Effect of High Rate Injection on Seismicity in The Geysers

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ABSTRACT

Projects to massively augment Geysers injection in first the southeast (1997) and later (2003) the northwest Geysers have had very different effects on induced seismicity based on a comparison of two 9.6 km^2 study areas. Each project startup resulted the following year in a new all-time peak in fieldwide injection and correlated with a new all-time peak in the number of M≥1.2 earthquakes. With the startup of the Southeast Geysers Effluent Pipeline (SEGEP) project in late 1997, injection rates approximately doubled in the southeast Geysers. In the southeast study area (SESA) a gradual increase from about five to 20 events per month occurred over the ensuing five year period and has subsequently declined to about 10 events per month. No correlation was seen between annual injection peaks and the frequency of M≥1.2 events. In the northwest Geysers a high temperature reservoir (HTR) up to 360 °C underlies the normal 240 °C reservoir and heavily influences seismic response to injection. Seismicity extends deep into the HTR. Annual winter peaks in injection have for decades been followed a few months later by peaks in seismicity as measured by the monthly count of M≥1.2 earthquakes. An approximate tripling of injection rate in the Northwest Study Area (NWSA) in late 2003 by startup of the Santa Rosa Geysers Recharge Project (SRGRP) was followed by a commensurate increase in seismicity. Since 2007 NWSA annual injection peaks are not followed by peaks in seismicity, even though peak injection rates have remained high and relatively constant. Moreover, since 2007 the monthly M≥1.2 count has fallen dramatically and apparently is no longer influenced by injection rates. This may have implications regarding the current state of the HTR in the NWSA.

In the northwest Geysers annual peaks in injection induced seismicity may be related to the amount of heat loss from reservoir rock, particularly in the HTR. During peak (i.e. winter) injection, the volume of saturated fracture porosity expands as the water front rapidly moves outward into hot, dry rock fractures. While the water front is expanding the saturated volume of rock, most heat flow from the rock is absorbed in raising the temperature of the water to the boiling point. Boiling is inhibited as the expanding water front results in generally higher hydrostatic pressures and cooler water temperatures within the saturated volume. At the outset of the dry season lower injection rates result in lower hydrostatic pressures and an increased rate of injectate heating and boiling. The water front stabilizes, then begins to recede as a result of boiling. Eventually, the rock is sufficiently cooled from heating and boiling of injectate that thermal contraction increasingly triggers microearthquakes (MEQs).

The "uncoupling" in the NWSA of annual peaks in injection and seismicity may indicate that separate injection water plumes have begun to coalesce, thereby deactivating the triggering mechanism.

Introduction

Induced seismicity is common to the entire Geysers steamfield, with thousands of earthquakes recorded annually. The vast ma-

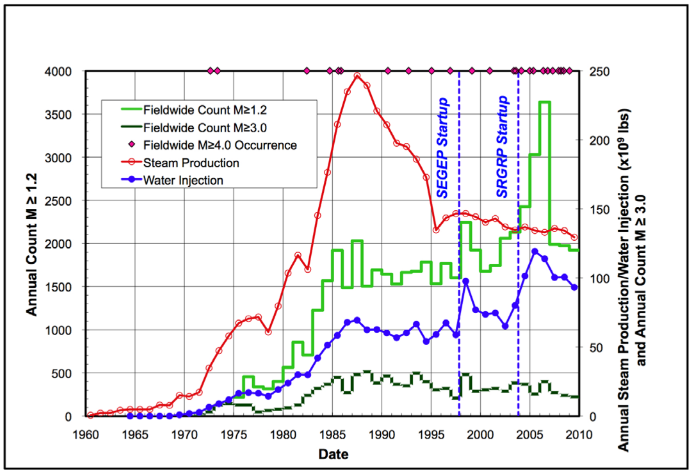

Figure 1. Annual fieldwide Geysers production, injection and earthquake counts.

jority have M<3.0 and are defined as microearthquakes (MEQs; Lee and Stewart, 1981). Geysers seismicity is recorded by a close-spaced array, installed by Lawrence Berkeley National Laboratory (LBNL), which, since 2003 functions as part of the USGS Northern California Seismic Network (NCSN). Induced seismicity in The Geysers began shortly after production commenced in any given part of the field. As development spread, seismicity followed and the number of earthquakes increased with fieldwide production and injection (Eberhart-Phillips and Oppenheimer, 1984). Geysers production peaked in 1987, as did condensate injection, with a correlative peak in seismicity, as measured by the number of events of M≥1.2 (Figure 1). After 1987 annual production declined rapidly through 1997 with injection rates declining more moderately. During this period the M≥1.2 count varied within a narrow range.

