PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

SPATIAL RELATIONSHIPS BETWEEN DYNAMIC RESERVOIR CHARACTERISTICS AND INDUCED SEISMICITY IN THE NORTHERN GEYSERS, CALIFORNIA

Katie L. Boyle and Ernest Majer

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94702
e-mail: Kboyle@lbl.gov

ABSTRACT

The Geysers is the largest-volume geothermal injection operation in the world, with injection volumes in the northern section of the field exceeding a total of 1.93E+9 kilopounds of water over the history of the field and total steam production in excess of 2.07E+10 kilopounds. The northwest Geysers area contains several high-volume injection wells located at the southwest section of a ring of seismicity that coincides with ongoing injection and production activity. The highest-volume producers in the NW Geysers reside on one side of low seismicity region (LSR) opposite the highest volume injectors; this region is locally referred to as the "doughnut hole." In the absence of simulation results to infer fluid flow paths, a number of hypotheses for the low-seismicity region have been suggested, including (1) an absence of flow or diminished flow through the low-seismicity region (reduced pore pressure), (2) cooling due to high volumes of cold injectate that have moved through the region and the ensuing diminished contribution of thermal contraction-induced microearthquakes, (3) near-complete release of stress due to a history of brittle failure in regions affected by flow. This article explores the first two ideas in the form of long-term trends in temperature and pressure at numerous production wells in the region, as well as fluid volume change and the spatial comparison of seismicity with injection and production at a number of wells. The low-seismicity region contains very few wells whose producing temperature and pressure could be included in calculations, but data from those wells suggests that temperature is decreasing near a high-volume injector in the LSR this well, and that pressure is both increasing and decreasing near this well. Instances of decoupled temperature and pressure are common for the field, and manifest as constant-pressure temperature change in the P-vs-T curves of wells in and outside of the LSR. The maximum fluid volume change, defined as amount injected minus the amount produced, overlaps spatially with the high-volume injectors in the southern LSR, and the minimum volume change occurs west of the LSR and in the northern LSR, suggesting that water produced from these regions is supplied by more than the adjacent low-volume injectors. Additional information comes from double-difference tomographic inversion for seismic velocity and wellbore water level. The combination of these varied data suggest that fluid is accumulating in the LSR, and that the diminished appearance of seismicity in this region may be related to the presence of this fluid.

INTRODUCTION

The Geysers

Production began in 1965 in the Geysers, and injection of seasonal runoff, streams, and rainwater began shortly after. From 1987-1990, the reservoir experienced a dramatic drop in production pressure associated with dry-out and conversion from a saturated steam to dry, super-heated steam state. Since then, there have been numerous attempts to restore reservoir pressure to its previous values through injection of effluent water from nearby communities, and most recently via a pipeline from Santa Rosa.

High-Volume Injection in the NW Geysers

The NW Geysers LSR was first identified by Stark (2003) as a visible ‘gap’ in deep seismicity in an area of especially high-volume coldwater injection (Figures 1 and 2). The majority of the injection activity comes from GDC26, a well in the southernmost extent of a prominent ring of microseismicity that maps to several other injection and production wells. Although the LSR contains very few wells, there is evidence that fluid is passing through based on a tritium tracer study (proprietary, Union Oil Company/Calpine, 1985), and in regional volume changes estimated from local well data which suggest a movement of fluid from south to north.

GDC26 has injected over 15000 Mgal of fluid over a 40-year period and is the highest-volume injector in the entire Geysers steam field. Injection in GDC26 started in 1984 and ended in early 2008. Although injection ended in 2008, the pattern of seismicity in the surrounding area has changed very little since. The location of GDC26 relative to prominent swarms of seismicity is depicted in Figures 1 and 2 using the 2005 LBNL-Geysers MEQ catalog as a representation of the typical distribution of seismicity observed since the start of LBNL monitoring.

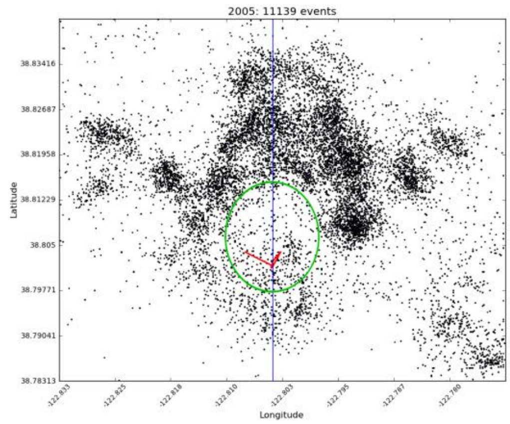


Figure 1. Plan view of seismicity in the NW Geysers with the directional survey of GDC26 shown in red. Blue line identifies cross-section depicted in Figure 2, below, and green oval approximates the LSR boundaries. North is upward.

