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Geothermal production and reduced seismicity: Correlation and proposed mechanism

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ABSTRACT

At Brady Hot Springs, a geothermal field in Nevada, heated fluids have been extracted, cooled, and re-injected to produce electrical power since 1992. Analysis of daily pumping records and catalogs of microseismicity between 2010 and 2015 indicates a statistically significant correlation between days when the daily volume of production was at or above its long-term average rate and days when no seismic event was detected. Conversely, shutdowns in pumping for plant maintenance correlate with increased microseismicity. We hypothesize that the effective stress in the subsurface has adapted to the long-term normal operations (deep extraction) at the site. Under this hypothesis, extraction of fluids inhibits fault slip by increasing the effective stress on faults; in contrast, brief pumping cessations represent times when effective stress is decreased below its long-term average, increasing the likelihood of microseismicity.

1. Introduction

Fluid movement has long been associated with geologic faults (e.g., Hubbert and Rubey, 1959). In the Basin and Range Province, many geothermal fields coincide with systems of normal faults (e.g., Faulds et al., 2013). One such example is the geothermal field at Brady Hot Springs, northeast of Fernley, Nevada, USA (henceforth, "Brady"). Likewise, fluid pressure and seismicity on faults are associated. The effect of fluid pressure changes on the occurrence of seismic events has been recognized at a number of locations around the world, where fluid injections have been correlated with increases in seismic activity (Ellsworth, 2013). Injecting fluids in the subsurface perturbs the natural long-term stress state of a reservoir by increasing pore pressure; this increase in pore pressure results in a decrease in effective stress on faults, which can induce fault slip and associated seismic events. According to the "critical stress" hypothesis, even a small change in ambient pore pressure could facilitate fault slip via this process (Zoback and Harjes, 1997). "Triggering thresholds" associated with fault failure have been suggested as low as 0.01 MPa to 0.1 MPa (Gomberg et al., 2001), although there appears to be spatial variability in this sensitivity, which is a subject of current research. A standard conversion from pressure change to equivalent fluid height change would then suggest that a local change in water pressure equivalent to approximately 10 m of hydraulic head change has the potential to initiate seismic events at susceptible locations. Based on this mechanism, several studies at geothermal fields have correlated seismicity rates with changes to monthly injection rates (i.e., total injection from all wells) or net production rates (i.e., total extraction minus total injection via wells) (Brodsky and Lajoie, 2013; Johnson et al., 2016; Trugman et al., 2016).

The effect of pore pressure has been studied most prominently where ambient fluid pore pressure on faults is presumed to have been increased by fluid injection. However, ambient pore fluid pressure may also be raised by the opposite mechanism – i.e.,

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a cessation of long-term extraction. Previous studies have noticed an apparent association between suspension of pumping operations and the occurrence of microseismicity at Brady (Davatzes et al., 2013a, 2013b). In this study, we analyze this association by quantifying the correlation in time and space, and we suggest a causal mechanism for the correlation. We present two data sets that support this correlation: a short-term record of pumping and pressure changes with minute-level information collected over a time interval of one month, and a comparable long-term daily record of pumping over a time interval of many years. We then correlate these data sets with records of local microseismicity to provide evidence that pressure perturbations associated with changes in pumping rates propagate quickly in the reservoir and consequently alter the effective stress on nearby faults. In comparing our study to earlier geothermal studies where correlations between operations and seismicity were evaluated, we note that our study takes advantage of: (1) Detailed records of the locations and daily timing of pumping rate changes (i.e., individual well flow rates); (2) Access to the positioning (depth, screen lengths) of all active site wells; and (3) Access to install a pressure observation well at the site during operations. These data have also been made available to the research community for further analysis on the Geothermal Data Repository (https://gdr.openei.org/) operated by the Department of Energy (DOE) Geothermal Technologies Office (Foxall, 2014, 2016; Lim, 2016, 2017).

2. Background

The site at Brady was initially developed in the 1920's for direct use (Lund, 1982). Then, in the 1950's, several parties performed exploratory drilling, and a geothermal power plant was established successfully in 1992, which has been operating continuously to the present day (Ettinger and Brugman, 1992). Since 2004, the site has been operated and monitored by ORMAT Technologies Inc. and its subsidiaries (henceforth “ORMAT”) and produces clean electrical power from geothermal energy at a rate of roughly 10 MWe. In collaboration with DOE, universities, and national laboratories, ORMAT has made historical records of site operations available for scientific investigations, and has also allowed access and experimentation by scientific researchers, in an effort to better understand the geothermal resource. The short-term data presented in this work represent the results of one such experiment, PoroTomo (Poroelastic Tomography), carried out in March 2016, during which ORMAT allowed access and use of the site for hydrologic and geophysical investigations. Longer-term data sources presented in this work represent other project efforts, including the “Brady EGS” and the “InSAR-MEQ” Projects, both funded by DOE.

