# COMPARISON OF MECHANISMS PROPOSED FOR INDUCED SEISMICITY AT THE GEYSERS GEOTHERMAL FIELD

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Three mechanisms are capable of explaining the induced seismicity at The Geysers field. Cooling and contraction may weaken the reservoir rock making it more susceptible to rupture. Conversely, the reservoir's location in a 100-km-wide region undergoing predominantly aseismic creep, suggests that strengthening of the reservoir rock may cause an increase in the component of seismic slip. This phenomena could be a result of a large pore pressure decline, or an increase in the coefficient of friction on the sliding fracture surfaces.

## INTRODUCTION

The Geysers geothermal field in Northern California (Fig. 1) is presently generating close to 1000 MW of electricity. Exploitation of the geothermal energy has caused measurable changes in the physical state of the reservoir. Withdrawal of steam has created an enlarging pressure sink around the production borefield (Lipman et al., 1978). A corresponding decline in gravity indicates that the steam is being derived from boiling pore water at production depths, and that there is negligible recharge to the reservoir (Isherwood, 1977). Both subsidence and horizontal shortening at rates of several cm/y have occurred during the mid 1970's (Lofgren, 1981). Marks et al. (1978) concluded from the limited available data that the present level of seismicity at The Geysers is higher than preproduction levels. Both the spatial coincidence of earthquake activity with the production borefield, and the unusually continuous nature of the activity, strongly suggest that the seismicity is induced (Bufe et al., 1981). The present rate of earthquake activity is approximately 35 times higher than that in the surrounding region.

While most of the changes that have occurred within The Geysers reservoir are readily explained by the mass withdrawal, the induced seismicity appears to be unique, and a mechanism for the earthquakes is not immediately obvious. A causal link between induced seismicity and increased pore pressure from injection of water down deep wells, or from the filling of large dams, is well documented. The physical basis for this phenomenon can be expressed as a wellknown frictional law of the form:

$$\tau = \mu(\sigma_n - cP) \qquad (1)$$

where $\tau$ = frictional resistance
$\sigma_n$ = normal stress
$P$ = pore pressure
$\mu$ = coefficient of dynamic friction
$c$ = $1 - Bg/Br$
$Bg$ = compressibility, of rock grains
$Br$ = compressibility of rock matrix

For most rocks $Bg \ll Br$, so $c = 1$; and for a wide range of conditions $\mu$ is in the range 0.6 to 0.9.

As The Geysers reservoir is being depleted of fluid, pore pressure is declining and therefore the frictional resistance, or effective strength, of the reservoir should be increasing with time. Normally, this would be expected to cause a decline in seismicity. As explained above, the steam withdrawal has had the opposite effect, and. therefore some other factor(s) must be causing the seismicity.

Three mechanisms are reviewed below. The first, proposed by Denlinger and Bufe (1980, 1981, in prep.) involves temperature changes in the reservoir rock caused by boiling pore water; the second and third mechanisms involve the conversion of aseismic creep to seismic slip as a result of production, and these are discussed in detail by Allis (1981, in prep.).

## THERMAL MECHANISM

Although steam is the mobile fluid phase at The Geysers, consideration of both the gravity changes, and the volume of steam produced, strongly suggest that boiling pore water at production depths is the source of the steam (Isherwood, 1977; Denlinger et al., 1981). This boiling is accompanied by a temperature decline of the reservoir rock. If 1% of the rock volume underqoes a conversion of liquid water to steam, the associated temperature decline would be about 5 °C. Denlinger and Bufe (1980, 1981 in prep.) suggest cooling of the reservoir rock may trigger seismic rupture. They consider the most likely mechanism to be contraction of fracture surfaces reducing the surface, frictional area in contact. An approximate balance between the volume increase associated with a pressure decline AP, and the volume decrease associated with a temperature decline AT is given by

