

## Tracer testing at the Habanero EGS site, central Australia

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### ABSTRACT

The Habanero Engineered Geothermal System (EGS) in central Australia has been under development since 2002, with several deep (more than 4000 m) wells drilled into the high-heat-producing granites of the Big Lake Suite to date. Multiple hydraulic stimulations have been performed to improve the existing fracture permeability in the granite. The stimulation of the newly-drilled Habanero-4 well (H-4) was completed in late 2012, and micro-seismic data indicated an increase in total stimulated reservoir area to approximately 4 km<sup>2</sup>. Two well doublets have been tested, initially between Habanero-1 (H-1) and Habanero-3 (H-3), and more recently, between H-1 and H-4. Both doublets effectively operated as closed systems and excluding short-term flow tests, all production fluids were re-injected into the reservoir at depth. Two inter-well tracer tests have been conducted since 2008, to evaluate the fluid residence time in the reservoir alongside other hydraulic properties, and to provide comparative information to assess the effectiveness of the hydraulic stimulations. The closed-system and discrete nature of this engineered geothermal reservoir provides a unique opportunity to explore the relationships between the micro-seismic, rock property, production and tracer data.

The most recent inter-well tracer test occurred in June 2013, which involved injecting 100 kg of 2,6 naphthalene-disulfonate (NDS) into H-1 to evaluate the hydraulic characteristics of the newly-created H-1/H-4 doublet. Sampling of the production fluids from H-4 occurred throughout the duration of the 3-month closed-circulation test. After correcting for flow hiatuses (i.e. interruptions in injection and production) and non-steady-state flow conditions, tracer breakthrough in H-4 was observed after 6 days (compared to ~4 days for the previous H-1/H-3 doublet), with peak breakthrough occurring after 17 days. Applying moment analysis to the data indicated that approximately 56% of the tracer was returned during the circulation test (vs. approximately 70% from the 2008 H-1/H-3 tracer test). This suggests that a considerable proportion of the tracer may lie trapped in the opposite end of the reservoir from H-4 and/or may have been lost to the far field. Flow capacity:storage capacity plots derived from the H-1/H-4 tracer test indicate that the Habanero reservoir is moderately heterogeneous, with approximately half of the flow travelling via around 25% of the pore volume. The calculated inter-well swept pore volume was approximately 31,000 m<sup>3</sup>, which is larger than that calculated for the H-1/H-3 doublet (~20,000 m<sup>3</sup>). This is consistent with the inferred increase in reservoir volume following hydraulic stimulation of H-4.

### 1. INTRODUCTION

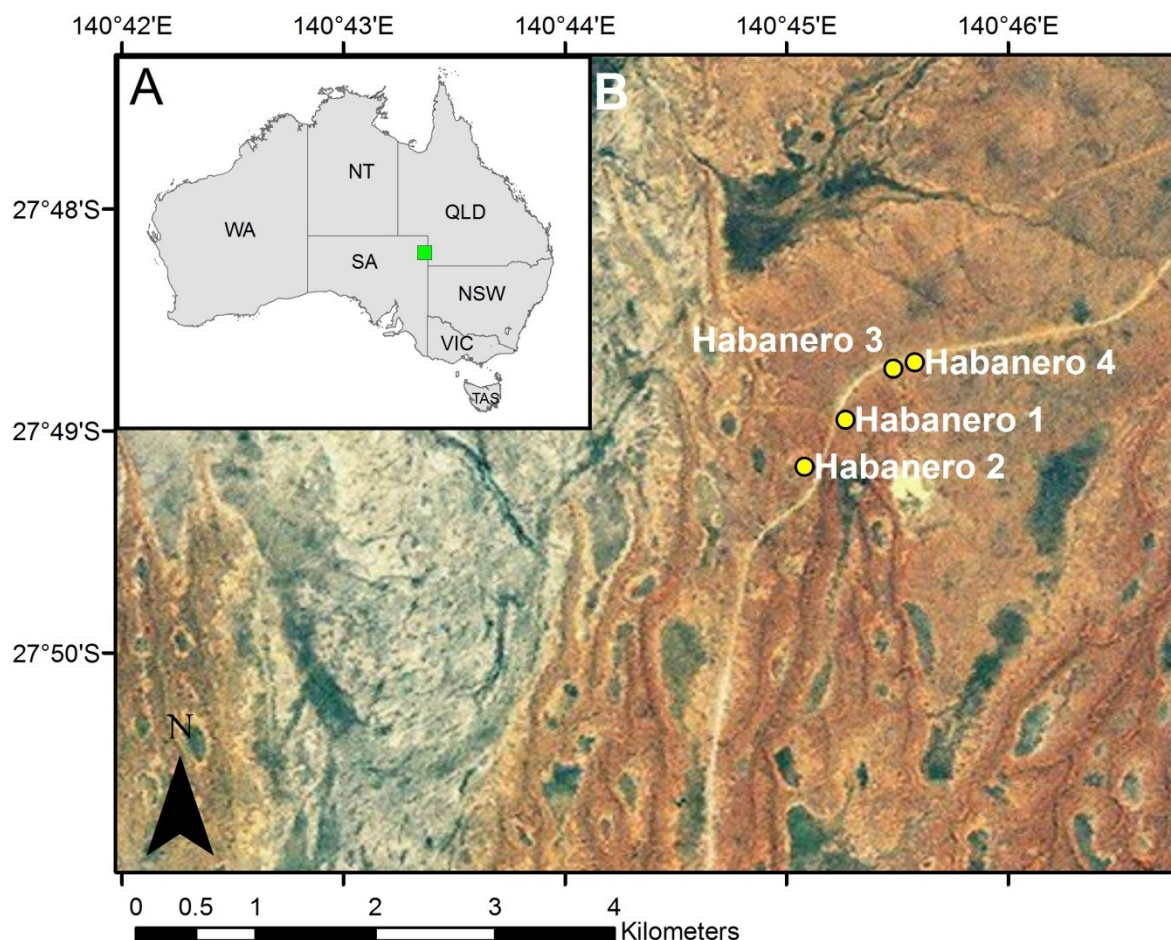
The Habanero Engineered Geothermal System (EGS) project in central Australia has targeted a conductive-style geothermal resource, where high-heat-producing granites of the Big Lake Suite are overlain by a thick (>3500 m) sedimentary package (the stacked Cooper, Eromanga and Lake Eyre basins) that provides sufficient thermal insulation to trap the radiogenic heat, resulting in temperatures above 244°C at depths less than 5 km (Wyborn, 2012; Hogarth et al., 2013). Development of the project began in 2002, and Geodynamics Limited demonstrated proof-of-concept in September 2013 through sustained operation of a 1 MWe pilot plant at surface (Mills and Humphreys, 2013). The reservoir for the engineered system is within the large granite plutons of the Big Lake Suite, which are intersected at depths of between 3600 and 3800 m in the Innamincka area (Wyborn, 2012). Since 2002, several deep (> 4000 m) wells have been drilled that have encountered over-pressured (reservoir pressure approximately 73 MPa) brines in pre-existing fractures within the granite (Wyborn, 2012). Four wells have been drilled at the Habanero site – Habanero-1 (H-1), Habanero-2 (H-2), Habanero-3 (H-3), and Habanero-4 (H-4) (Figure 1). Two other deep wells have been drilled: Jolokia-1 (located ~10 km to the west of the Habanero wells); and Savina-1 (~20 km west of the Habanero wells). Multiple hydraulic stimulations have been performed at Habanero to improve the existing fracture permeability in the granite and create a reservoir that enables appropriate heat-exchange with the surrounding granite, and sufficient fluid-flow between injection and production wells (McMahon and Baisch, 2013). Currently, the total stimulated area is on the order of 4 km<sup>2</sup>, as has been mapped from micro-seismic monitoring during and after the successive hydraulic stimulations. Current understanding is that the stimulations have reactivated existing fractures in an interpreted paleo-fault zone in the granite that is on the order of five metres thick, and dips sub-horizontally to the south-south west (Figure 2; Hogarth et al., 2013).

