Referee comments on GI-2015-5

Referee #1:

Synopsis
The manuscript describes a DTS cable-based method of estimating the speed with which a heat tracer pulse moves through a borehole. The experiment makes such determinations in a rock well pumped at different rates and finds a linear relationship between pumping rate and water velocity between two fracture sets. The quality of the relationship diminishes as water flows by the second fracture set.

General Comments
The application described in this article is, to the best of my knowledge, novel and timely. The method and results described in this article constitute worthy contributions to the growing use of DTS in hydrological work. On this basis the work is publishable. However, the manuscript may or may not be suitable for print as submitted, depending on the author's vision for it. The length, scope and detail provided in this paper is appropriate for a Correspondence or Note paper, but is less than expected for a full research article. For example, the article is entirely concerned with flow rates in a pumped borehole with virtually no discussion on how this relates to flow rates in the surrounding formation. Further, an estimate was given for the rate of water flow due to density differences between the ambient water and the heated water, but the details of the calculation were omitted as were any cited sources for making an estimate of this kind. This kind of calculation is not straightforward and deserves a higher measure of explanation in a full research paper.

The scope of the article is quite narrow and should be broadened a little to include discussion on how the estimated velocities could be used for practical advantage. Too little given on how this would work be useful in determining ambient flow in the formation, which is presumably an ultimate goal. From the limited information provided, it appears that density flow would be a large concern except where ambient flows were substantial. An expanded discussion of the limiting conditions would be a useful addition.

The total Qs don't add up to match the pumping rate. The discussion was a bit vague on why, except noting that 1) some density flow is likely occurring, and 2) the effect of poorly resolved plumes above B3-1. Are those the only sources of error here?

The flow in the borehole this test is unquestionably turbulent. How will this relate to near laminar flow in fractures under conditions without pumping? Some discussion of the nature of flow (turbulent vs. laminar) in fractures should be alluded to? Will the linearity seen here be the rule? A little discussion on this would be appropriate since it could be an important aspect of the methods ultimate viability.

In summary, I recommend publication as a Note, with minor revisions. I recommend major revisions if this work is to be published as a full research article. Additional detailed comments follow, below.

PageNo	***Line No.***	***Comment***
3	*18*	*Some mention of density flow due to varying salt content should be made. In open water, such as the case of a borehole, the tiniest difference in fluid density (fourth or fifth decimal place) will result in very noticeable flow.*
3	*14*	*The discussion seems to be limited to the case where flow enters the borehole from a single fracture. If there are multiple fracture sets the 1D model won't work - at least not without special considerations. Since the paper goes on to discuss a multi-fracture system, this issue should be brought up at this point.*
4	*20*	*The DTS cable was continuous to a depth of 80 m yet the data are truncated at a depth of 68 m, where the heater was placed. Why? From the reader's point of view, background variability might be discerned from the lower section of the cable, which would help evaluate the sensitivity of measurements above 68 m depth.*
5	*19*	*The 'elongated' plumes in the shallowest locations in Figure 2 are not visually discernable at all. Also, the symbols in Figure 2 are not explained in the caption or legend. I think they identify the curve peaks. The one in (e) that is associated with line 8 is very peculiar - what is going on there?*
5	*15*	*More detail is needed to show how the sampling interval ends up being 1.1 m (and later 1.8 m). The moving average is fine, but what is the spacing of the individual points that are averaged, and on a continuous cable how are those points determined to be at the minimum point spacing?*
6	*16*	*More details on the Rayleigh number calculation is warranted since the value reported represents the lower limit of flow detection for the system.*
6	*6*	*Why should contributions from B3-2 and B3-2 be hard to resolve? Qtot is constant and you can calculate Q at the bottom, Qbottom+Qmiddle, and Qbottom+Qmiddle+Qtop=Qtot. Need more explanation.*

Referee #2:

The presented new approach for measuring in-well flows using Distributed Temperature Sensing is very interesting and, in my view, promising due to the high spatial resolution (along the well) and the nowadays relatively cheap and accessible fiber optic technology.

I have only a minor concern about the data treatment presented data in section 3 paragraph 15. "...data were then subsequently further averaged ... and smoothed spatially with a 9 point moving average...". Even though the data shown in figure 2 are very convincing, I am not sure that this is the best way to analyze the collected data.

If I understand, the spatial distribution of temperature at each time is represented by a vector (a column in figure 2) where the measurement noise is represented by the "salt&pepper" isolated points. To remove this experimental noise and extract the physical signal representing the fluid flow, the authors have smoothed each spatial distribution with a moving average. Before doing that, would not it be worth to define a "background temperature distribution" (which is a temporal average, few minutes I imagine could be enough, of the well temperature before the heating phase), which contains the base state temperature, and the "spatial variance to its mean", which contains information about the noise, and re-normalize each temperature distribution with respect to that information?