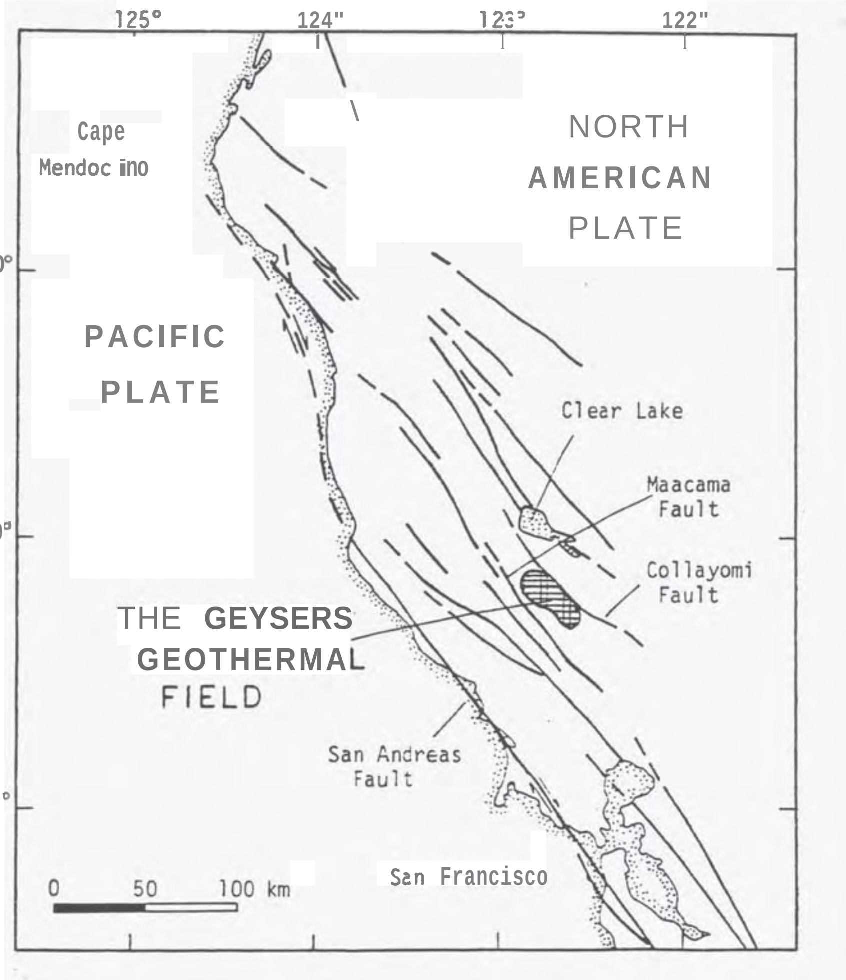


Fig. 1. Location of The Geysers geothermal field in the San Andreas Fault system of northern California (after McLaughlin, 1981). Fault traces are dashed where approximate.

$$C\Delta P = kK\Delta T$$

where–): = volume coefficient of thermal expansion ($5x10^{-5}$ /°C) and K = bulk modulus ($10^{5}$ bars). Inserting the values, a temperature decline of 1°C *is* equivaient to a pore pressure decline of 5 bars (Denlinger and Bufe, 1981). The actual temperature decline that has occurred at The Geysers is not known. However, comparison of the gravity changes that occurred between 1974 and 1977, the volume of the reservoir, and the known mass of fluid produced during that time, suggests that volume of water which has flashed to steam is less than about 1% of rock volume (Denlinger et al. 1981). Although this is very small, the thermal contraction effects may still be dominant. This mechanism has not been observed or tested in the laboratory.

PORE PRESSURE MECHANISM

across the fault s
estimated to be 55

1975; Lofgren, 1981).