Geochemical tracers have been used for many years to improve the understanding of reservoir dynamics in geothermal systems. They are commonly used to map flow pathways between injection and production wells in a geothermal field, to monitor the effects of reinjection and identify wells that might experience premature thermal breakthrough if not carefully managed. Tracer tests can also provide information about reservoir fluid residence time, fluid recharge location or direction, swept pore volumes, inter-well connectivity, temperatures, fracture surface area, flow-storage capacity relationships and volumetric fluid sweep efficiencies. In addition, tracer data can be used with numerical transport codes to help validate 2D or 3D reservoir models. Thus, tracer tests can provide powerful insight into geothermal reservoir characteristics, and they can be performed at many stages of project development, from small-scale demonstration projects (e.g. an injection-production well doublet) through to large-scale commercial fields (e.g. Wairakei, New Zealand). The Habanero EGS project provides an opportunity to examine tracer dispersion in a

constrained, relatively small, relatively ‘closed’ reservoir where fluid flow is predominantly controlled by pumping at surface (cf. a natural convective system). Moreover, tracer testing at this site offers the ability to compare estimates of reservoir (pore) volume obtained from numerical modelling and history matching (refer to Llanos et al., 2015) with maps of micro-seismic events associated with hydraulic stimulations.

The first inter-well tracer test was conducted at the Habanero EGS site in late 2008: this test involved the injection of 100 kg of 1,3,5-naphthalene trisulfonate (NTS) and 50 kg of fluorescein into H-1 and monitoring the returns of these tracers in H-3. After correcting for breaks in injection and production, this test indicated that the first tracer breakthrough occurred after 4 days, and total swept pore volumes on the order of 18,500 m<sup>3</sup> (Yanagisawa et al., 2009; Yanagisawa et al., 2010).

The H-4 well was drilled in 2012 following the abandonment of H-3 due to a casing failure and subsequent well blow out (Wyborn, 2012), and it was used as the production well in the H-1/H-4 doublet. An inter-well tracer test was conducted within this new doublet in June 2013, to determine fluid-flow patterns during flow back of H-4 and during the closed-loop circulation test between the H-1 and H-4 wells. This paper reports these new results and discusses the implications for the Habanero reservoir.