Anyway, I recommend the publication of this manuscript.

Authors' response to referee comments:

Referee #1

"The application described in this article is, to the best of my knowledge, novel and timely. The method and results described in this article constitute worthy contributions to the growing use of DTS in hydrological work. On this basis the work is publishable. However, the manuscript may or may not be suitable for print as submitted, depending on the author's vision for it. The length, scope and detail provided in this paper is appropriate for a Correspondence or Note paper, but is less than expected for a full research article."

We thank the reviewer #1 for their comment on the style of the research article and in depth review. We had always envisioned that we would present this in a Technical Note or Methods Note form, and wish that this be considered as such rather than a full research article.

"For example, the article is entirely concerned with flow rates in a pumped borehole with virtually no discussion on how this relates to flow rates in the surrounding formation."

The aim of the method presented is to determine vertical flow rates inside the well rather than natural gradient flows in the aquifer. In the introduction we state that the flow in the well is completely different to natural gradient flow in an aquifer: "In all cases, the flows are not indicative of flow in the formation itself since the presence of the well as a high permeability vertical conduit may allow the short circuiting of flow." Nevertheless, we aim to quantify the in-well flow as this can still be an important diagnostic.

"Further, an estimate was given for the rate of water flow due to density differences between the ambient water and the heated water, but the details of the calculation were omitted as were any cited sources for making an estimate of this kind. This kind of calculation is not straightforward and deserves a higher measure of explanation in a full research paper."

We have now expanded details of this calculation in the discussion as we feel that even in a Methods Note, further explanation is required as pointed out by the reviewer.

"The scope of the article is quite narrow and should be broadened a little to include discussion on how the estimated velocities could be used for practical advantage. Too little given on how this would work be useful in determining ambient flow in the formation, which is presumably an ultimate goal."

This is not the aim – rather, to simply measure the flow in the well.

"From the limited information provided, it appears that density flow would be a large concern except where ambient flows were substantial. An expanded discussion of the limiting conditions would be a useful addition."

In the discussion section, we now discuss the measurement limitations in terms of maximum and minimum velocities and depth resolution.

"The total Qs don't add up to match the pumping rate. The discussion was a bit vague on why, except noting that 1) some density flow is likely occurring, and 2) the effect of poorly resolved plumes above B3-1. Are those the only sources of error here?"

$Q_{B3-1,2,3}$, which should equal to the pumping rate Qa, is at most 20% below this figure. The data from above fracture B1, from which $Q_{B3-1,2,3}$ is calculated, are only marginally above the noise level. This, therefore, likely contributes significantly to this error. We also now list other potential sources of error.

“The flow in the borehole this test is unquestionably turbulent. How will this relate to near laminar flow in fractures under conditions without pumping? Some discussion of the nature of flow (turbulent vs. laminar) in fractures should be alluded to? Will the linearity seen here be the rule? A little discussion on this would be appropriate since it could be an important aspect of the methods ultimate viability.”
We agree that when pumped, the flow in the well will be turbulent. However, we have not added a discussion of the nature of the flow in the fractures, or, whether the linear scaling would always be a feature, as we feel this goes beyond the scope of this method paper.

Detailed comments:
“Some mention of density flow due to varying salt content should be made. In open water, such as the case of a borehole, the tiniest difference in fluid density (fourth or fifth decimal place) will result in very noticeable flow.”
We have added a sentence stating this.

“The discussion seems to be limited to the case where flow enters the borehole from a single fracture. If there are multiple fracture sets the 1D model won't work - at least not without special considerations. Since the paper goes on to discuss a multi-fracture system, this issue should be brought up at this point.”
We now go on to explain that multiple fractures increase the complexity of the response in borehole dilution tests.

“The DTS cable was continuous to a depth of 80 m yet the data are truncated at a depth of 68 m, where the heater was placed. Why? From the reader's point of view, background variability might be discerned from the lower section of the cable, which would help evaluate the sensitivity of measurements above 68 m depth.”
We have re-plotted the data so that the instrument noise relative to the T-POT signal strength can more easily be seen. The data were truncated since we also carried out other experiments (that we do not aim to publish) in the section below the T-POT heater. This caused some warming below fracture B3-3, and since there is no vertical flow in the well here, the heat remained for a long time and appeared in variable extents in Figure 2a-e. This was decided to be more confusing, hence we do not show data from here.