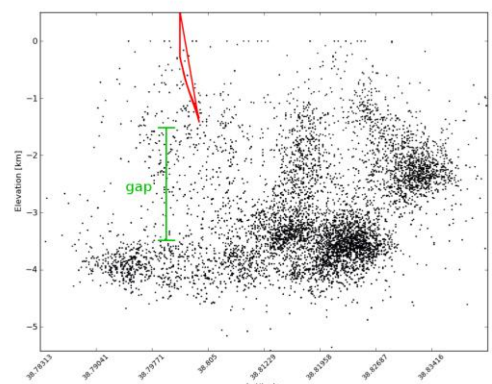


Figure 2. YZ slice of seismicity taken at lat = 38.801 (blue line on Figure 1) with the GDC26 directional survey shown in red. x-axis = latitude, y-axis = elevation. North is to the right.

For the time period depicted in Figures 1 and 2 (year 2005), the total amount injected in GDC26 was 940.79 Mgal. Note the sparse cloud of seismicity extending downward from the bottom of GDC26, and the slightly denser cluster at a depth of -4km. Note the dense clusters of both shallow and deep seismicity (shown in Figure 1) to the north of GDC26, associated with several lower-volume injectors and upwards of 50 producers north of the LSR. The shallow seismicity is not present below the bottom of GDC26. The reservoir activity in this region is complicated, and overlapping injection and production schedules confound the problem of correlating seismicity with injection and production volumes over time. Figure 3 shows injection amount in GDC26 vs. local (within a 1km radius) seismicity for the entire injection history of the well (1984 – 2008).

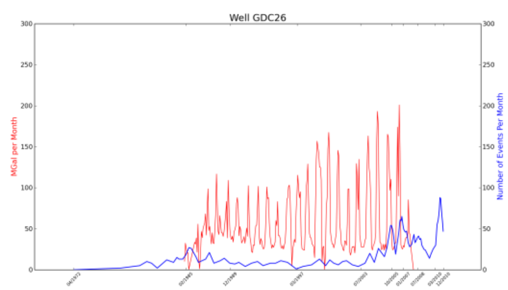


Figure 3. Injection amount vs. local seismicity for GDC26 over entire life of well.

The increase in monthly number of events in 2005 can be attributed to a combination of factors including an increase in injected water due to the Santa Rosa Wastewater injection program and increasing in MEQ monitoring capabilities that occurred gradually over the period of 2003-2005, when 15-20 USGS/Calpine recording stations were replaced with an array of approximately 30 4.5 Hz geophones operated by Lawrence Berkeley National Lab.

The seismicity around any given well in the NW Geysers is confounded spatially and temporally by overlapping injection schedules. Figure 4 shows the production in a well located about a quarter-km NW of GDC26.

Notice that the seismicity patterns are nearly identical at both this well and the one depicted in Figure 3, even though the injection/production schedules are different. It is very difficult to tell whether the peaks/troughs in seismicity are due to injection or production activity. While the high-frequency fluctuations in recorded events seem to map to the injection schedule, the longer-period trends in monthly number of events may also correlate with longer-period production trends.

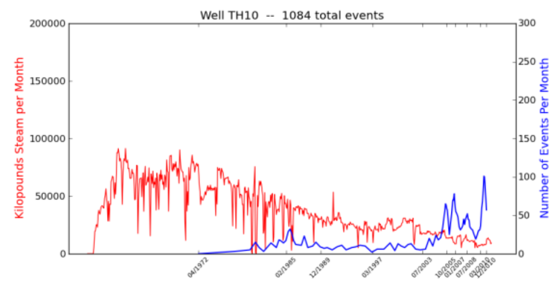


Figure 4. Production amount vs. seismicity for TH10, a producer near GDC26.

Cumulative Injection and Production in the NW Geysers

The cumulative injection for all northern Geysers wells during the period of 1972 – 2010 is depicted in Figure 5.

The largest production volume in the NW Geysers occurs just north of GDC26, which may indicate that the high volumes of fluid being injected in GDC26 are moving northward to be produced by 5-6 high-volume production wells. Cumulative production for the NW Geysers is shown in Figure 6.

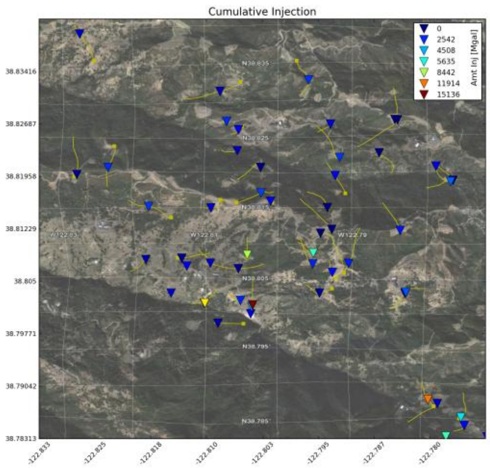


Figure 5. Cumulative injection for the period of 1972-2010 for NW Geysers wells. Injection amount plotted at the average water level along directional survey where available; otherwise, injection amount plotted at wellhead. Note: Dark red l is GDC26.