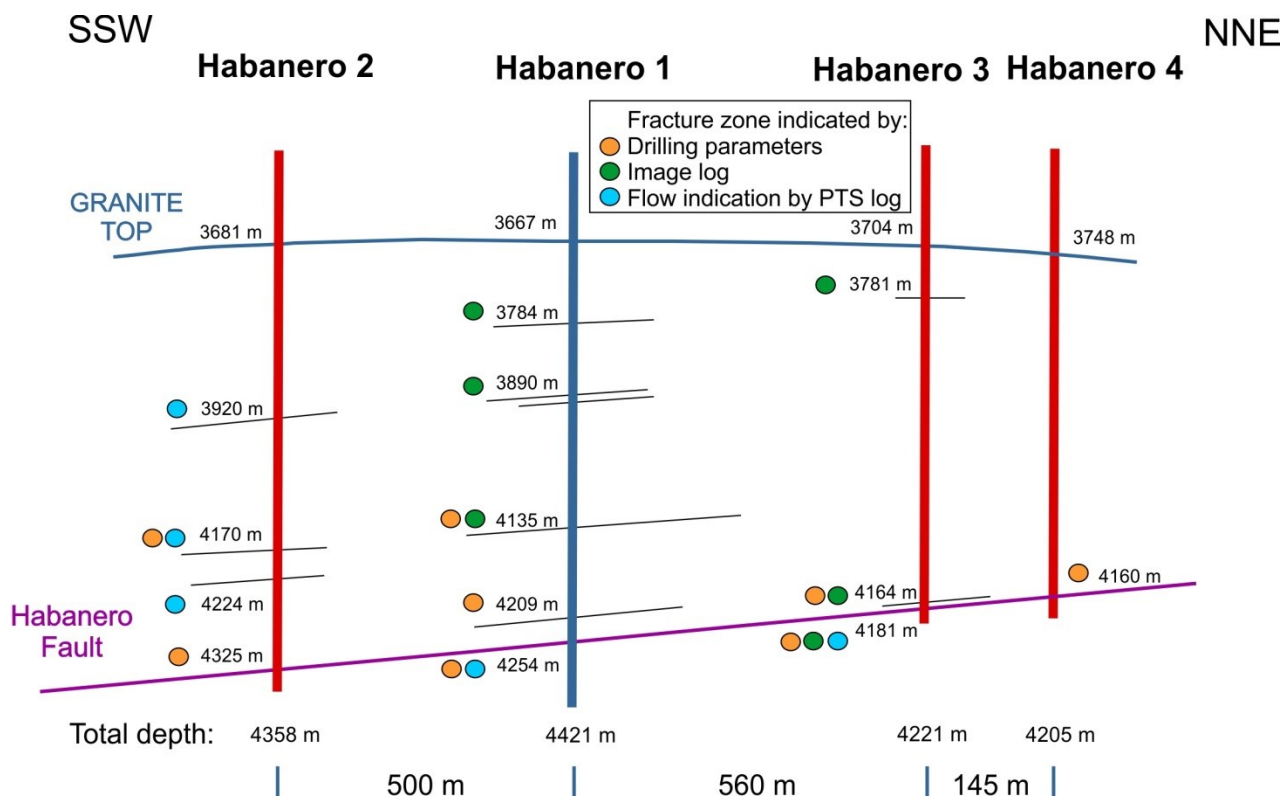
**Figure 1: Location of the Habanero EGS site: (a) approximate geographic location as indicated by the green box, (b) location of the Habanero wells.**

## 2. METHODS

### 2.1 Field methods

One hundred kilograms of the tracer 2,7-naphthalenedisulfonic acid, disodium salt (NDS) was mixed into 36,500 m<sup>3</sup> of fresh water and injected continuously during the hydraulic stimulation of H-4 in November 2012. During the subsequent closed-loop circulation test commencing in April 2013, 100 kg of the tracer 2,6-NDS was mixed into approximately 1 m<sup>3</sup> of water and injected into well H-1 on the 4<sup>th</sup> June 2013.

Water was sampled using 125 ml Nalgene bottles at various locations in the pond that contained the stimulation fluid and also at regular intervals during the stimulation. Produced brine was sampled at H-4 during the open flow and closed-loop circulation tests and collected in 125 ml Nalgene bottles after flowing the produced fluid through cooled stainless steel tubing to ensure that the sampling occurred below the boiling point.



**Figure 2: Schematic cross section of the Habanero wells, identifying major fractures encountered in the wells and the interpreted “Habanero fault zone” that dips to the S-SW.**

## 2.2 Laboratory methods

Tracers of the naphthalene sulfonate family were developed at the Energy and Geoscience Institute (Rose et al., 2001a), and have since been used in tracer tests around the world, including the Western U.S. (Rose et al., 1997, 1999, 2001b, 2002b, 2003), Ohaaki, New Zealand and Awibengkong, Indonesia (Rose et al., 2000, 2001a), Soultz, France (Sanjuan et al., 2006), Bulalo, Philippines (Rose et al., 2002a), and Los Azufres, Mexico (unpublished). There is some evidence that the naphthalene sulfonate tracers may begin to isomerise or partially decay to secondary compounds after prolonged periods (months to years) at high temperatures (>220°C). At Dixie Valley in Nevada for example, high background levels of some naphthalene sulfonate tracers were observed in the reservoir, even though these had not previously been injected into the reservoir (refer to Rose et al., 2002b). Similar observations were made at the Rotokawa geothermal field in New Zealand (reservoir temperature is up to 337°C), where 2-naphthalene sulfonic acid was detected in the reservoir despite never having been injected (Mountain and Winick, 2012). Given the small reservoir size and associated short fluid residence time, any potential non-conservative behaviour of the naphthalene sulfonate tracers in the Habanero reservoir (maximum measured temperature of 244°C) was not expected to be a problem.

The collected samples were sent to the EGI Tracer Development Laboratory in Salt Lake City for analysis for 1,3,5-naphthalene trisulfonate (1,3,5-NTS), 2,6-naphthalene disulfonate (2,6-NDS), 2,7-naphthalene disulfonate (2,7-NDS) and fluorescein using High Performance Liquid Chromatography. The detection limit does not exceed 0.200 parts per billion (ppb) for the naphthalene sulfonates and 0.020 ppb for fluorescein. For further detail in analysis methods, refer to Rose et al. (2001a).

## 2.3 Numerical methods

The moment-analysis approach was applied to the tracer data to derive hydraulic properties of the Habanero reservoir. Moment analysis (otherwise known as method of moments) is based on the analysis of tracer residence times. Tracer breakthrough curves (and their associated age distribution functions) closely match a probability distribution function (pdf), and thus the statistical properties of the measured breakthrough curve can be used to assess tracer transport processes in a reservoir (refer to Danckwerts (1953), Levenspiel (1972), Robinson and Tester (1984), Shook (2003), Nalla et al., (2005), and Shook and Forsmann (2005)). Probability distributions are well characterised by measures of central tendencies, including mean, variance, skewness and other higher-order measures. These are related to the moments of the pdf, for example the first temporal moment corresponds to the mean residence time of the tracer in the reservoir, and the second temporal moment (the variance) reflects the amount of dispersion of the tracer plume in the reservoir.