“The 'elongated' plumes in the shallowest locations in Figure 2 are not visually discernable at all. Also, the symbols in Figure 2 are not explained in the caption or legend. I think they identify the curve peaks. The one in (e) that is associated with line 8 is very peculiar - what is going on there?”
There is now an explanation of the symbols in the text and figure caption. In Figure 3e, the peak associated with the 8 minute temperature depth profile appeared in a strange location as the T-POT signal was at or below the noise level by this time, hence determining the location using the automated method resulted in some clearly incorrect locations. In fact, after subtracting background temperature profiles as suggested by Referee #2, this point now is located at a more realistic depth, which is a merely due to a coincidence rather than an improvement in the signal to noise ratio.

“More detail is needed to show how the sampling interval ends up being 1.1 m (and later 1.8 m). The moving average is fine, but what is the spacing of the individual points that are averaged, and on a continuous cable how are those points determined to be at the minimum point spacing?”
In the revised manuscript we now explain the moving spatial and temporal averaging used to arrive at the curves in Figure 3. The 1.1 m number comes from averaging 9 temperature measurements, each spaced by 0.12 m. However, we now no longer refer to this, as the ‘smoothed’ curves in Figure

3 still contain data spaced by 0.12 m. So the comparison of this with a 1.1 m averaged DTS temperature measurent is not valid, unless we were to then interpolate the smoothed data set every 1.1 m.

"More details on the Rayleigh number calculation is warranted since the value reported represents the lower limit of flow detection for the system."
We have now significantly expanded on this in the discussion section.

"Why should contributions from B3-2 and B3-2 be hard to resolve? Qtot is constant and you can calculate Q at the bottom, Qbottom+Qmiddle, and Qbottom+Qmiddle+Qtop=Qtot. Need more explanation."
We now explain this in the text that the transmissivity of B3-1 is << B3-2, hence the contribution of B3-1 to the flow as a % of what is already there is too small.

Referee #2

I have only a minor concern about the data treatment presented data in section 3 paragraph 15. "...data were then subsequently further averaged ... and smoothed spatially with a 9 point moving average...". Even though the data shown in figure 2 are very convincing, I am not sure that this is the best way to analyze the collected data.

If I understand, the spatial distribution of temperature at each time is represented by a vector (a column in figure 2) where the measurement noise is represented by the "salt&pepper" isolated points. To remove this experimental noise and extract the physical signal representing the fluid flow, the authors have smoothed each spatial distribution with a moving average. Before doing that, would not it be worth to define a "background temperature distribution" (which is a temporal average, few minutes I imagine could be enough, of the well temperature before the heating phase), which contains the base state temperature, and the "spatial variance to its mean", which contains information about the noise, and re-normalize each temperature distribution with respect to that information?

We thank Reviewer #2 for their suggestion on the treatment of the data. We have now subtracted a pre-test temperature-depth profile from each T-POT test. This was taken as an average of 12 DTS temperature profiles (a 1 min equivalent average), using data immediately prior to the initiation of heating in each. This normalisation has slightly altered the calculated velocities and flows in Figure 4b, hence these have been updated. Additionally we have plotted Figure 2 with a colour scale that starts at 1 standard deviation (a measure of instrument noise from a constant temperature bath) above 0°C change in temperature from the reference profile, so the plume, and its significance relative to measurement noise, can more easily be seen.

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Thermal-Plume ~~fiber~~ fibre Optic Tracking (T-POT) test for flow velocity measurement in groundwater boreholes

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Abstract

We develop an approach for measuring in-well fluid velocities using point electrical heating combined with spatially and temporally continuous temperature monitoring using Distributed Temperature Sensing (DTS). The method uses a point heater to warm a discrete volume of water. The rate of advection of this plume, once the heating is stopped, equates to the average flow velocity in the well. We conducted Thermal-Plume fibre Optic Tracking (T-POT) tests in a borehole in a fractured rock aquifer with the heater at the same depth and multiple pumping rates. Tracking of the thermal plume peak allowed the spatially varying velocity to be estimated up to 50 m downstream from the heating point, depending on the pumping rate. The T-POT technique can be used to estimate the velocity throughout long intervals provided that thermal dilution due to inflows, dispersion, or cooling by conduction do not render the thermal pulse unresolvable with DTS. A complete flow log may be obtained by deploying the heater at multiple depths, or with multiple point heaters.