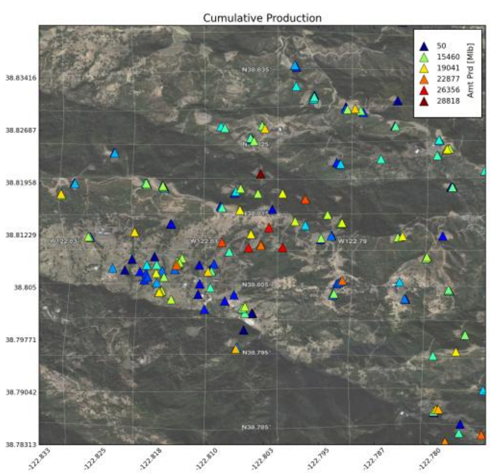


Figure 6. Cumulative production for the period of 1972-2010 for NW Geysers wells. Production amount plotted at the wellhead.

Note that the production amounts in the southwest are much lower than those in the north.

__Induced Seismicity and Dynamic Reservoir Properties__

Figure 7 shows the seismicity, injection, and production for a 6-month period in 2005.

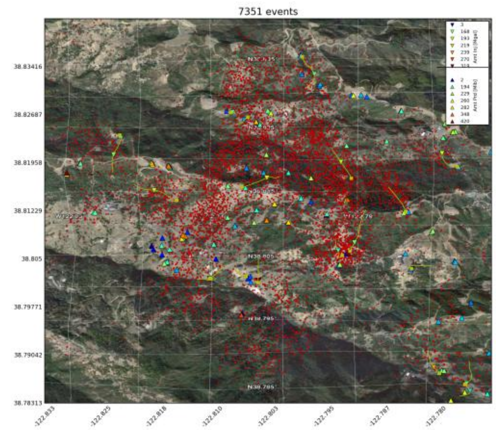


Figure 7. Injection, production, seismicity for a 6-month period in 2005.

Note the presence of a LSR: a region of disproportionately lower rates of seismicity compared to surrounding regions. The LSR contains very few injectors and producers, but from those present, an estimate of fluid volume change (net amount injected minus amount produced) can be made by adding injection volumes for all wellheads within the gridblock and subtracting from this the volume of fluid produced by wells within this gridblock. Injection amounts were tallied in the gridblock containing the latitude and longitude of the average water level (as a function of rate) for the well, or at the wellhead when water level data were not available. The uncertainty in 'injection point' is, therefore, on the order of a typical horizontal well deviation when water level is not known. Even when water level is known, the uncertainty in the location of water entry into the formation is still high. Water could enter the formation at all known steam entries below the water level, and so defining a 3-dimensional nucleation point is extremely challenging. With these concepts in mind, Figure 8 shows estimated volume change for the NW Geysers.

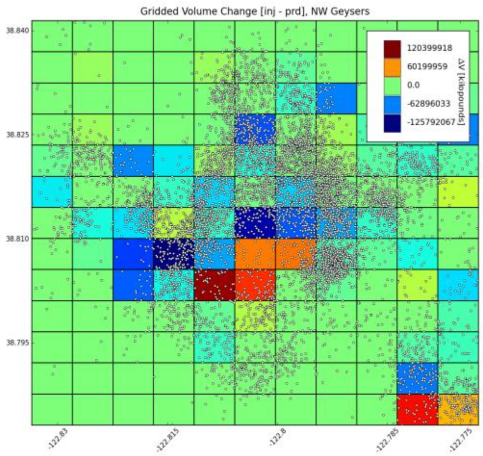


Figure 8. Fluid volume change (amount injected minus amount produced) for the period 1972 – 2010 gridded to the half km. 2005 MEQ catalog plotted for spatial reference.

There appears to be more fluid injected than produced in the LSR near GDC26 and more fluid produced than injected in the ring of seismicity surrounding the LSR. This suggests that the fluid being injected in GDC26 is moving out of the LSR to the north and west, and so seismicity is reasonably expected to occur along the flowpath. The flowpath is not known, but the 1985 tracer test results confirm that fluid is moving from southern LSR wells to northern LSR wells, but provide little information about how they traverse the region in between. It is, of course, possible that fluid is moving around the LSR and not through it, explaining the lack of seismicity at the LSR center, but the physical barriers leading to such a system are not known. The main steam reservoir is underlain by a high-temperature reservoir (HTR), where temperatures can exceed 350C (Walters, et.al, 1992), but it is unknown whether the presence of the HTR or its heat source could be responsible for the lack of seismicity.

