# Analysis of transient temperatures in the Buckman municipal well field, Santa Fe, New Mexico, United States of America

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## Abstract

In this study we use repeat measurements of temperature profiles in drill holes to monitor the dynamic recovery of a municipal well field and to identify the source of anomalously high geothermal gradients in one part of the well field. Based on the analysis of temperature logs and on the geologic knowledge of the Buckman well field, which is located near Santa Fe, New Mexico within the Rio Grande rift, we have developed a hypothesis for the cause of increasing temperatures in monitoring wells SF4, SF3 and SF2. Temperature was measured in the wells using a thermistor attached to a wireline cable. After analyzing repeat temperature logs of SF4, SF3, SF2 and SF6, we observed that SF4 has the highest change in temperature of ~ 0.5 $^{o}$C, which affects the entire well casing. At well SF3, only the top part of the well casing has warmed. SF2 presented variable cooling and heating across the years. At SF6, temperatures remain unchanged since 2013, suggesting that the observed temperature changes in SF3 and SF4 are not related to calibration issues. The high geothermal gradients in this area are explained by the fact that two of the four wells are located in the hydrologic discharge area where small normal faults concentrate upward flow of deep, thermal waters from underlying bedrock. Analysis suggests that a possible heat source for these wells is a normal fault located immediately to the west of SF4.

## Introduction

The Buckman municipal well field (BWF) is an important source of water for the city of Santa Fe, New Mexico. Santa Fe is located within the Española Basin, one of a series of basins formed during extension of the Oligocene to Pliocene Rio Grande rift. The aquifers tapped by the BWF are located in rift basin-fill sediments belonging to the Santa Fe Group deposited by alluvial fans derived from mountain ranges to the east and west that are interbedded with sandy and gravelly, south-flowing ancestral Rio Grande axial fluvial deposits (Koning et al., 2007). The nine wells that make up the older part of the BWF produced water at high rates between 1989 and 2003, which caused water levels in the field to drop in excess of 100 meters. Pumping rates were reduced in 2004 and water levels have risen 120 to 170 m since 2003 (Shomaker and Associates, 2014). Four additional wells and water diversion from the Rio Grande now supplement the water production of the original nine wells in the BWF. Several monitoring wells were installed in the BWF by the U.S. Geological Survey following the precipitous drop in water levels.

Students attending the Summer of Applied Geophysical Experience (SAGE) field school in Santa Fe have had the unique opportunity to measure temperature profiles in the monitoring wells in the BWF between 2013 and 2016. Here we report the results of repeated measurements in four monitoring wells (SF2, SF3, SF4 and SF6), discuss the changes in temperature through time that have occurred as water levels in the well field have risen and propose two hypothesis to explain these changes in temperature. We also discuss the spatial variability of geothermal gradients among the wells in the context of geologic structures that have been mapped in the area.

Wells SF2, SF3 and SF4 are only a few hundred meters apart from each other, while SF6 is located 6 km to the southeast (***figure 1*** and ***table 1***). There is a mapped fault west of SF4 and the map (***figure 1***) also presents the location of the schematic cross section and the supposed discontinuity, addressed latter on in this work.

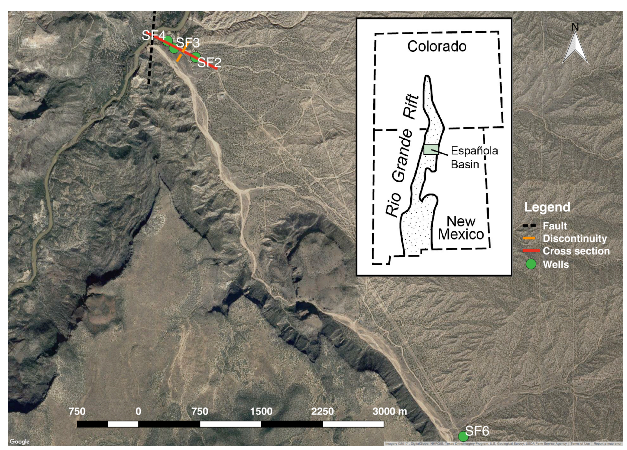


***Figure 1***: Map of the study area, displaying the location of the wells, mapped fault, conceptual cross section, supposed discontinuity and with sketch of the Española Basin position within the Rio Grande Rift and the estate of New Mexico.