1 Introduction

The measurement of the vertical flow in wells can improve our conceptual understanding of subsurface fluid movement, which can aid in, for example, groundwater resources management or geothermal resource assessments. In open or long-screened wells penetrating multiple permeable units or fractures, vertical flow typically occurs in hydraulically unstressed conditions due to the natural occurrence of a vertical head gradient. Flow logs obtained in unstressed conditions gives a qualitative guide to fracture inflow and outflow zones (Hess, 1986). Alternatively, flow logs obtained in a pumping well at multiple different pumping rates allow the depth variability of transmissivity to be estimated (Paillet et al., 1987). Flow logs in observation wells affected by nearby pumping enables the connectivity of fractures to be determined (Paillet, 1998; Klepikova et al., 2013). In all cases, the ~~flows are not~~ in-well flow is not directly indicative of flow in the formation itself since the presence of the well as a high permeability vertical conduit ~~may allow~~ allows the short circuiting of flow. ~~Flow~~ In addition, flow logs have inherent value for geochemical sampling campaigns. Ambient vertical flow through the well may redistribute contaminants and mean that passive sampling approaches do not reproduce the same depth variability as ~~there is~~ present in the aquifer itself (Elci et al., 2003). Typical flow logging techniques involve lowering an impeller or electromagnetic flowmeter down a well and either measuring continuously (trolling) or at multiple points with the probe held stationary. At low flows a heat pulse flowmeter may be used at fixed depths (Paillet, 1998) .

Alternatively, tracer based approaches may be used. Most commonly, a tracer is emplaced over the entire length of the borehole and the change in concentration monitored over time. Typically, slightly saline (Maurice et al., 2011), or distilled water (Doughty et al., 2005) is added since fluid electrical conductivity (EC) can be easily logged with an EC meter. The EC is then monitored over depth and time by making repeated logs. The dilution of the saline profile at inflow locations or increase in EC if using distilled water can be used to estimate ~~inflows. Vertical~~ horizontal flow through the aquifer using simple analytical solutions (Pitrak et al., 2007) . If there is vertical flow in the well~~then results in a front that~~ , a salinity front then migrates up or down the well. ~~The movement of this front can be modelled using 1-D simulations using the advection-dispersion equation (Maurice et al., 2011)~~ In the case of multiple inflows with multiple salinity fronts, the response over depth and time may become complex and require numerical modelling (Maurice et al., 2011) , or inversion methods to extract the vertical flow profile (Moir et al., 2014) . A limitation of this method is that when the vertical velocity or losses from the borehole to the aquifer are high, the EC signal rapidly dissipates and monitoring this process over a large depth interval with a single EC logger yields an incomplete dataset. Additionally, density induced flow effects in well bores are significant even for small gradients of fluid density (Berthold, 2010) .

Instead of a hydrochemical signal that can be difficult to monitor over space and time, Leaf et al. (2012) introduced a slug of warm water to a target depth. By using temperature as the tracer, it is possible to monitor the response continuously over depth and time along a ~~fiber~~ fibre optic cable installed in the well with the Distributed Temperature Sensing (DTS) technique (see Selker et al. (2006) for a description of the DTS method).

Leaf et al. (2012) heated water at the surface and injected it at multiple depths to ~~then~~ identify the flow direction and velocity. However, the process of heating water is cumbersome and, its injection is likely to result in head changes in the well resulting in an altered flow regime particularly if ambient or low pumping rate conditions are of interest. ~~Sellwood (2012)~~ Sellwood et al. (2015) adapted this method by using an electrical heater to generate the thermal disturbance and carried out tests under non-hydraulically stressed conditions in a dual permeability sandstone aquifer. In this study we deploy a single electrical heater to warm a discrete interval of water at depth in a pumping well in a fractured rock aquifer, monitored with DTS. We apply post-collection averaging to the DTS temperature data and track the peak of the plume over time to estimate the mean vertical velocity. We call this method Thermal-Plume ~~fiber~~ fibre Optic Tracking (T-POT).

2 T-POT Field Application

We deployed T-POT at the ~~Stang-er-Brune research site , Ploemeur,~~ H+ network research site (hplus.ore.fr/en), Ploemeur France (Figure 1a). The site has multiple boreholes up to 100 m deep, penetrating ~~micashist~~ micaschist and granitic rock. Open fractures, although sparse (< 5 hydrogeologically significant fractures per borehole), are reasonably transmissive (up to 4x10^{-3} m^{-2} d^{-1}). We show T-POT results from borehole B3 (~~0.11 m~~ 11.8 cm diameter), which is intersected by three previously identified transmissive fractures (Figure 1b). Fractures B3-2 and B3-3 have similar transmissivities ($\sim$ 2x10^{-3} m^{-2} d^{-1}), while B3-1 is approximately an order of magnitude less transmissive Klepikova (2013).

