 6 the contribution from each of the effective channels is plotted. The greatest consistency in the fitting of the models for the three tracer types was achieved when channel 2 provided the bulk of the contribution to the concentration peaks centered after two weeks and channel 1 made the bulk contribution to the tails.

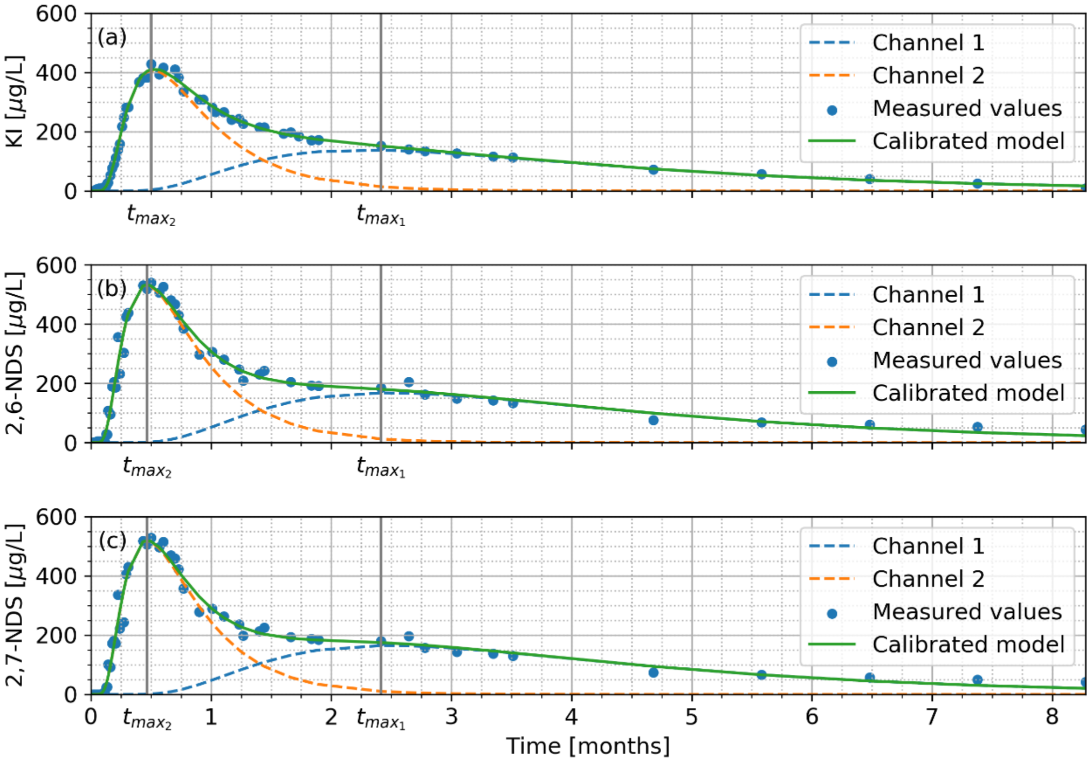

Figure 7. Concentration calculated by the calibrated flow models compared to the measured concentration values for (a) the KI tracer, (b) the 2,6-NDS tracer, and the 2,7-NDS tracer. The contribution for each of the two channels used in the models are shown as dashed lines and the time of peak concentration (t_{max}) in each channel is marked by vertical lines.

6.3 Comparison with the 2013-2014 Tracer Test

In the 2013-2014 tracer test in Krafla (Júlíusson et al., 2015) three tracers were injected into well K-39: 2,6-NDS, methanol which follows both phases and perfluoromethylcyclohexane (PMCH) which partitions into the vapour phase. However, as discussed by Júlíusson et al. (2015), the only tracer measured in K-19 was the vapour phase tracer PMCH which reached the peak concentration in about 7 weeks. Therefore, the 2,6-NDS which showed clear returns in 2016 must have had a different fate altogether in 2013. Possible causes are: (i) thermal degradation due to higher reservoir temperature near well K-39 after a shorter period of injection into the well, (ii) phase segregation in the producing aquifer due to the high enthalpy of the well in 2013, (iii) problems with sampling the liquid phase in 2013 also due to high discharge enthalpy, or (iv) that the geothermal fluid followed a different flow path due to a different temperature-pressure regime in the reservoir at the time. However, as confirmed by the recovery of PMCH in well K-19 in the 2013-2014 tracer test, there certainly was a fluid connection from the well to K-39 at the time.

These changes in the well or the reservoir, are probably due to injection into well K-39, which started in 2013. Two explanations for this are considered most probable, and it is not unlikely that both contribute to the changes observed. The first is that due to higher temperature of the reservoir rocks in 2013-2014, the naphthalene sulphonate tracer injected into K-39 completely decomposed before reaching well K-19. The other is that during the 2013-2014 tracer test, well K-19 produced almost dry vapour and due to the high aquifer vapour fraction, the relative mobility of the liquid phase was very low compared to the vapour phase mobility (Preuss, 2002) and thus, the majority of the liquid phase was retained in the formation and did not reach the wellbore.