***Table 1***: Geographic coordinates of the wells here studied.

| Well Name | Latitude (º) | Longitude (º) |
|---|---|---|
| SF2B | 35.8334 | -106.1584 |
| SF3A | 35.8344 | -106.1613 |
| SF4A | 35.8352 | -106.1622 |
| SF6 | 35.7919 | -106.1222 |

**Methods**

The temperature-logging equipment consists of a thermistor attached to a wireline cable that measures resistance as a function of depth. Resistance is converted to temperature using a laboratory calibration based on a platinum thermistor. Resistance was recorded in water at 1-m-depth intervals at a rate of 2 m/minute using a digital multimeter and a computer. Water level in the well was measured using an electronic probe before logging began.

Monitoring wells in the BWF consist of three piezometers that sample waters from different depths (a=deepest); the wells in the piezometer nest are located within 3 meters of one another. The monitoring wells have screens only about 3 meters tall at the very bottom of the well that sample a discrete horizon. Monitoring well SF6a is located between the original BWF and the four new wells in the field; this well was logged in June 2013, June, 2014, and June 2016. Three of the monitoring wells in the original BWF, SF2, SF3, and SF4 were measured three to five times—for example, SF2b was measured in June 2013, December 2013, June 2014, June 2015, and June 2016. Water levels rose abruptly in the BWF in the spring of 2015. SF3a and SF4a were artesian in June 2015, and thus were not measured because the wells had been capped. Manning (2009) also logged SF2b and SF6a in the summer of 2005; temperature logs are not available prior to 2013 for the other monitoring wells. We were able to generally reproduce Manning's logs to within ±0.1°C, except in one short interval in SF2b.

To determine whether the measured changes in temperature through time observed in the wells was caused by a heat source located below bottom of the wells or by a heat source associated with a mapped fault in the area, a simple thermal diffusion length calculation was done:

$$L = \sqrt{\kappa t}.$$

Where L is the diffusion length. In other words: if a temperature change occurs at some time, after a given time interval, the change will have propagated over a distance $L=(k*t)^{1/2}$, through a medium with given thermal diffusivity. Thermal diffusivity is:

$$\kappa = \frac{k}{\rho C_p}$$

where k is thermal conductivity, ρ is density, C is specific heat. Typical thermal diffusivity values for saturated sand and saturated silt are, respectively, 0.079 $m^2$/day and 0.056 $m^2$/day (British Geological Survey, 2011).

**Results**

With the data acquired from the wells, four graphs were plotted for this study. The SF4 plot (***figure 2***) shows data from two wells in the piezometer nest, which are SF4a and SF4b, with information from measurements made in 2013, 2014, 2015, 2016. Between 2013 and 2014, the temperatures throughout the hole remained the same. Then abruptly in 2015, when the wells started flowing, the temperatures rose. Temperature has increased along the entire length of the wells between 2014 and 2016, with constant increase in temperature for both wells. Temperature has increased 0.33 ºC from 2014 to 2016 at SF4a and 0.4 ºC in the same period at SF4b. The geothermal gradient at SF4a and SF4b are 76.8 and 62.9 ºC/km, respectively.

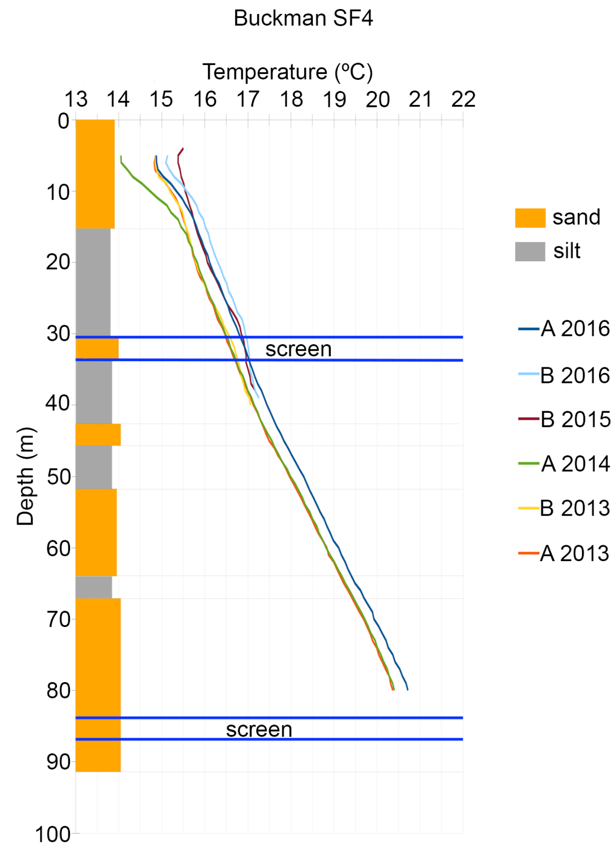


***Figure 2***: Temperature log of SF4a and SF4b, from 2013 to 2016.

The SF3 graphic (***figure 3***) shows data from SF3a and SF3b, with information from measurements made in 2013, 2014, 2015, 2016. Again, we observed no change in the temperatures measured between 2013 and 2014, and then after the wells started flowing in 2015, the temperatures rose. Temperature has increased along the entire length of SF3b, but at SF3a, comparing the curves of 2014 and 2016, temperature remained almost the same at the bottom of the well and increased more going up-hole. The temperature increased 0.19 ºC from 2014 to 2016 at SF3a and 0.27 ºC from 2015 to 2016 at SF3b.