As detailed in Shook and Forsmann (2005), the steps required for accurate tracer moment analysis are as follows:

1. Correct the tracer recovery for thermal decay
2. Normalise the tracer history and display as a residence time distribution
3. Deconvolve the output signal
4. Extrapolate the history to late time
5. Calculate mean residence time and swept volume

## 6. Calculate flow geometry.

The tracer breakthrough curve is normalized to create an age distribution function  $E(t)$ , using Equation 1.

$$E(t) = \frac{C(t) \cdot Q}{M_{inj}} \quad (1)$$

where  $E(t)$  is the age distribution function (units of  $1/t$ ),  $C(t)$  is the tracer concentration at time  $t$ ,  $Q$  is volumetric flow rate, and  $M_{inj}$  is tracer mass initially injected.

Thus  $E(t) dt$  is the fraction of tracer in the production fluid that has a residence time within the reservoir between  $t$  and  $t + dt$ . The mean residence time  $\tau$  is then calculated from  $E(t)$  using Equation 2.

$$\tau = \frac{\int_0^{\infty} E(t)t dt}{\int_0^{\infty} E(t) dt} \quad (2)$$

Levenspiel (1972) demonstrated how the mean residence time (the first temporal moment) can be used to calculate the total pore volume swept by a tracer, as given in Equation 3.

$$V_p = \frac{m}{M_{inj}} \cdot Q \cdot \tau \quad (3)$$

where  $V_p$  is pore volume,  $m$  is mass recovered,  $M_{inj}$  is mass injected,  $Q$  is flow rate and  $\tau$  is mean residence time.

The key assumptions in the moment analysis technique are steady state fluid flow (steady state injection and extraction), so that swept pore volumes, streamline position and flow geometries etc. do not vary as functions of time; and, the tracer must behave conservatively (i.e. no reactive behavior such as sorption, radioactive or thermal decay).

The main limitation of tracer testing is that the spatial distribution of flow properties is not obtainable (i.e. individual flow paths cannot be resolved, as the tracer breakthrough curve represents multiple tracer flow paths in the reservoir). In addition, it should be remembered that moment analysis can only estimate pore volumes that are swept by the injectate, and parts of the reservoir that are not in contact with this injectate cannot be interrogated via tracers. Thus the pore volume estimates are always referred to as ‘tracer-swept pore volume’.

## 3. RESULTS

### 3.1 Raw data

Figure 3 illustrates the raw tracer dataset, of tracers that were detected following the stimulation of H-4 (2,7-NDS) and during the circulation test between H-1 and H-4 (2,6-NDS). The data are plotted as a function of the time in days since the start of the tracer test on 4<sup>th</sup> June 2013. The tracer 2,7-NDS was introduced into the H-4 stimulation fluid before the circulation test and its concentration gradually dropped as H-4 production continued, finally approaching a constant concentration of about 460 ppb.

The 2,6-NDS tracer that was used to tag the circulation fluids first arrived after about 13 days, peaking at about 24 days. Like the 2,7-NDS, this tracer reached a reasonably steady (but higher) concentration of about 600 ppb. The tracer 1,3,5-NTS that was used in the 2008-09 circulation test between H-1 and H-3, was still present in the reservoir at a steady-state concentration of about 150 ppb. Fluorescein, which was also used in the previous circulation test, was not observed, having completely thermally degraded.

### 3.2 Steady-state corrected data

Prior to interpretation of the tracer data using moment analysis, the data were corrected in two ways to account for the non-steady state flow conditions that were experienced in the H-1/H-4 doublet during the tracer test (i.e. interruptions to flow due to pump shutdowns). The first correction involved removing any days where injection and production were both not occurring in the doublet, to produce a corrected time scale that corresponded to the raw tracer data (Figure 4a). The flow hiatuses included the following days: 10-12 June 2013, 13 August, 23-24 August, 28 August-1 September. It was assumed that minimal tracer advection occurred in the reservoir on the days where both H-1 and H-4 were not flowing (there may have been some advection due to the pressure relaxation in the reservoir but this was considered to be minimal). The second correction involved averaging out the flow rate, by assuming a constant 15 kg/s flow rate and using the H-4 daily production cumulatives to generate a new ‘pseudo-day’ timescale for the tracer data. The tracer data was interpolated to fit this new ‘pseudo-day’ timescale (Figure 4a). After correcting the tracer data for non-steady state conditions in the doublet, the first tracer arrival in H-4 occurs after 6 days, and peak tracer concentration occurs after 17 days.

Correspondingly, tracer breakthrough occurred after approximately 8000 m<sup>3</sup> of fluid was produced, and peak tracer concentration corresponds to a cumulative production volume of 25,000 m<sup>3</sup> (Figure 4b).