We used a 2 kW rated heating element as the heat source (Figure 1c), lowered down to 68 m ~~bgl~~ depth for the duration of the experiment. Additionally, an ~~armored fiber~~ armoured fibre optic cable was installed ~~throughout~~ in the well down to a depth of approximately 80 m~~bgl~~. This allowed temperature measurements to be made over a time average of 5 seconds and sampling interval of 0.12 m with DTS by connecting it to a Silixa Ultima base unit. The cable was configured for a duplexed single ended measurement. The DTS data were calibrated using 3 reference sections from a cold and ambient bath, according to the method described by Hausner et al. (2011). The standard deviation of temperature in the cold and ambient baths for the 5 second integration time averaged 0.38 and 0.33 °C respectively over the duration of the T-POT tests.

We ran a series of tests at different pumping rates to determine the fracture inflow for each pumping rate, in order to evaluate the T-POT method. For each pumping rate, a similar procedure was followed: heat for $\sim$ 10 minutes, then switch off the heating and simultaneously turn on the pump at the selected rate. We repeated this procedure for pumping rates of 7.3, 40.0, 86.6, 104.0, 136.2 L min^{-1}. During each experiment we measured the pumping rate manually and with an in-line flowmeter, drawdown, electrical power supplied to the heating element, and temperature along the length of the borehole with DTS.

3 T-POT Results and Interpretation

Figure 2 shows successive DTS temperature depth profiles from the 5 T-POT experiments. A background temperature depth profile, defined by a 1 minute time average immediately prior to the start of heating, was subtracted from each dataset. During the heating phase ($t < 0$ min), it appears that the plume develops asymmetrically, with the base of the plume at 68 m at the approximate depth of the heater. The heater is switched off at $t = 0$ and at this moment pumping is initiated. The plume is then advected upwards at higher velocity. In all cases, the linear path of the plume in the temperature-depth-time plot suggests a uniform velocity from 68 m to around 45 m, as would be expected given the lack of transmissive fractures and uniform borehole diameter in this interval. At 45 m, the temperature signal is significantly ~~diluted~~ reduced and the plume then continues to move upwards at higher velocity (steeper gradient in Figure 2c,d,e). This coincides with a transmissive fracture identifiable in previous flowmeter tests and optical borehole logs (Le Borgne et al., 2007).

~~The~~ To aid the identification of the plume peak, the 5 second time averaged and 0.12 m spatially sampled DTS temperature data were then subsequently further averaged to give the equivalent of 15 second time averaged DTS temperature data~~, and smoothed spatially~~. Each point was then spatially smoothed with a 9 point moving average ~~(approximately~~

~~equivalent to sampling every 1.1 m)~~window. These are plotted as temperature-depth profiles in Figure 3. Below 45 m, the plume is clearly defined. Above the inflow from B3-2 at 45 m, the plume ~~is much more elongated (Figure 2~~becomes much less discernible (Figure 3c,d,e).

The depth location of the maximum temperature was then extracted and plotted over time (Figure 4). While the peak of the plume remains below fracture B3-2, the plume is readily resolvable in the temperature data. Linear least-squares regression yields an $r^2 \geq 0.98$ for all of the pumping rates. The average flow velocities v_1 and v_2 were calculated from the gradient of the best fit line through plume peak location data. The corresponding volumetric flow rates Q_{B3-3} and $Q_{B3-1,2,3}$ were calculated from v_1 and v_2 respectively using the known borehole diameter over this interval.

~~Immediately above B3-2~~Above 45 m, the peak of the plume was not detected for 1 - 2 minutes after the arrival of the plume peak at B3-2. This is because in this situation, the inflow from B3-2 greatly dilutes the thermal signal, such that until most of the plume has moved above the fracture, the highest temperature (and plume peak, as identified with this method), remains at the depth of the fracture. Once identified again, now at approximately the depth of B3-1, the peak location data show that the plume is now travelling at higher velocity. ~~It is now~~ Here it is much less detectable, with an r^2 for the three cases where the plume passes this point of ~~0.87, 0.39, and 0.54~~0.76, 0.65, and 0.91. However, it is not possible to separately assess the flow contributions of B3-2 and B3-1, ~~so~~ since two separate contributions are not apparent in Figures 2-4. Therefore we are only able to estimate Q_{B3-3} (the flow below 45 m) and $Q_{B3-1,2,3}$ ~~represents the total~~ representing the cumulative flow contribution from all transmissive fractures intersecting the well.

4 Discussion

The upwards expansion of the plume during the heating phase is driven by upward ambient fluid flow in the borehole. The rate of the ambient flow component between B3-3 and B3-2 has been measured at approximately 5 L min^{-1} in previous studies (Klepikova, 2013).