The geothermal gradient at SF3a and SF3b are 69.2 and 63.7 ºC/km, respectively.

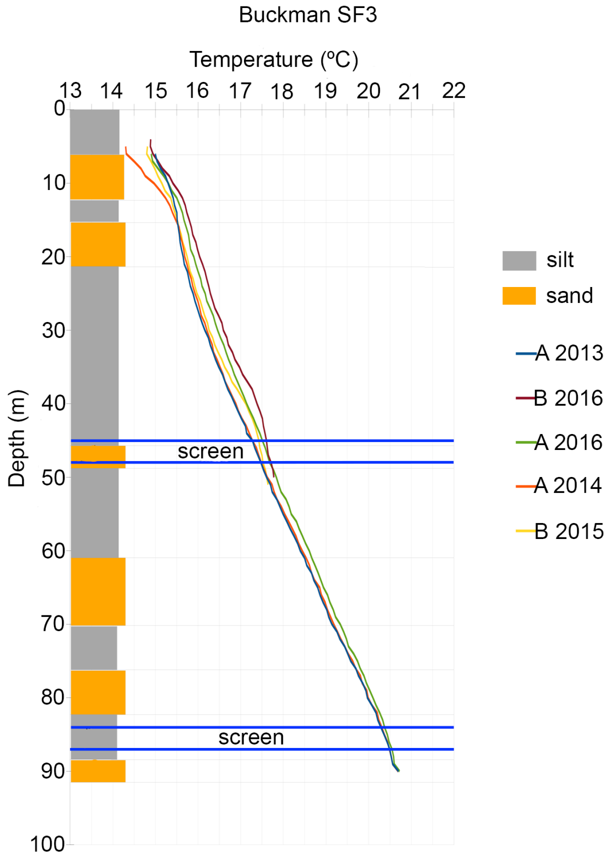


***Figure 3***: Temperature log of SF3a and SF3b, from 2013 to 2016.

Wells SF2b and SF2c are presented in the same plot (***figure 4***), showing data collected from 2013, 2014, 2015 and 2016. At SF2c, from 2013 to 2016, the temperature increased approximately 0.109 ºC in the entire well. While at SF2b, from 2013 to 2016, the average temperature decreased 0.031ºC. Hence, temperature changes at SF2b and SF2c are considerably small and both cooling and heating happen in these wells. The geothermal gradient at SF2b and SF2c is, respectively, 45.9 and 35.6 ºC/km.