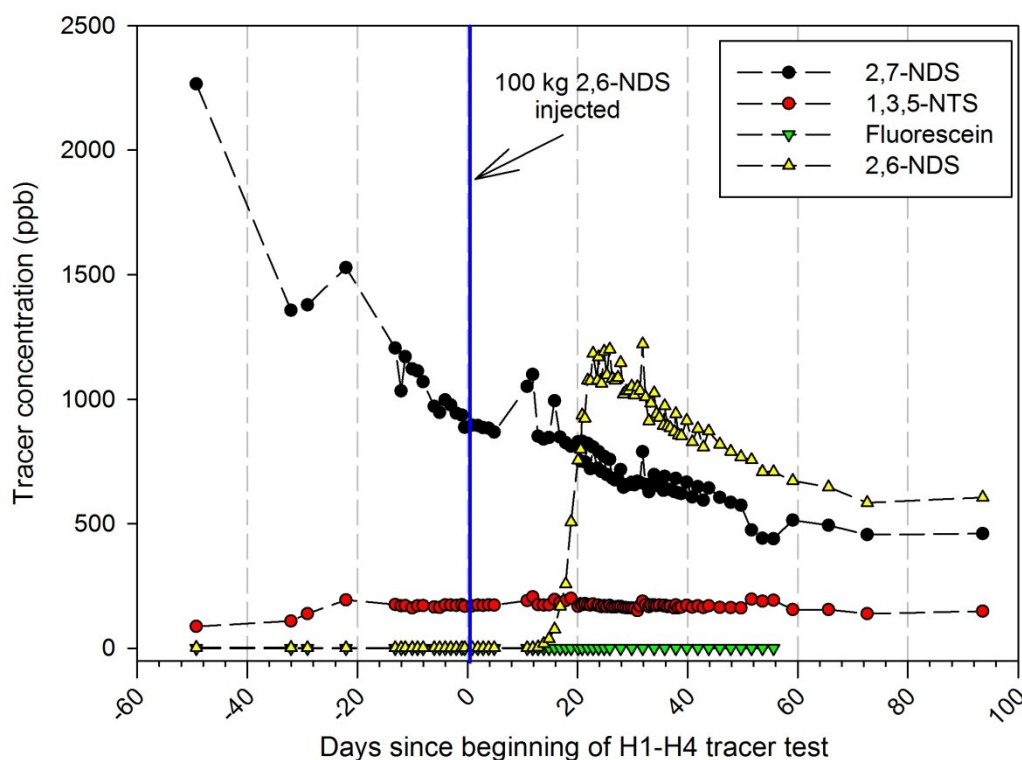


Figure 3: Tracer returns to H-4 as measured during flow-back, following the stimulation of H-4 and during the circulation test between H-1 and H-4.

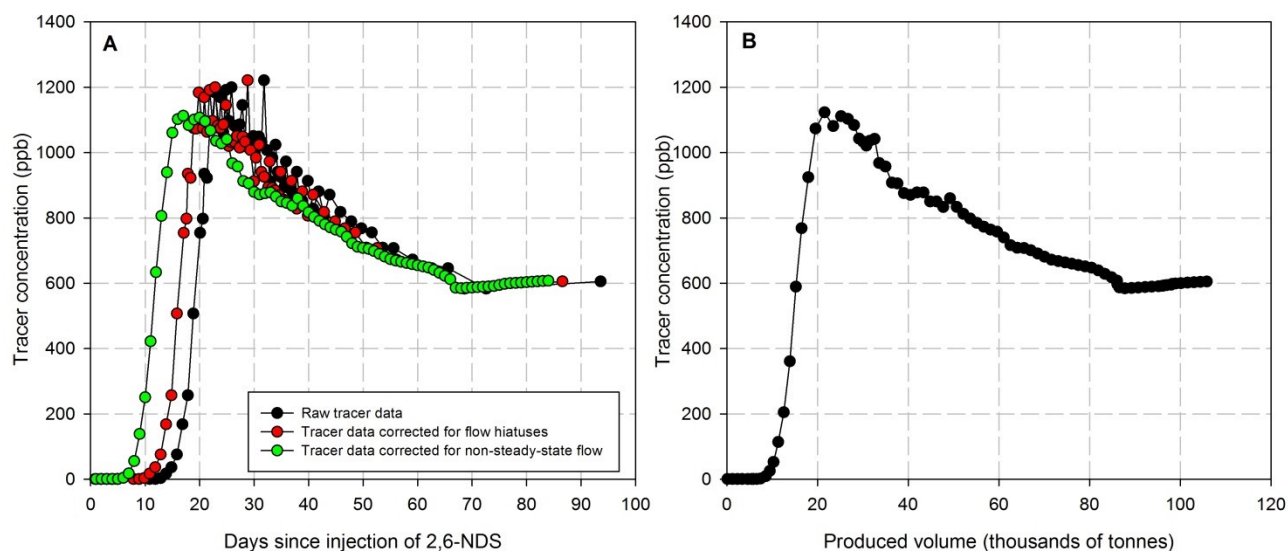
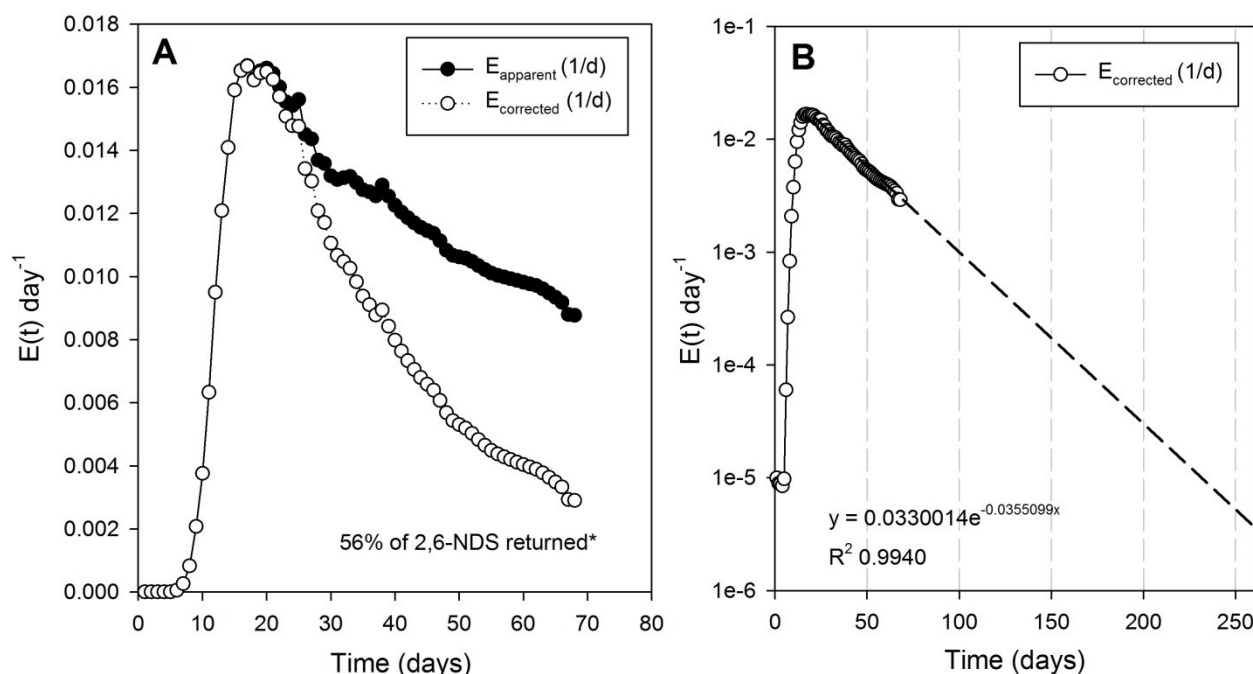