~~The upwards growth of the plume could also be due to free convection due to buoyancy, as occurs in groundwater wells even for small temperature gradients (Sammel, 1968) . Scaling the results of Berthold and Resagk (2012) by calculating a Rayleigh number using the borehole diameter here, suggests that in the absence of any forced convection, free convection would give rise to flow velocities of the order of 0.5 cm s^{-1}. This is similar to the velocity that would be expected under ambient flow conditions, so it is possible that both effects are occurring. However, here we do not focus on ambient flow velocities but note that the buoyant effect will place a limit on the low end of the velocity range that can be measured.~~

When pumping at 7.3 L min^{-1}, the calculated flow between B3-3 and B3-2, Q_{B3-3}, is almost ~~50more than~~ double the abstraction rate. At this low pumping rate, the hydraulic head in the borehole remains higher than the hydraulic head in B3-1, so that B3-1 remains an outflow. The flow from B3-3 is proportional to the pumping rate (r^2 =0.99), as would be expected from linear scaling behaviour, giving us confidence in these flow estimates.

~~The~~ The discrepancy between $Q_{B3-1,2,3}$ and Q_a is at most 20%. Much of this error may arise from the error determining the plume location above B3-1. Further additional sources of error that may contribute to the discrepancy in flow estimates are the high sensitivity of the volumetric flow estimate to borehole diameter used for the calculation, and error in independently measuring the flow at the surface. The inability of the method to reliably track the velocity immediately downstream of fracture B3-2 in the present study is due to the strong dilution effect by inflow from the fracture of a similar magnitude to the vertical flow in the borehole. The relatively low r^2 for the peak depth-time data beyond this fracture and discrepancy from Q_a is because the resulting plume is much more dispersed with a poorly defined peak. ~~One way to derive more reliable velocity estimates would be to use a numerical modelling approach to model the plume migration. This issue would not be present for outflows, where the plume would simply begin to move more slowly~~The T-POT method as used here, would more likely perform better in cases where there are multiple outflows, rather than inflows. This is because inflows affect both the size and change the shape of the signal.

Free convection due to T-POT heating induced buoyancy, as occurs naturally in groundwater wells even for small temperature gradients (Sammel, 1968) , may disturb the in-well flow. The potential for heat transfer by natural convection in a fluid is expressed by the Rayleigh number, given by:

$$Ra = \frac{\beta g \Delta T/\Delta z}{\kappa \nu} r^4 \tag{1}$$

where β is the thermal expansion coefficient, g is acceleration due to Earth's gravity, $\Delta T/\Delta z$ the temperature gradient, κ the thermal diffusivity, ν kinematic viscosity, and r the characteristic length, which in this case is the borehole radius. For the T-POT experiments here in a borehole with radius 0.059 m, with $\Delta T/\Delta z$ at most 0.5 °C m^{-1} during the heating phase, and substituting values of 2x10^{-4} °C^{-1}, 9.81 m s^{-2}, 0.14x10^{-6} m^2 s^{-1}, and 1x10^{-6} m^2 s^{-1} for β, g, κ and ν respectively gives a Ra of 85,000. Scaling the results of Berthold and Resagk (201 who imaged flow velocities due to free convection in a vertical cylinder, using this Rayleigh number, suggests that in the absence of any forced convection, free convection due to T-POT heating would give rise to flow velocities of the order of 2 cm s^{-1}. This is similar to the velocity that would be expected under ambient flow conditions. However, this velocity is the velocity magnitude in a diametrically anti-symmetric convection cell. Therefore even though the velocity due to natural convection is of a similar magnitude to the ambient flow, if the convection cells are relatively small then the warming front would not propagate up the well at this rate. A further in depth analysis is beyond the scope of this paper, but we note that if present, the development of large convection cells would place a lower limit on the velocity estimate that can be obtained with the T-POT method.

The upper limit of velocity estimation is reached when the plume travels the length of the monitoring interval in less than the integration time of the DTS temperature measurement (i.e. $v_{max} = Z/t_i$, where Z is the length of flow path away from the heater in the direction of flow, and t_i is the integration time of the DTS temperature measurement). The depth resolution of the velocity estimate using the T-POT method are flow velocity dependent. At high velocities, the depth spacing between velocity estimates is $t_i v$. At low flow velocities, the spatial sampling of the DTS instrument determines the number of velocity estimates with depth that the T-POT method can provide.

The basic method, using DTS with a ~~FO cable and a point source of heat~~ fibre optic cable and point source electrical heating in the well, can be easily adapted ~~for future~~ to include the use of multiple heaters or more prolonged heating in a constant source type experiment. ~~Time~~ While the method at present assumes a constant velocity profile in time, time varying velocities could be monitored by cycling through heating and non-heating phases. The method is completely complementary to and can be easily used alongside other ~~fiber-optic downhole~~ fibre-optic down hole tests and to validate vertical velocity estimates made by other Active-DTS methods such as Read et al. (2014).