If fluid is moving through the LSR, one possible explanation for the lack of seismicity is that plumes of injectate have coalesced in this region, having de-stressed the matrix in doing so (Beall, 2007) and potential cooling the region. Another explanation is that the temperature contrast between the cold injectate and hot reservoir rock is affected by the shallower extent of the High-Temperature Zone in this region. The gap in seismicity represents a region where the water temperature has reached the reservoir temperature (no thermal contrast), positioned below the normal reservoir (where seismicity occurs as cold injectate warms to reservoir temperature), and just above the upper surface of the HTR, where seismicity also occurs because the temperature contrast between the rock and heated water increases dramatically (Stark, 2003). The temperature and pressure properties of the LSR and surrounding region may provide information about its dynamic state. If temperature in the LSR is declining, it could suggest that the rock has cooled and thus there is a diminished contribution of thermal contrast to the occurrence of induced seismicity. If pressure is dropping in the LSR, it may suggest that fluid is not flowing into it, but is being diverted elsewhere.

Some information may come from wellhead pressure and temperature measurements, which are made monthly at most production wells. Since there are relatively few producing wells within the LSR, the pressure and temperature data points in that region are few, and so little can be said about the areas in between wells. Additionally, challenges in measuring wellhead temperature may cause scatter in temperature vs. time data.

The expectation is that temperature will be declining over time in all regions in the NW Geysers due to the high volumes of cold injectate being introduced and the steam being produced, carrying with it the reservoir rock’s heat. A coupled decline in pressure is expected. As temperature and pressure decrease, the expectation is that more liquid phase will be left behind and so the saturation of regions where liquid is pooling should be increasing slightly.

METHOD

Study Area

The study area boundaries extended from longitudes -122.83355 to -122.77255 and from latitudes 38.78313 to 38.84145. This encompasses the wellheads of over 300 injection and production wells. Approximately half of these wells were production wells with publicly available temperature and pressure data. The plots below illustrate the method used to estimate changes in reservoir properties over time; a specific well has been selected to provide an example of each reservoir property considered. The interest was in potential variation of 1) pressure change, 2) temperature change, and 3) superheating over the study area; specifically, were there any anomalies in these properties associated with the LSR?

Production Data

Wellhead pressure and temperature was analyzed for 152 wells in the NW Geysers for the period of 1990 – 2010. Production data was obtained from the Department of Oil, Gas, and Geothermal Resources (DOGGR) website operated by the California Department of Conservation. To circumvent peaks and troughs in reservoir properties accompanying the dramatic reservoir dry-out, only data from 1990 onward were used.

Datasets of log10(pressure) vs. time were fit via linear regression to obtain a rough estimate of monthly pressure change over the 20-year study period. Figure 9 shows data from one well with the linear fit superimposed over the raw data.

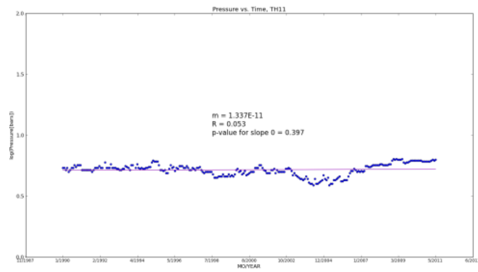


Figure 9. log(p) vs. time in well TH11, with slope obtained from linear regression.

The change in temperature over time was estimated in a similar manner (Figure 10), but showed much higher scatter than did the pressure data.

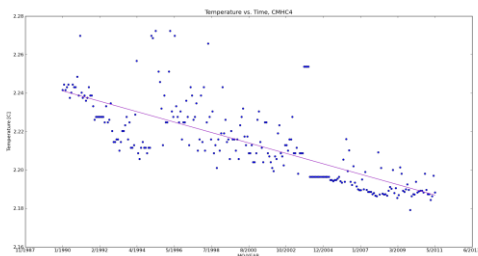


Figure 10. log(T) vs. time in well CMHC4, with slope obtained from linear regression.

Most wells show significant periods of superheating in plots of temperature vs. pressure. Figure 12 shows data from well CMHC6518, exhibiting this behavior.

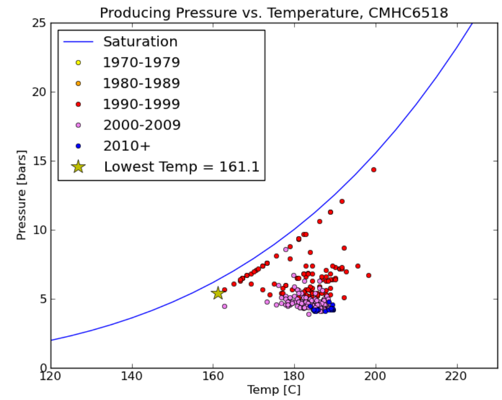


Figure 11. Temperature vs. pressure for production well CMHC6518, showing sustained period of superheating in 2000-2009.