Figure 4: (a) 2,6-NDS breakthrough as observed in Habanero-4, corrected for production/injection hiatuses (red curve), and corrected for non-steady-state flow (and interpolated to achieve revised daily increments (pseudo-days) – green curve). (b) 2,6-NDS tracer concentration in Habanero-4 Vs. cumulative production volume (volume calculated assuming fluid density at 200°C and 73 MPa (864 kg/m<sup>3</sup>))

### 3.3 Moment analysis

For the Habanero tracer test, it was assumed that no thermal decay of the 2,6 NDS tracer occurred. The tracer signal was normalized to create a residence time distribution, by using the flow-rate adjusted tracer data, a volumetric flow rate of 1500 m<sup>3</sup>/day (calculated assuming 15 kg/s of 200°C fluid, with a density of 864 kg/m<sup>3</sup>) (Figure 5a). After exponential extrapolation of the tail of the residence time distribution (Figure 5b), the moment analysis calculation indicates the tracer-swept pore volume between H-1

and H-4 to be approximately 31,000 m<sup>3</sup>. This number should be considered an approximation only, given the number of assumptions and corrections for steady state flow (and the uncertainty associated with the exponential tail extrapolation). The mean residence time was calculated as 40.5 days. Integration of the extrapolated residence time distribution indicates that approximately 60% of the tracer mass would eventually be recovered in the production well, had sampling and production continued. Therefore, the remaining 40% of the original tracer mass injected either still lies in parts of the reservoir that are more poorly-connected (e.g. stagnant), or alternatively, the tracer has been lost to the far field (i.e. the Habanero reservoir is not a closed system). The residence time distribution was truncated at day 68, to facilitate the exponential tail extrapolation. Including the apparently-increasing tracer concentration in late time (indicated in Figure 4a) increases the calculated swept pore volume and mean residence time, and given that this upward trend in late time is based on one anomalous data point (refer to Figures 3 and 4a), it seems reasonable to exclude these interpolated data from the calculation.



**Figure 5: (a) Residence-time distributions (RTD) of the 2,6-NDS tracer in the Habanero reservoir as observed between H-1 and H-4, illustrating the original, and deconvolved RTD (corrected for fluid reinjection); (\*after deconvolution, before extrapolation of break-through-curve tail). (b) Extrapolation of the break-through-curve tail (note logarithmic scale on y-axis).**

### 3.4 Comparison with the Habanero-1/Habanero-3 doublet test (2008)

The raw tracer data from the 2008/2009 tracer test between H-1 and H-3 were processed in the same way as the 2013 test data, and the moment analysis approach was applied. To account for the non-steady-state flow conditions, days flow hiatuses were removed (5-16 January, 6, 8 and 10 February 2009) and an average flow rate of 14 kg/s was used to normalize the tracer breakthrough data and enable plotting against a pseudo-day timescale.

As seen in the normalized tracer data, the first tracer breakthrough in H-3 occurs at ~4 days, and peak tracer concentrations are observed at ~7 days (Figure 6a). Moment analysis of the H-1/H-3 data results in a swept pore volume estimate of approximately 20,000 m<sup>3</sup>, and a tracer mean residence time of 21 days. In addition, approximately 70% of the 1,3,5-NTS tracer was returned over the duration of the circulation test (Figure 6b). After extrapolating the tail of the residence time distribution, integration of  $E(t)$  using this extrapolated curve indicates that 80% of the tracer would have eventually been recovered had circulation and sampling continued. Thus 20% of the tracer may have dispersed into more stagnant parts of the reservoir and remained there, or alternatively, the tracer was lost from the reservoir and dispersed into the far field. The predicted ultimate tracer recovery for this H-1/H-3 doublet (80%) is higher than that for the H-1/H-4 doublet (60%): this would appear consistent with the increase in stimulated reservoir volume between the two tracer tests, and the associated likelihood that more stagnant zones exist in the reservoir.

Figure 7 illustrates the differences between the two inter-well flow tests: both tracers are plotted on the same axis, which highlights both the lag in tracer breakthrough for the H-1/H-4 doublet and the smaller amplitude (i.e. lower concentrations) of the 2,6-NDS breakthrough curve. These results are consistent with the larger well separation between H-1 and H-4 compared to H-1 and H-3 (700 m vs. 555 m).