5 Conclusions

We deployed the T-POT method in a groundwater well in fractured rock. By heating a discrete volume of the resident water in the borehole, estimates of vertical in-well velocity were obtained by tracking its subsequent migration with DTS. The ~~method yielded velocity data every 0.3 - 1.8 m (pumping rate dependent), after post-collection averaging of the temperature data. The~~ plume was significantly reduced beyond a major inflowing fracture but was still detectable, albeit with much increased uncertainty. The advantage of this method is that it is quick and simple, especially if the well is already instrumented for ~~FO~~ fibre optic temperature monitoring.

Acknowledgements. Funding for this work was provided by the INTERREG IV project CLIMAWAT, the national network of hydrogeological sites H+, the ANR project CRITEX ANR-11-EQPX-0011, and a Natural Environment Research Council (NERC) studentship (NE/J500069/1) to Tom Read. Part of the support for the participation of John Selker and provision of some of the ~~fiber~~ fibre optic cables were provided by the Center for Transformative Environmental Monitoring Programs (CTEMPs) funded by the National Science Foundation. The data collected for this study will be available from the national network of hydrogeological sites H+, at http:// hplus.ore.fr/en/.

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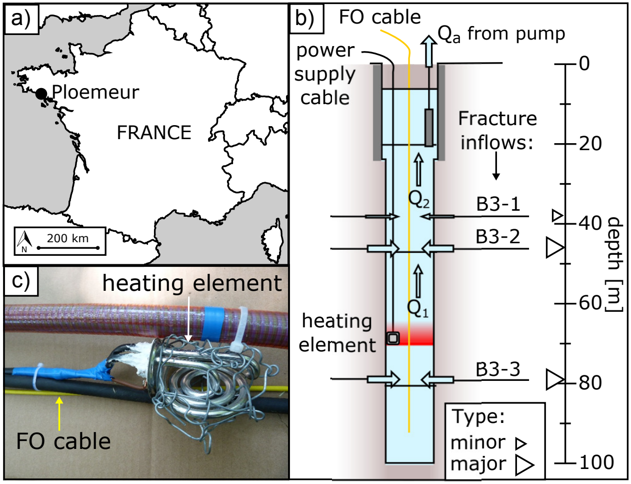


Figure 1. a) Location of the Ploemeur research site, b) heating element and ~~fiber~~ fibre optic cable along which temperature is measured, c) schematic of the set-up in borehole B3 at the site

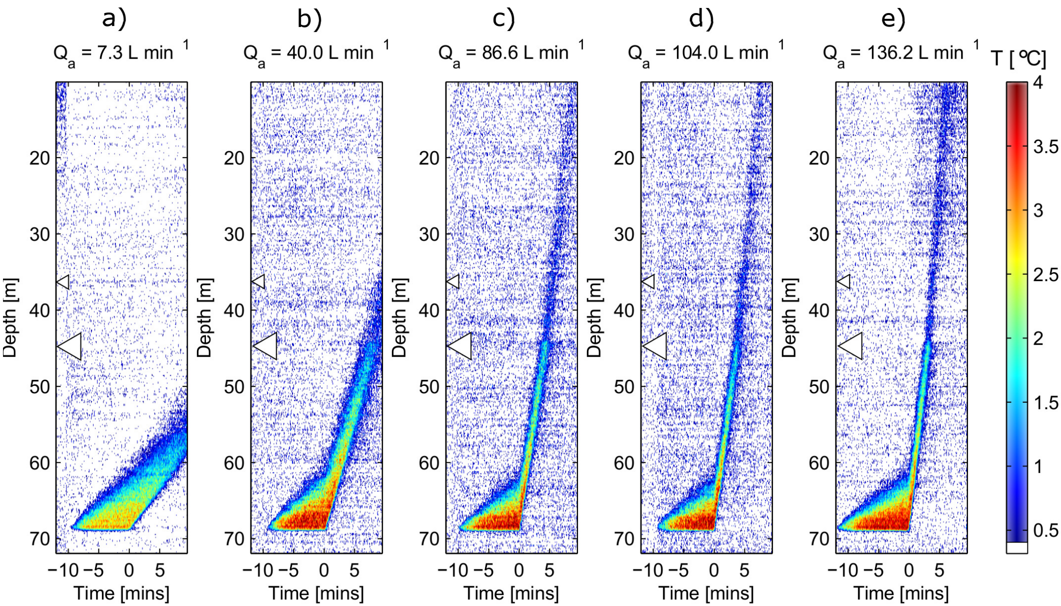


Figure 2. Temperature ~~distibution~~ distribution with depth and time for T-POT tests at abstraction rates of a) 7.3, b) 40.0, c) 86.6, d) 104.0, and e) 136.2 L min^{-1}. The temperature data have a background profile subtracted, with the lower limit to the colour scale starting one standard deviation (from reference bath temperature measurements) above 0°C change