Sudden increases in overall injection rates in late 1997 and 2003 resulted from the startup of projects to inject reclaimed waste water from Lake County (the Southeast Geysers Effluent Pipeline, SEGEP) and Sonoma County (the Santa Rosa Geysers Recharge Project, SRGRP), respectively. Both projects resulted the following year in new all-time peaks in fieldwide injection and correlated with new all-time peaks in the number of M≥1.2 earthquakes. In the years following the startup of SEGEP, the number of M≥1.2 events returned to pre-SEGEP levels. Post-SRGRP startup, the number of M≥1.2 events has declined from its peak (in 2006) by 47% but is still slightly above pre-SRGRP levels (Figure 1). A curious fact is that only 10% of the M≥1.2 earthquakes making up the new all-time high count in 1998 following the startup of SEGEP actually took place in the southeast Geysers, where all the new SEGEP injection occurred.

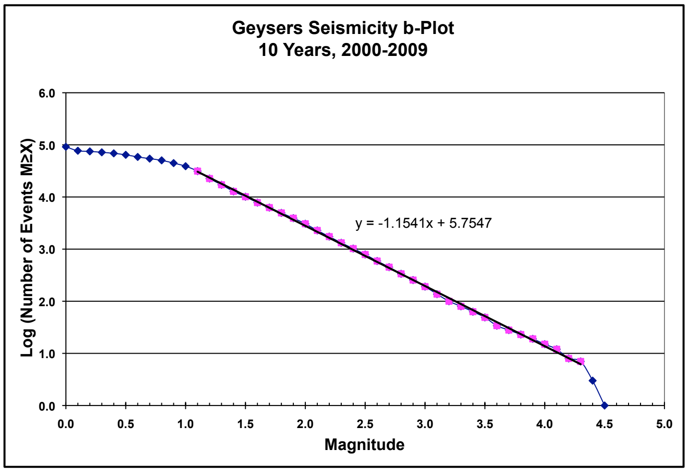

Figure 2. Ten-year Geysers fieldwide seismicity b-plot (2000 through 2009).

Geysers Magnitude-Frequency Relationship

Geysers seismicity follows a typical magnitude – frequency relationship (Lee and Stewart, 1981) such that the number of seismic events increases by approximately a factor of ten for each one unit reduction in magnitude. The plotted distribution for ten years of data, 2000-2009, follows this relationship up to M4.3 (Figure 2). The linearity of the plot suggests that the seismic record for this period is essentially complete (i.e. all events recorded) down to about M1.2. The largest event of the ten year period is M4.5. The largest ever recorded was M4.6 in 1973.