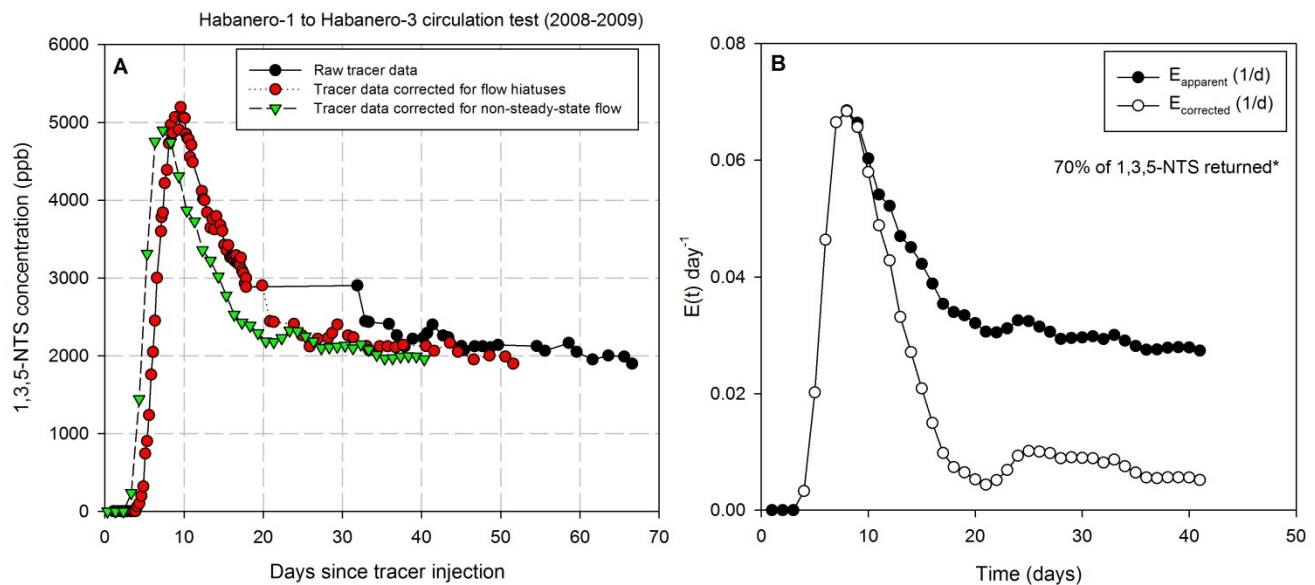


Figure 6: (a) 1,3,5-NTS breakthrough as observed in Habanero-3, corrected for production/injection hiatuses (red curve), and corrected for non-steady-state flow (and interpolated to achieve revised daily increments (pseudo-days) – green curve). (b) Calculated residence time distribution for the H-1/H-3 tracer test, illustrating the original and deconvolved distributions (accounting for tracer reinjection). (\*after correcting for fluid reinjection and before extrapolation of the break-through-curve tail).

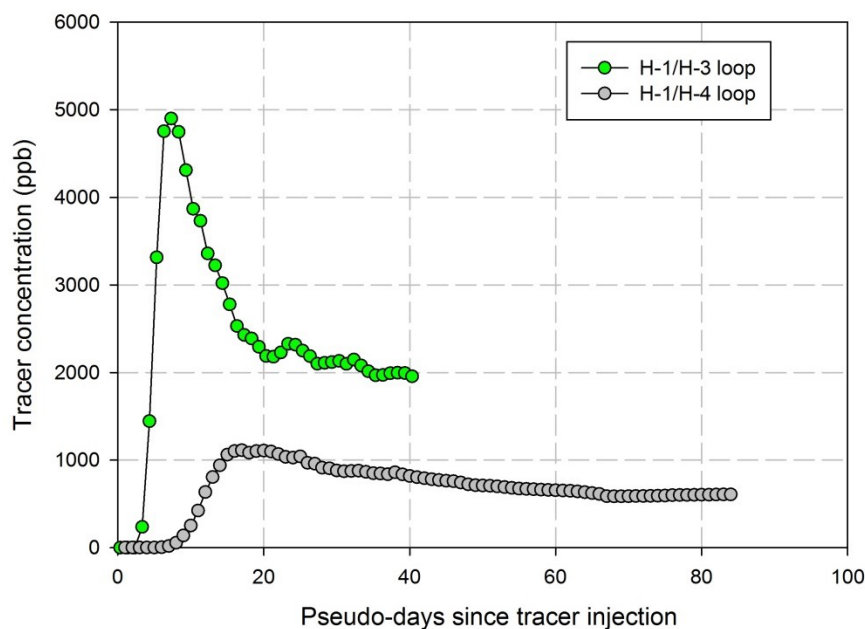


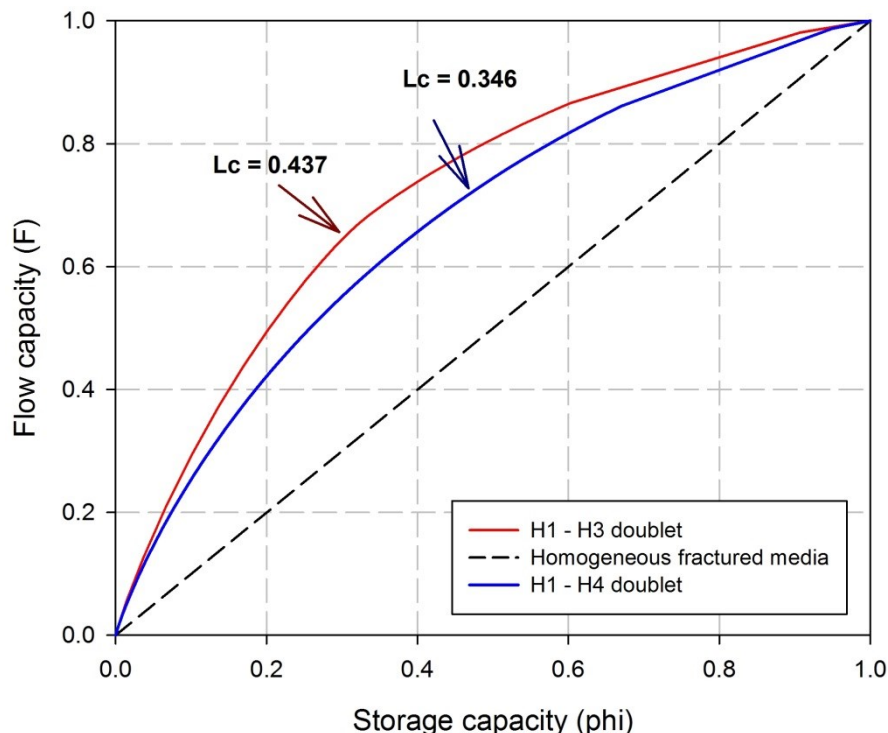
Figure 7: Tracer breakthrough curves for the two inter-well tests (H-1/H-3 and H-1/H-4), both corrected for non-steady-state flow and interpolated to achieve revised daily increments (pseudo-days)