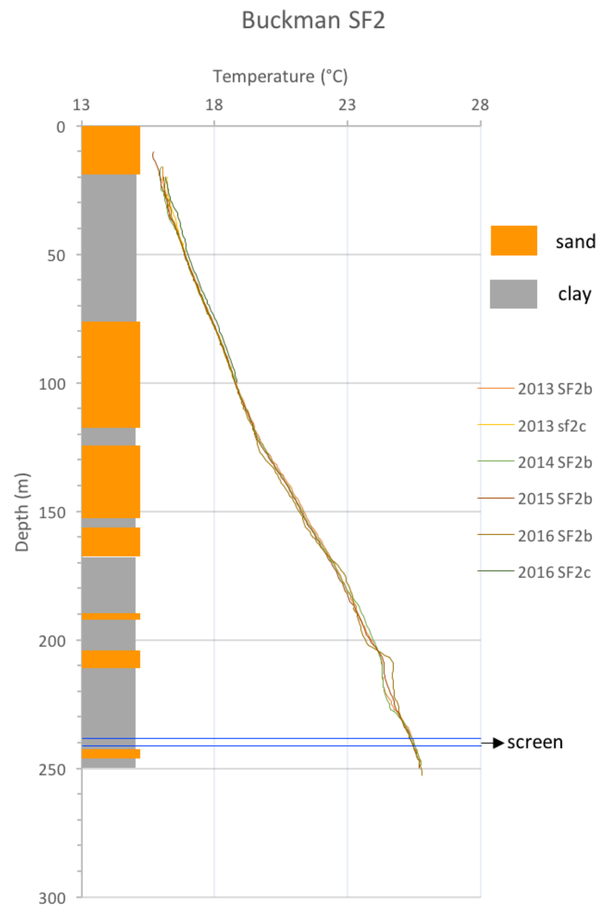


***Figure 4***: Temperature log of SF2b and SF2c, from 2013 to 2016.

The plot of SF6 (***figure 5***) contains information from measurements made in 2009, 2013, 2014, 2016. This well is in an area of the Buckman Field where temperature is not changing. In fact, its temperature has not changed since 2009. SF6 was used here in this study as a control well, to show that changing temperatures in SF4 and SF3 are not related to calibration issues of the thermistor. The geothermal gradient at SF6 is 35.2 ºC/km.

Two of the four wells are located in a hydrologic discharge area, where small normal faults concentrate upward flow of deep, thermal waters from underlying bedrock (Johnson et al, 2013), which explains the high geothermal gradients in this area.

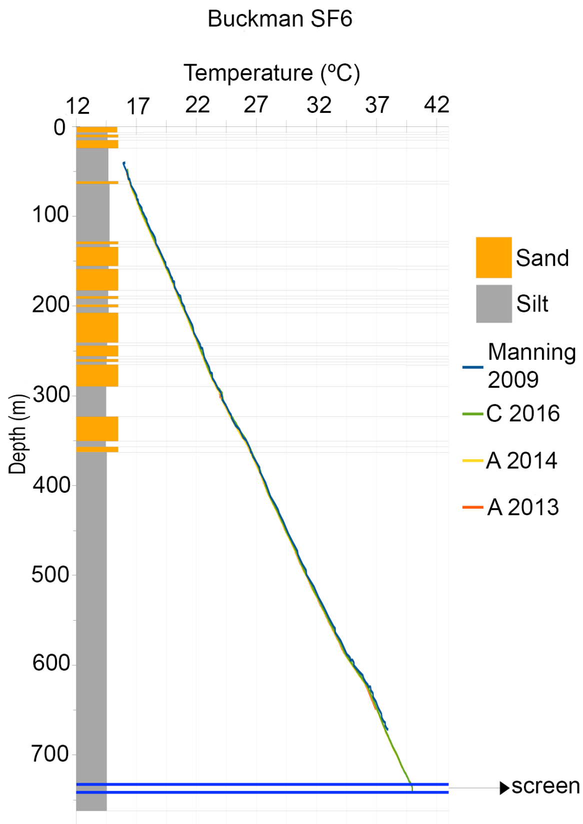


***Figure 5***: temperature log of SF6, with data from 2009, 2013, 2014 and 2016.

Next, we test the hypothesis that the heat responsible for the warming of SF3 and SF4 is coming from a source below the bottom of the wells. This hypothesis is based on the idea that, as water levels rise since pumping has decreased in the recent years, water coming from deep in the basin is warming up these wells. If we assume conductive heating of the wells from a warm aquifer located below the wells, then the diffusion length of the temperature change based on the thermal diffusivity values given above and a time interval of two years (2014 to 2016; 730.5 days) is 6.6 m for saturated sand and 6.4 m for saturated silt. This means that only the bottom 6 meters of these wells would have experienced an increase in temperature, as exemplified in ***figure 6***, and not the entire well, as happened with SF4. In ***figure 6***, the black line represents the temperature curve for 2014 and the red line represents the change in temperature that would have happened after 2 years, according to the diffusion length calculation. Because the temperature change would have affected only the bottom 6 meters of these wells, the hypothesis of heat coming from below the wells is rejected.