Both processes are expected to have been affected by reinjection of power plant effluent into well K-39 from 2013 to 2016. Firstly, the reinjection (at a temperature of 126°C) will have cooled the reservoir rocks somewhat and therefore decreased the probability of thermal degradation of the NDS molecules. Secondly, increasing reservoir pressure due to reinjection into well K-39 has lowered the enthalpy of the feeding aquifer of K-19, so that it no longer boils in the formation, resulting in a higher liquid fraction at the well head. This is apparent from Figure 6, which shows the measured discharge enthalpy of the well in the years 2012-2018. The enthalpy clearly drops from almost dry vapour enthalpy (>2600 kJ/kg) in 2012 and 2013 down to about 2000 kJ/kg in 2014 before further dropping and stabilising at around 1700 kJ/kg in 2016 and 2017. No temperature logs have been measured in well K-19 since before 2000 due to a restriction in the wellbore.

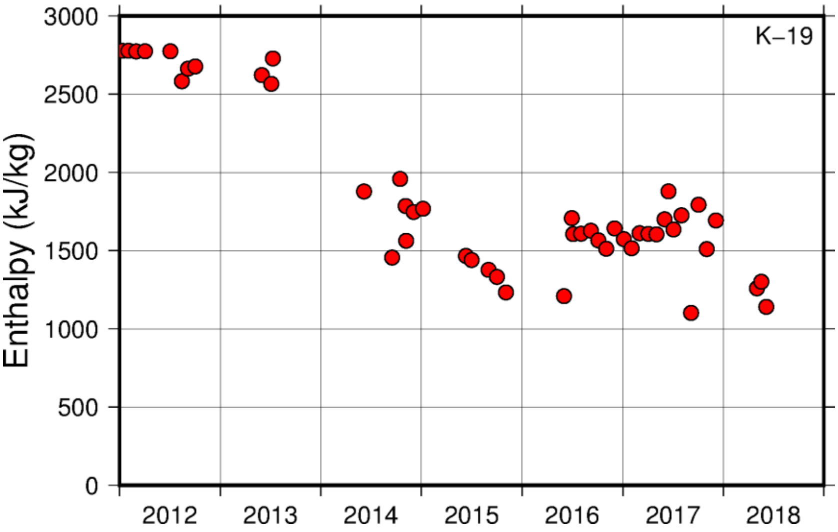

Figure 8: Measured enthalpy of well K-19 from 2012 to 2018.

Júlíusson et al. (2015) used the recovery curve for PHCH to calculate the volume and Péclet number for the flow path between K-39 and K-19, and found values of 8985 m^3 and 2.2, respectively. The estimates based on the current study for V_x range from 15000 m^3 to 20200 m^3 for channel 1 and from 2150 m^3 to 2330 m^3 for channel 2. The calculated Péclet number is close to 5 for both channels, which is somewhat larger than the values of Júlíusson et al. (2015). The calculated recovery of the three tracers in the current study is 3.8% for KI, 4.4% for 2,7-NDS and 4.7% for 2,6-NDS, whereas the calculated recovery of PMCH in 2013 was 2.2%.

7. CONCLUSIONS

Three tracer compounds were injected into well K-39 in Krafla in 2016 as part of the EU-funded IMAGE project (Gadalia et al., 2016). Two of the compounds were sodium salts of naphthalene sulphonic acids, which have been widely used in geothermal systems but are assumed to suffer thermal degradation at temperatures in excess of 340°C, and the third was the assumedly thermodynamically stable potassium iodide.

Five monitoring wells were selected based on their location and enthalpy, but only one of the wells, K-19, showed tracer returns during the initial two month sampling period. After the first two months, sampling from the other monitoring wells was discontinued but K-19 was sampled for additional six months. The monitoring of the five wells displayed that despite earlier tracer tests employing NDS compounds (in 2009 and 2013) the NDS background remained below the quantification threshold (0.1 µg/L) whereas the iodine background was relatively variable (from <0.9 to 6 µg/L). The background concentrations did not disturb the detection of iodine. However, those variations are interpreted as a result of the reservoir heterogeneity.

In K-19, the first detection of tracers occurred less than 26 h after the injection time. An uncertainty remains on those breakthrough values due to a significant (up to 90%) dilution of the samples with condensate during this first period of sampling so that these time periods may be shorter. To correct for sample dilution, chloride was measured in all samples and a dilution factor calculated based on the measured and expected chloride concentrations. The occurrence of the tracer peaks is more constrained although the shapes of the peaks are not very sharp.

A comparison of the tracer return curves for potassium iodide and the two NDS compounds in K-19 suggests no thermal breakdown of the latter. This is contrary to the results of the 2013-2014 tracer test (Júlíusson et al., 2015) in which no 2,6-NDS from well K-39 was observed in K-19, whereas the vapour-phase tracer PMCH showed a clear connection between the wells. This was taken as a sign of thermal breakdown of 2,6-NDS. This may result from a possible cooling of this part of the geothermal reservoir, resulting in less or no thermal degradation of the NDS molecules, a decrease in enthalpy of well K-19 yielding a higher liquid fraction in the well, or both.

One-dimensional convection-diffusion models were fitted to the measured concentration data, resulting in a good fit for all tracer compounds. The calibrated parameters show excellent correspondence between each of the tracer models. This corroborates that all the tracers give the same result when interpreting the tracer tests and suggests that no thermal breakdown of two NDS compounds has occurred. The values for the tracer recoveries, representative volumes and Péclet numbers for the current study are somewhat higher than those calculated by Júlíusson et al. (2015), based on PMCH recoveries.

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