Another indicator of dynamic reservoir properties may come in the form of injection well water level over time (Figure 13).

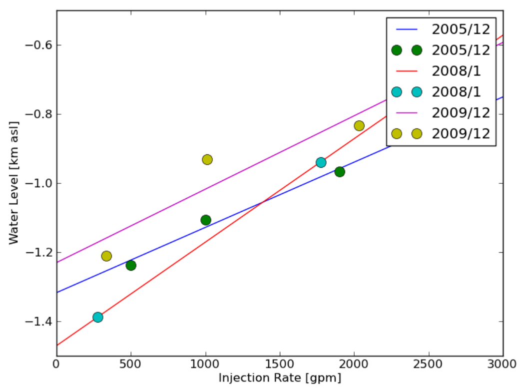


Figure 12. Water level as a function of injection rate and injectivity test date in a NW Geysers well.

Water level is measured during injectivity tests, and is a function of injection rate. Several injectivity tests are conducted over the life of a well, and changes to rate-dependent water level are noted. A water level which rises over time for the same injection rate can be an indicator of several things, including decreased permeability due to scaling or exsolution of silica in fractures, and high reservoir pressure in the region immediately around the well due to local fluid coalescence. The latter should be accompanied by an increase in liquid saturation at nearby production wells over time.

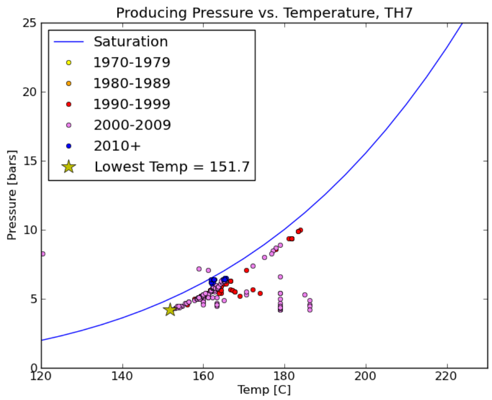
RESULTS

Spatial Distribution Seismicity and Properties

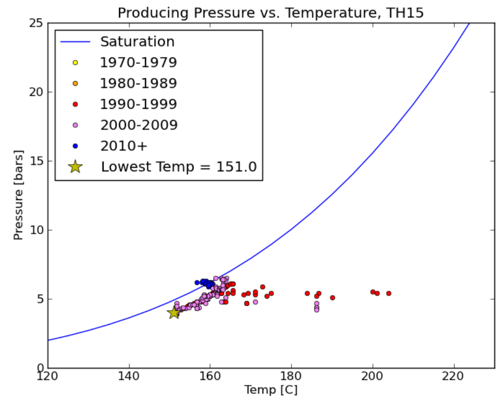
There are only a few wells in the center of the LSR, and so inference about reservoir properties in this region must be made using these wells and wells situated around the LSR perimeter. The group of 5 producers adjacent to GDC26 will be referred to as the GDC26 Local Producer Group (GPLG). The GPLG group contains TH7, TH10, TH11, TH15, and THORNE10. The patchy distribution of producers will leave much of the LSR unaddressed, but where production data is sparse, seismic tomography may provide insight into reservoir properties.

Pressure vs. Temperature

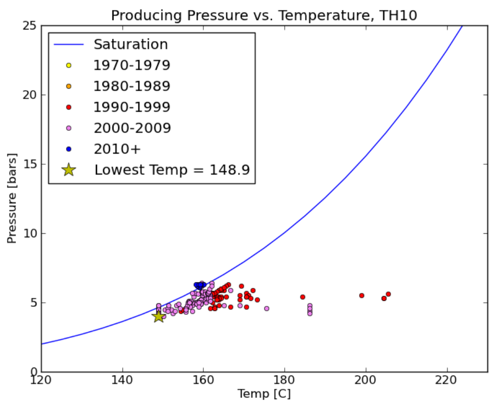
GPLG wells generally appear to experience less superheating than neighboring wells, with exception of THORNE10, which exhibits a significant amount of superheating. Plots of pressure vs. time for the five GPLG wells are shown in Figures 13 and 14, along with plots of four wells in the region surrounding the LSR.