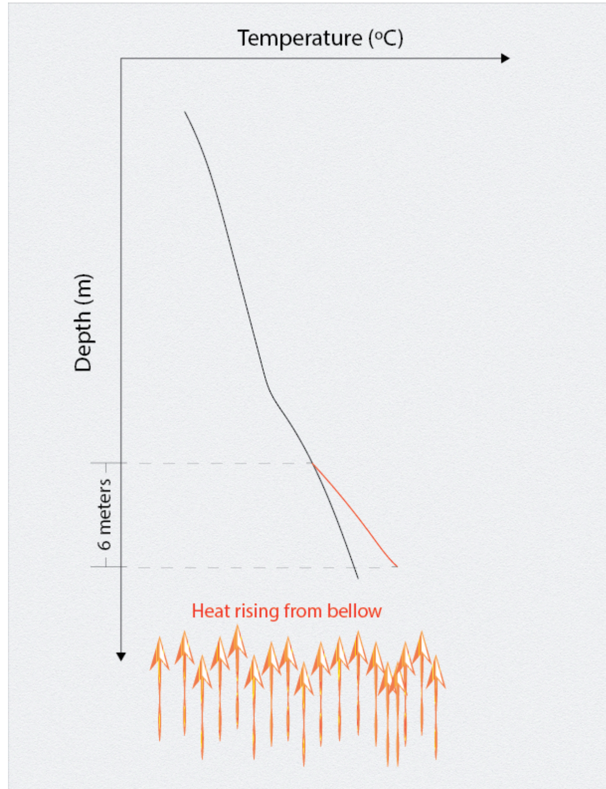


***Figure 6***: sketch for the expected temperature curve behavior based on the first hypothesis.

The second hypothesis is that heat is coming from the side via warm water moving up a normal fault west of SF4 and SF3. A mapped fault is located to the west of SF4, which is the well that shows highest temperatures and greater change in temperature. East of SF4 is SF3, which also has a high geothermal gradient and has a smaller change in temperature through time, followed by SF2, that experienced only localized temperature changes in this period of time.

The hypothesis of heat coming from west of the wells is represented in a schematic cross section (***figure 7***) that crosses the mapped fault, SF4, SF3, and SF2, respectively. A structural or stratigraphic discontinuity appears to separate the different thermal regimes of SF2 and SF3. This subsurface conceptual model illustrates the patterns of temperature increase in SF4 and SF3 from 2014 to 2016. Additionally, it also presents the subsurface geology, based on the stratigraphic fence diagram of the Buckman well field, from Koning et al (2007). The Vallito Member, present in the conceptual cross section, is part of the Chamita Formation within the Santa Fe Group.

The fault is filled with warm water that is coming from a deep source, flowing considerably fast, so that water temperature is the same over much of the faults upper reaches. Because water in the fault is warmer than the surrounding rocks, heat is being conducted away from the fault and this heat is warming up SF4. It is important to notice that this heat reaching SF4 is constant in all the well, from top to bottom, so, temperature is increasing uniformly at SF4. We also know there is no water flowing laterally away from the fault, because SF4 has a linear temperature gradient. Thus, around SF4, the isotherm is almost vertical. Past SF4, the heat then travels in the direction of SF3. When it reaches SF3, this heat warms the upper part of the well, as can be seen when analyzing the SF3 temperature log. Therefore, the isotherm close to SF3 is curved as shown in ***figure 7***. East of SF3, this heat coming from the fault does not influence temperatures in SF2, which leads us to infer that there is a hydrologic discontinuity between SF3 and SF2 that may be related to the discontinuous nature of sandstone lenses in the rift-fill sediments that form the BWF aquifer.

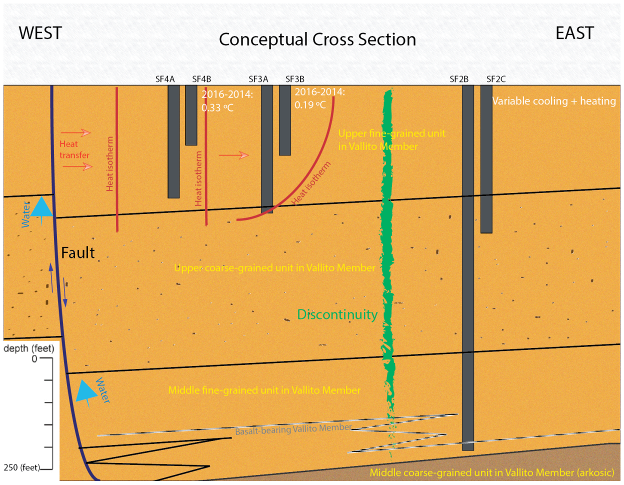


***Figure 7***: schematic cross section representing the hypothesis of heat coming from the fault to the west of the wells. Geologic information based on the work of Koning et al (2007).

## Conclusions

In conclusion, SF4 has the highest change in temperature, the highest temperatures and the temperature change affects the entire well. As for SF3, only the top part of the well is warming up. At SF6, temperature has not changed since 2013, so the observed temperature changes in SF3 and SF4 are not related to calibration issues. Most importantly, the source of heat is located to the west, as opposed to from below. The elevated geothermal gradients in SF3 and SF4 discovered by SAGE students in 2013 are changing and the temperatures are rising as water levels return to normal and the Buckman well field recovers from overpumping. Further studies will be conducted in this area by continuing to analyze temperature logs in these wells and nearby wells.

## Acknowledgments

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