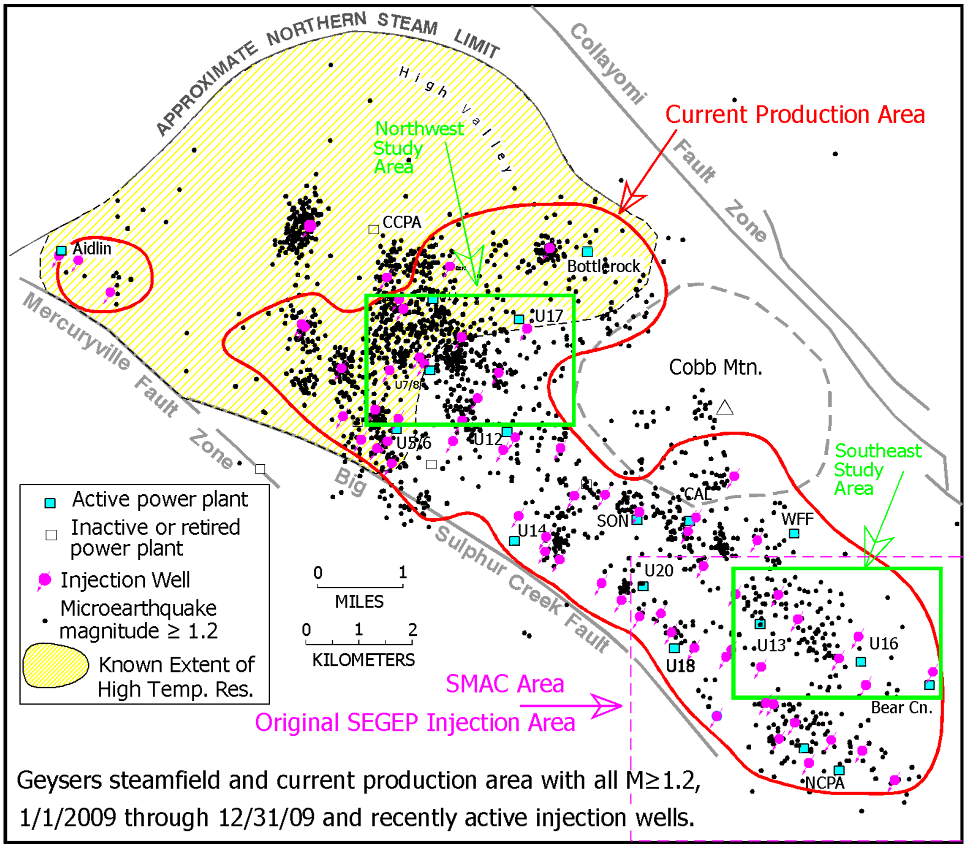

Figure 3. Geysers steamfield, known extent of HTR and current production area with 2009 events M ≥1.2. Also shown are northwest and southeast study areas and SMAC area.

Areal Distribution of Production, Injection, Seismicity, and the High Temperature Reservoir

Figure 3 shows the outline of The Geysers field, the currently productive area, recently active injection wells and 2009 M≥1.2 earthquakes recorded by the USGS NCSN. The Aidlin plant and production wells, in the extreme northwestern part of the field, are isolated from the main production area. A high temperature vapor dominated reservoir (HTR), with temperatures up to 360 ºC, underlies the "normal", 240 ºC reservoir in the northern part of the field (Walters et al., 1992). The known extent of the HTR is shown in Figure 3 (Walters and Beall, 2002). A large, unproductive area exists in the northwestern end of the field between the "Approximate Northern Steam Limit" and the currently productive area. Production in this area has been hampered by high noncondensible gas concentrations and corrosive (HCl bearing) steam which is thought to originate in the HTR.

The pattern of seismicity in the southeastern part of the producing Geysers field differs significantly from that observed in the northwest. The major differences are that the frequency of events is much greater in the northwest part of the production area and that earthquake activity extends to much greater depth in the northwest (Priess, et al., 2002). These differences have been noted since the southeastern part of the field expanded to its limits of production in the mid-1980's. Stark (1992, 2003) showed that injection into the northern part of the current production area interacts with the HTR to induce seismicity at depths as much as 3 km (10,000 ft) deeper than the injection wells. He also noted spatial and temporal correlations of seismicity with injection indicating that most Geysers seismicity is injection related. An examination of Figure 3 supports that conclusion. The Prati 9 injection well, located to the west of the former CCPA power plant, is situated within a dense cluster of seismicity, even though it is located well outside the current production area. A northwest – southeast cross section through The Geysers steamfield, showing the vertical distribution of seismicity as well as geologic and steamfield markers (top of steam reservoir, top of felsite, top of HTR), is shown by Beall and Wright (this volume) in a related paper.