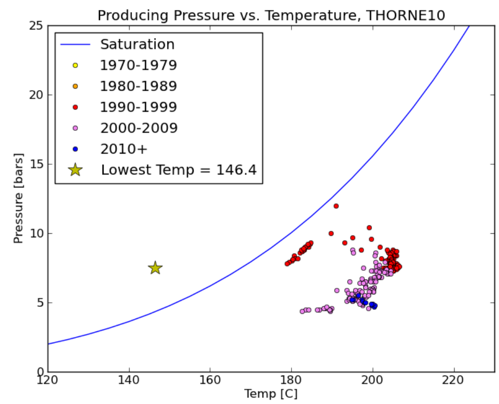
(a)



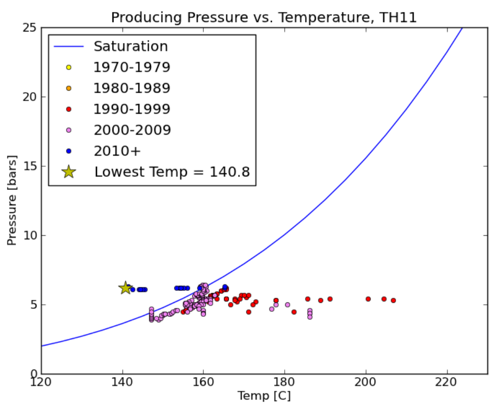
(d)



(b)



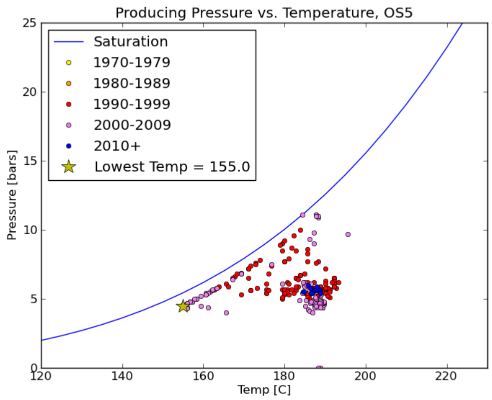
(e)



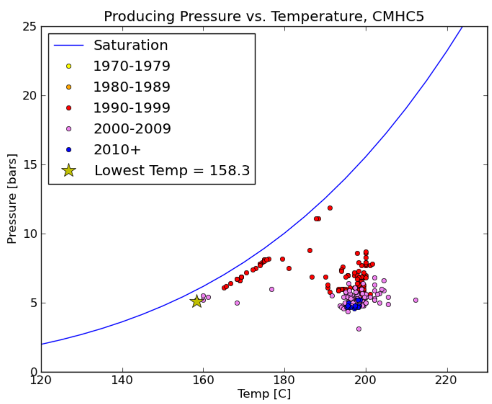
(c)

Figure 13. Pressure vs. temperature for GLPG wells.

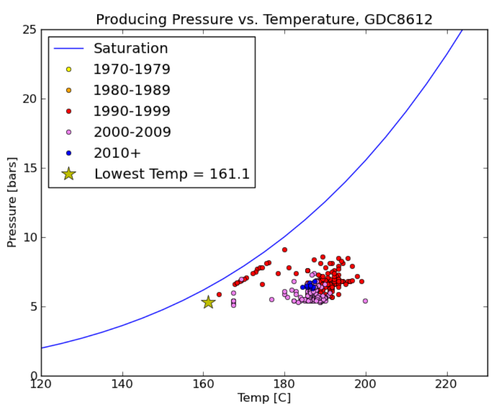
Four of the five GLPG wells exhibit minimal superheating, while Thorne10, which is deviated approximately 1.5 km to the west, shows marked superheating. Approximately half of the wells with available pressure and temperature data exhibit superheating, with majority of such wells occurring to the immediate west of the LSR. Four such wells are shown in Figure 14.



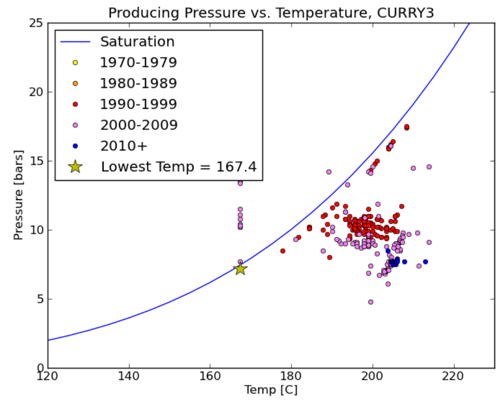
(a)



(b)



(c)



(d)

Figure 14. Pressure vs. temperature for several wells outside of the LSR.

The grouping together of wells with similar trends in superheating reflect sensitivity to local reservoir activity, and suggest that transit of reservoir fluids may be happening more slowly than the pressure change introduced by injection and production. The lower tendency toward superheating in the GLPG wells suggest that fluid is remaining near these wells long enough to be produced, and to produce steam which largely lies along the saturation curve.