Although some of the strain in the vicinity of The Geysers reservoir is clearly localized as slip on major fault zones, pervasive aseismic creep on a large number of minor faults and fractures is probably also occurring (Allis, 1981 in prep.). Both the presence of serpentinite bodies, which are commonly associated with the Franciscan assemblage, and high pare pressures, would facilitate creep. Berry (1973) suggests

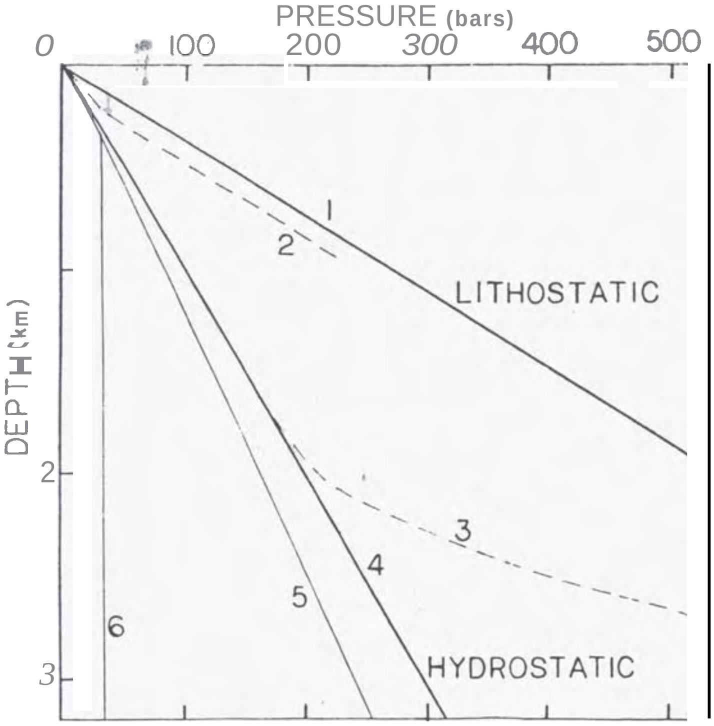


Fig. 2 1, Lithostatic gradient (assumed density of 2.7 $Mg/m^3$); 2, characteristic pore pressure curve for Franciscan terrane (after Berry, 1973); 3, characteristic pore pressure curve for Gulf of Mexico sediments; 4, hydrostatic gradient (cold water); 5, hydrostatic gradient (250°C); 6, saturated steam curve measured in wells at The Geysers.

that most of the Franciscan terrane of northern California may be characterized by overpressuring, with pore pressure approaching lithostatic at very shallow depth (curve 2, Fig. 2). Wherever this is the case, the rocks will have very low strength, and permanent aseismic creep probably dominates seismic slip. Overpressuring in The Geysers prior to exploitation is unlikely, because the surface thermal manifestations imply hydraulic continuity between the deep reservoir and the surface. Nevertheless, the location of the reservoir in a region undergoing both aseismic creep and seismic slip may be crucial to understanding the changes in seismicity that have occurred with exploitation.

Laboratory studies of the mode of deformation of core samples suggests a significant change occurs with increasing effective pressure. Byerlee and Brace (1968) found that for a variety of rock types (serpentinite and limestone were notable exceptions) steady sliding on fault surfaces was stable at low confining pressure.' At confining pressures above about 1 kbar, the fault motion changed to stick-slip, and the magnitude of the stress drop during rupture increased with increasing pressure.

This same mechanism could be causing the seismicity at The Geysers if large changes in pore pressure have occurred with exploitation. The initial pressure distribution at The Geysers is poorly known, and is controversial. The most widely accepted model is that the field was vapour dominated from 300 m to over 3 km depth before exploitation. Temperature and pressure throughout the reservoir were close to 35 bars and 240°C, and the reservoir was grossly underpressured with respect to hydrostatic pressure (Fig. 2). Exploitation has caused pressure to decline further, and the most heavily produced areas of the borefield now have pressures below 20 bars (Lipman et al. 1978). If this is the case, then confining pressure (i.e. lithostatic - pore pressure) has undergone an increase of only a few percent with exploitation and it is unlikely to be an important factor inducing the seismicity.