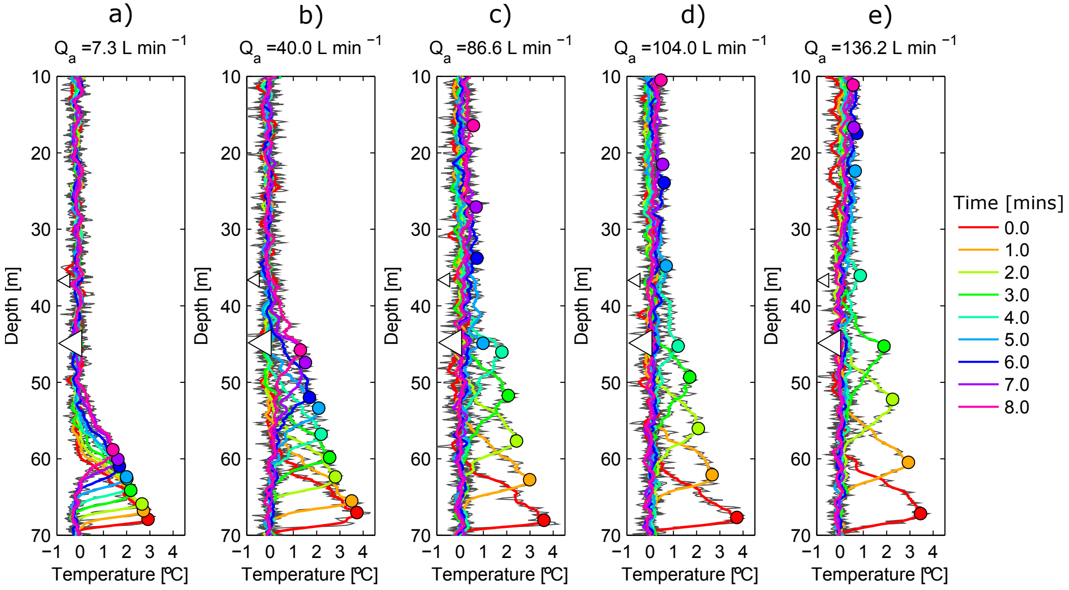
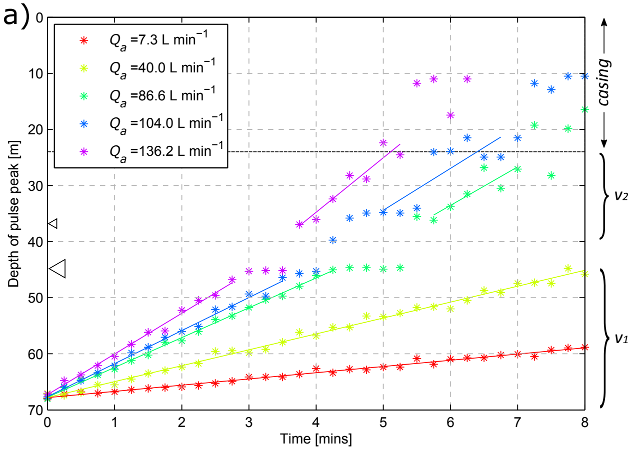


Figure 3. Temperature-depth profiles after pumping begins for the T-POT tests at abstraction rates of a) 7.3, b) 40.0, c) 86.6, d) 104.0, and e) 136.2 L min^{-1}. The coloured profiles are 15 second time averaged data that has then been spatially smoothed with a 9-point moving window. Filled circles identify the location of the plume peaks



b)

v_1 [cm s^{-1}]		v_2 [cm s^{-1}]	r^2 (v_1)	r^2 (v_2)	$Q_{B3\text{-}3}$ [L min^{-1}]	$Q_{B3\text{-}1,2,3}$ [L min^{-1}]	Q_a [L min^{-1}]
✳	1.85	-	0.99	-	12.12	-	7.3
✳	4.73	-	0.99	-	31.01	-	40
✳	8.86	11.45	1.00	0.76	58.12	75.10	86.6
✳	9.82	12.44	0.99	0.65	64.40	81.61	104
✳	12.09	16.20	0.99	0.91	79.34	106.32	136.2

Figure 4. Temperature peak depth over time for each of the pumping rates, with linear least-squares regression best fit lines used to estimate the in-well vertical flow velocity