Water Level

Over time, GDC26 appears to be experiencing a steady water level as a function of injection rate, although one outlier from a 2002 injectivity test showed anomalously low water levels in the well at an injection rate typically associated with higher water levels. With this data point included, the water level in GDC26 shows a net increase over time, but this outlier may be attributable to operational interruptions having nothing to do with pressures in the nearby formation. For this reason, the water level provides little insight into the pressure near the wellbore. No water level data is available for wells in the GLPG. Although these are production wells, many of the wells in the Geysers switch between injection and production, and injectivity tests during such a switch could have made water level data available.

Dynamic Pressure

There is no anomalous pressure change associated with wells proximal to the LSR, with exception of a producer with more dramatically-declining pressure present in the GPLG. Overall pressure is gently declining in the GPLG, with exception of one well that is slightly increasing in pressure. The pressure changes in this group of wells are comparable to those of the surrounding wells.

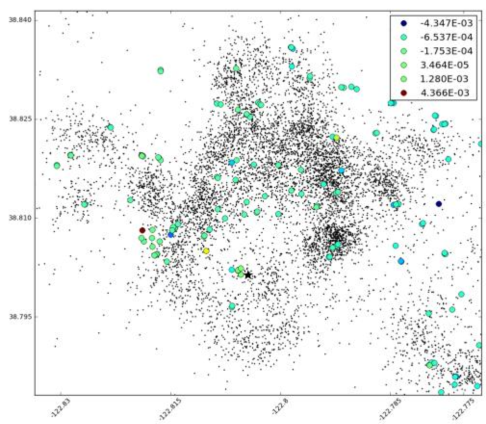


Figure 15. Plan view of approximated pressure change for NW Geysers. .

Temperature

There is no anomalous temperature change associated with wells proximal to the LSR. Temperatures in the GLPG are decreasing slightly with time, with a few wells on the perimeter of the LSR experiencing temperature increase.

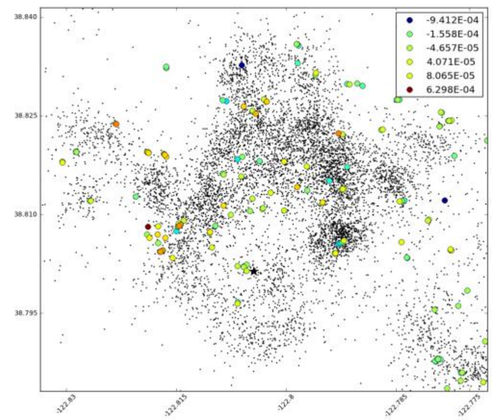


Figure 16. Plan view of approximated temperature change for NW Geysers.

Vp/Vs Ratios in 2005

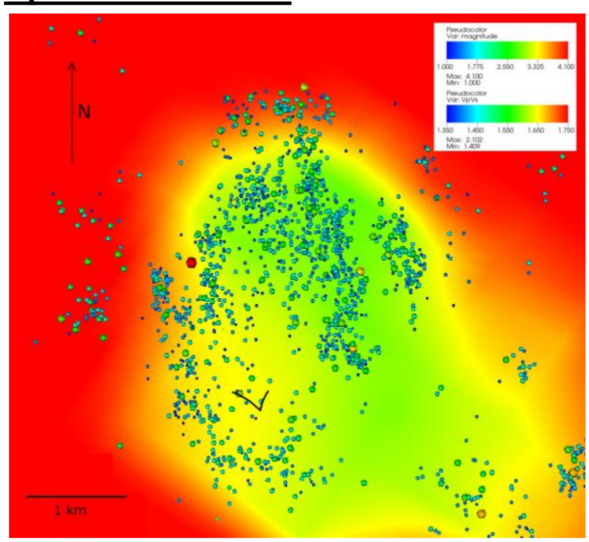


Figure 17. Plan view of V_P/V_S from double-difference tomography, co-plotted with microseismicity and approximate GDC26 well trajectory. Note: colors restricted to range 1.35 – 1.75 to better resolve differences in V_P/V_S in this region.

In Figures 19 and 20, the plot colors have been restricted to the range 1.35 – 1.75 to resolve fine-scale differences in V_P/V_S in this region. Outside the region, all V_P/V_S values greater than or equal to 1.75 (the upper bound of the plot colors) have been forced to red.