However, both Weres et al. (1977) and Mahon et al. (1980) have proposed, for different reasons, that The Geysers reservoir may have been predominantly liquid dominated before exploitation. If so, the drop in fluid pressure, or rise in confining pressure, with exploitation has ranged from around 50 bars at 1 km to over 200 bars below 3 km depth (Allis, 1981, in prep.). This rise in confining pressure within the reservoir could be ample to change the mode of deformation from stable, aseismic creep to unstable seismic slipping.

## COEFFICIENT OF FRICTION MECHANISM

Although increasing confining pressure is an obvious mechanism for changing stable sliding to stickslip behaviour, it is conceivable that some other factor could cause the same effect. Stetsky (1978) points out that stickslip motion is also enhanced by the presence of strong, brittle minerals such as quartz and feldspar, by low temperatures, by an absence of gouge (i.e. clays) and by lower surface roughness. If production of steam from the reservoir has caused a change in the physical state of the rock, or its fracture surfaces, with a resultant increase in the coefficient of friction (μ), then a transition from stable, sliding to stick-slip motion could be induced. For most rocks under a wide range of conditions, μ lies in the range 0.6-0.9 (Byerlee, 1978). However, gouge material such as montmorillonite or vermiculite can have a very low coefficient of friction. Although unproven in the laboratory, a significant increase in μ could have been produced by drying out of the reservoir rock, and/or by deposition of silica from the boiling of pore water (Allis, 1981, in prep.). The latter factor could be dominant if some pore water, as well as steam, moves from the rock matrix towards the major fissures during production. Because of thermal bufferring by the reservoir rock, the thermodynamic path of the mobile fluid tends towards isothermal expansion rather than isoenthalpic expansion, and drying and superheating of the steam occurs. Deposition of silica in the fractures and fault zones would accompany this expansion process, and a significant increase in the overall coefficient of friction for the reservoir could result.

## DISCUSSION

Three mechanisms for the induced seismicity in The Geysers reservoir have been outlined above. The first implies that thermal contraction has weakened the reservoir rock, making it more susceptible to rupture. The other two imply that strengthening of the reservoir rock has occurred, either by a large drop in pore pressure or by an increase in the coefficient of friction, and aseismic creep has been replaced by seismic slip. Only the declining pore pressure mechanism has been reported from laboratory studies of core deformation. However this mechanism implies that The Geysers reservoir was liquid dominated before exploitation. Although this is controversial the available evidence favours a vapour dominated reservoir initially. A problem with the thermal contraction mechanism is the lack of induced seismicity at other geothermal fields where temperature changes much larger than those inferred for The Geysers reservoir have occurred.

Temporal changes in the characteristics of the induced seismicity should differentiate between weakening or strengthening of the reservoir rock. Strengthening should cause a decrease in the b-value (i.e. an increase in the number of larger magnitude events compared to smaller magnitude events) and an increase in the size of stress drops during earthquakes. Weakening of the reservoir rock should have the reverse effect.

The b-value for earthquakes at The Geysers is quite high (1.2) (Bufe et al., 1981), but no trend in b-value has been reported. However, between 1972 and 1977 when there was a four-fold increase in the rate of steam withdrawal, the magnitude of the largest earthquake recorded each year at The Geysers progressively increased from 3.1 to 3.8 (Ludwin and Bufe, 1980). Although not definite, this trend could reflect increasing strength of the rock. Thus the only mechanism which satisfies the apparent constraints from both reservoir pressure and seismicity characteristics is an increase in the coefficient of friction.

It is also possible that more than one mechanism is important. At production depths, silica deposition and drying of the reservoir rock could be dominant. During production, the vapour dominated zone has probably expanded downwards and laterally. Therefore pore pressure decline may also be important in the deeper portions of the reservoir. The absence of seismicity below about 5 km depth probably reflects ongoing aseismic creep due to high temperature.

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