### 3.5 Storage capacity: flow capacity relationships

The concept of comparing cumulative flow capacity (transmissivity) vs. storage capacity (porosity-thickness) originates in petroleum literature, where paired variations in these two characteristics as measured from core and log data are used to help define reservoir and seal units or formations (e.g. refer to Eberli et al., 2004). The cross-plot is often referred to as a Lorenz Plot, where the relative distributions of transmissivity and storativity are sorted from best to worst (governed by the transmissivity). The Lorenz coefficient is a measure of the contrast between the homogeneous (0) to most heterogeneous case (1).

As detailed in Shook (2003), tracer data can be used as proxies to estimate this relationship, given that the cumulative pore volume of a reservoir fracture network is proportional to the mean residence time of the tracer. The storage capacity is the time-weighted reservoir volume seen by the tracer at time  $t$ , and the flow capacity is the amount of tracer recovered in the production well via this

reservoir volume. For the H-1/H-4 doublet, the flow capacity: storage capacity plot illustrates that the Habanero reservoir appears to be a non-homogeneous fracture network, given that almost half of the flow produced is travelling via around 25% of the pore volume (Figure 8). This finding would appear consistent with the reality that few natural fracture networks are homogeneous, and the Habanero reservoir is also likely to have a range of ‘fast’ flow paths and ‘slow’ flow paths within the stimulated fracture zone in the granite. The Lorenz coefficient obtained from the tracer data is 0.35. Estimates of relative transmissivity and storativity for the H-1/H-3 doublet are similar to the H-1/H-4 doublet, with a Lorenz coefficient of approximately 0.44 (indicating moderate heterogeneity in the reservoir) (Figure 8).



**Figure 8: Comparison of the relative transmissivity and storativity for the two Habanero doublets, calculated using the tracer test data. The Lorenz coefficients ( $L_c$ ) for each doublet are similar, and indicate that the reservoir is moderately heterogeneous.**

### 3.6 Discussion

Absolute mass recoveries from geothermal tracer tests are commonly less than 100% (Rose et al., 2004; Iglesias et al., 2011; Mattson et al., 2011). The Habanero reservoir appears discretely contained within a granite pluton of the Big Lake Suite and fluid flow between the H-1/H-4 well doublet is artificially-controlled through pumping at the surface, thus it may be expected to behave as a relatively-closed system. However, the reservoir appears to have some connectivity to the far field as evidenced by the tracer data (i.e. less than 100% predicted ultimate mass recovery for both inter-well tracer tests), and also production history and pressure behavior in the reservoir. During open-flow testing of the H-3 well in 2009 and 2010, the reservoir pressure was drawn down by ~2 MPa from ~75 MPa to 73 MPa (Wyborn (2012)). After shut-in of the well, the reservoir pressure gradually recovered (it took a couple of years for the reservoir pressure to fully recover (refer to Wyborn (2012))), indicating that pressure support/recharge was occurring. In addition, similar reservoir over-pressures were encountered in other wells drilled by Geodynamics Limited 18.5 km to the west of the Habanero well cluster, which have been speculated to reflect a lack of reservoir compartmentalization in fractured, granite reservoirs (and thus fluid connectivity) (Wyborn, 2012).

## 4. CONCLUSIONS

The tracer tests conducted in the Habanero reservoir have provided insight into the fluid flow behaviour of the reservoir, and the change in reservoir properties through time as a result of successive hydraulic stimulations. The inter-well test conducted between H-1/H-4 in 2013 indicated a swept pore volume of 31,000 m<sup>3</sup> and a fluid mean residence time of approximately 40 days. When the data were corrected for non-steady-state behaviour (i.e. interruptions to production or injection), the first tracer breakthrough was predicted to occur after 6 days. These numbers are all larger than for the first inter-well tracer test performed at the site in 2008/2009 between H-1/H-3 (pore volume of 20,000 m<sup>3</sup>, mean residence time of 21 days, and 4 days for first tracer breakthrough). This is consistent with the interpreted increase in reservoir area following the hydraulic stimulation of H-4 in late 2012, as well as a slightly larger well separation (700 vs. 555 m).

Estimated flow capacity: storage capacity relationships for the Habanero reservoir using the tracer data indicate that the reservoir is moderately heterogeneous, and likely has some fast and slow flow pathways within it. In addition, tracer mass recovery calculated from extrapolated breakthrough curves indicate that not all of the tracer would have eventually been produced during each tracer test. For the H-1/H-3 inter well test, 80% of the tracer would be recovered, and for the H-1/H-4 tracer test, approximately 60% of the tracer would eventually be recovered. Thus the ‘missing’ tracer was either trapped in the reservoir in more poorly-connected



fractures (i.e. stagnant zones), or lost to the far-field (i.e. the Habanero reservoir is not a closed system). In reality, both factors may play a role.

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