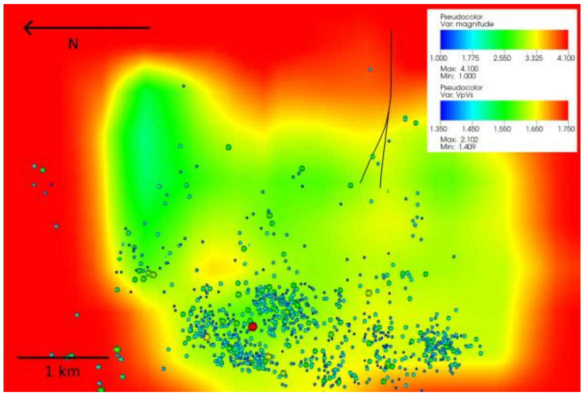


Figure 18. S-N view of V_P/V_S from double-difference tomography, co-plotted with microseismicity and lower extent of GDC26 well trajectory. Note: the double trajectories correspond to both the original well trajectory and the re-drilled trajectory. Colors restricted to range 1.35 – 1.75 to better resolve differences in V_P/V_S in this region.

While dynamic steam quality does not reveal any anomalous behavior around the high-volume injector, a snapshot of V_P/V_S taken using double-difference tomographic inversion of the 2005 LBNL-Geysers MEQ dataset reveals that GDC26 and the LSR might differ in steam quality properties from the surrounding area. The entire study region is characterized by generally low Vp/Vs values, with a slight increase in Vp/Vs approximately halfway down the trajectory of GDC26 to a depth of approximately -3.7km. This region of increased V_P/V_S spreads out gradually with increased depth from the GDC26 terminus and encompasses much of the LSR to the north. Low values of V_P/V_S have been shown to correspond to areas of heavy depletion and marked pressure drops (Foulger et.al, 1997) and also with relative dryness (Julian et. al, 1996). The slightly higher values of V_P/V_S beneath GDC26 and in the LSR suggest the presence of greater quantities of pore fluid in these regions. The lower values of V_P/V_S to the north of the LSR suggest relative dryness around the cluster of producers located at its northern extent. There is a faint gap in the higher V_P/V_S values just under the bottom of GDC26 (a depth of approximately 2.5 km) which may suggest the presence of an impermeable boundary here. This gap may also be an artifact of the distribution of seismicity, but since most of the source-receiver raypaths that resolved these velocity values came from a greater depth, that is unlikely.

CONCLUSION

Dynamic Properties

A group of producers proximal to GDC26 shows a slight decrease in pressure and a decrease in temperature over time, however there are no significant spatial anomalies in dynamic reservoir properties in LSR as obtained from wellhead production data. The trends of the GLPG mirror those of the majority of the study area. GLPG wells generally exhibited less constant-temperature pressure change/superheating than did wells in the region surrounding the LSR with exception of Thorne10. Thorne10 is on the other side of the other GLPG producers, and is deviated 1.5 km to the west, so it is likely supplied by injection west of the LSR than from injection in GDC26. The water level in GDC26 shows a slight increase over time, but this may be due entirely to an outlier. Limited water level data was available, with one data point measured every 2-3 years.

Static Properties

Seismic tomography using data from the 2005 LBNL MEQ catalog reveals a low V_P/V_S anomaly coincident with the LSR, with higher V_P/V_S values in the immediate vicinity of GDC26. The higher V_P/V_S values around GDC26 extend to a depth of approximately -3.7 km, with a low-V_P/V_S gap just beneath the wellbore terminus and continued higher V_P/V_S values beyond this gap. These results suggest that fluid is accumulating beneath GDC26 and in the LSR.

ACKNOWLEDGMENTS

We would like to thank Mark Walters, Craig Hartline, and Joe Beall, Calpine Corporation, for access to data and input. This work is funded by Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Program of the U.S. Department of Energy under ***Contract No. DE-AC02-05CH11231***.

REFERENCES

Beall, J.J., Wright, M.C., Pingol, A.S., and Atkinson, P. (2010). Effect of High Rate Injection on Seismicity in The Geysers. *Geothermal Resources Council Transactions*, **34**, 1203-1208

Foulger, G.R., Grant, C.C., Ross, A. (1997). Industrially induced changes in Earth structure at The Geysers geothermal area, California. *Geophysical Research Letters*, **24**, 135-137.

Julian, B. R., Ross, A., Foulger, G.R. (1996). Three-dimensional image of reservoir depletion at The Geysers geothermal area, California, from V_P/V_S ratios. *Geophysical Research Letters*, **23**, 685-688.

Reyes, J.L.P., Li, K., and Horne, R.N. (2003). Estimating water saturation at The Geysers based on historical pressure and temperature production data and by direct measurement. *Geothermal Resources Council Transactions*, **27**.

Stark, M. (2003). Seismic evidence for a long-lived enhanced geothermal system (EGS) in the northern Geysers reservoir. *Geothermal Resources Council Transactions*, **27**, 727-731.

Unocal/Calpine Tracer Study, *Proprietary*, 1985. Author: Steve Enedy

Walters, M.A., Haizlip, J.R., Sternfield, J.N., Drenick, A.F., and Combs, J. (1992). A vapor-dominated high-temperature reservoir at The Geysers, California. Geothermal Resources Council Special Report, 17, 77-87.