The study area at Brady is located in the Basin and Range Province of western Nevada, USA approximately 80 km northeast of Reno along Interstate Highway 80. This region is characterized by a transtensional tectonic regime, and is dominated by normal faults striking SW–NE (Fig. 1). In the vicinity of Brady, Faulds and colleagues (Faulds et al., 2006, 2010) have mapped surface fault and formation boundaries, collected seismic reflection profiles, recorded gravity data, and examined well cores. Building on these observations, several studies have interpreted and integrated existing data sources to develop 3-D geologic models for the subsurface structure beneath Brady (Jolie et al., 2015; Siler et al., 2016; Witter et al., 2016). These geologic models show two distinct sets of normal faults, with one set dipping to the NW and the other to the SE. The faults cut through a series of sedimentary units of Pliocene to Miocene age and through volcanic, intrusive igneous, and metamorphic rock layers of Miocene to Mesozoic age. The damage zones associated with this intricate network of faults form the geothermal resource tapped by production wells at Brady (Ali et al., 2016; Davatzes et al., 2013a; Laboso and Davatzes, 2016; Siler et al., 2016). These studies suggest that the geothermal reservoir is partially recharged by highly permeable conduits along faults, which channel fluids from shallow aquifers to the deep geothermal reservoir.

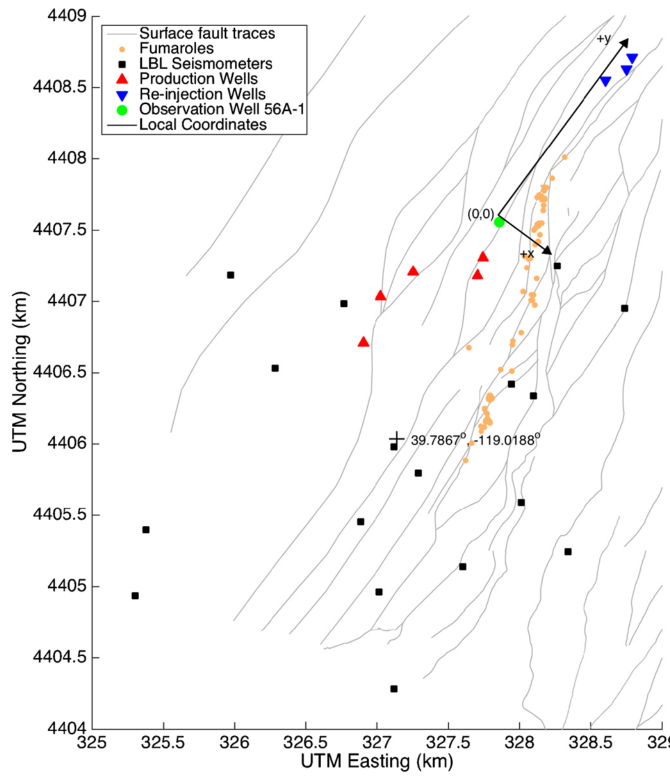

Fig. 1. Local map of Brady Hot Springs showing well and seismometer locations, surface fault expressions (Faulds et al., 2010), and local coordinate scheme, as used in Fig. 3. Fiducial point represents latitude and longitude for Brady well 15–12.

The operational infrastructure at Brady includes several deep production wells that range from approximately 400 m to 1800 m below land surface (bls). Insulated pipes carry super-heated brine to the Brady power plant, where geothermal energy is extracted through a dual-flash system (the Ormat Energy Converter) that drives a set of turbines. After heat extraction, the cooled water is recycled back into the subsurface. Most of the cooled fluid flows into three much shallower injection wells (∼200 m bls) located approximately 2 km northeast of the plant, while a small proportion is redirected to a similarly shallow offsite injection well approximately 6 km to the south of the geothermal plant in a separate basin. A negligible amount of brine is pumped for direct use by a nearby vegetable drying plant.

3. Data

3.1. Long-term pumping records

Daily extraction and injection volumes at the Brady site have been continuously recorded by ORMAT and were supplied to the PoroTomo project for dates between 2004 January 1 to 2016 March 28. The data set includes: (1) daily observation of extraction and injection flow rates in gallons per minute, recorded primarily through manual gauge readings; and (2) a record of the daily time online, in minutes, for each well. For the time interval coincident with the seismic event catalogs discussed later, the database contains a complete daily record, although the time series contains several gaps before 2008. To find the total daily extracted and injected volumes, we multiplied the flow rate recorded by the number of minutes of operation for each well and converted the