Geysers Injection

Injection in The Geysers has historically consisted primarily of power plant condensate. As noted above, however, injection of reclaimed waste water, starting with SEGEP in 1997 and SRGRP in 2003 resulted in new all-time highs in Geysers annual injection, as shown in Figure 1. SEGEP water was, until recently, entirely injected in the southeast Geysers. SRGRP injection has generally been concentrated in the north central part of the current production area (Figure 3). Significant variations in the patterns of seismic response to injection exist between the northwest and southeast parts of The Geysers production area. Moreover, the response of seismicity to injection varies over time. Evidence presented below suggests that the seismic response to injection of at least a large portion of the HTR has recently undergone a significant change. For comparison purposes, 9.6 km^2 (3.6 mi^2), rectangular study areas have been delineated in both the northwestern and southeastern production areas of The Geysers (Figure 3), here designated as the NWSA and SESA, respectively.

Seismic Response to High Rate Injection in the SESA

In the SESA and in the southeast Geysers as a whole, the startup of SEGEP injection in late 1997 resulted in approximately a doubling of injection rates (Figure 4). Although this had no immediate effect on the frequency of M≥1.2 earthquakes in the SESA, over the next five years the monthly average gradually rose from about five to 20 events per month. Since 2002 the frequency of M≥1.2 earthquakes has declined, averaging about 10 per month in recent years. Although no SRGRP water has been injected into the SESA, there is a substantial increase in injection that occurs coincident with the start up of SRGRP injection in the north Geysers. The reason for this is that some SEGEP water was taken out of the south Geysers and piped to the north, beginning in May 2002, in order to test the new wells and pipelines that had been prepared for SRGRP injection. With the start up of SRGRP, SEGEP water was no longer needed and was again injected entirely in the south Geysers.

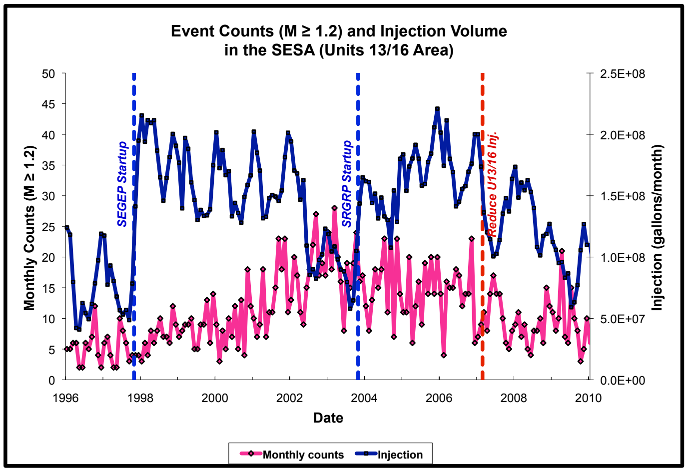

Figure 4. Monthly earthquake count (M≥1.2) and injection volume in the SESA.

Beall et al. (1999) and Smith et al. (2000) reported that in the southeast Geysers, annual peaks in seismicity were discernable as measured by the total event count. Beall et al. noted this for data obtained with an array operated at the time by Unocal. Smith et al. made this observation for both the Unocal array and the USGS (NCSN) array prior to its incorporation of the LBNL stations in 2003. In both reports, however, the annual peaks in seismicity occur prior to annual injection peaks, raising the possibility that many of these events were not injection related. The current study suggests that detection of annual peaks in seismic activity was possible only when all recorded events were included, including those below the magnitude threshold at which all events are recorded (e.g., M1.2 in this study).

The discovery that a deep, saturated zone had formed over much of the Units 13/16 steamfield (SESA) area (Wright and Beall, 2007) prompted a decision in February 2007 to greatly reduce injection rates in this area. From the winter 2005-2006 peak, SESA injection has been reduced to the extent that injection rates are, on average, now similar to the pre-SEGEP period (Figure 4).

Seismic Response to High Rate Injection in the NWSA

In the NWSA injection rates approximately tripled after SRGRP injection began in late 2003 (Figure 5). The frequency of M≥1.2 earthquakes in the NWSA rose from about 30 per month to over 100 per month through 2006, in apparent response to new all-time highs in monthly injection. In the NWSA, peaks in injection during the winter months have typically been followed three to five months later by peaks in the M≥1.2 count. This behavior is apparent in Figure 5. Stark (2003) notes that high temperature reservoir seismicity has exhibited this relationship to injection since at least 1976. Since 2007, however, in the NWSA annual injection peaks are no longer followed by peaks in seismicity, even

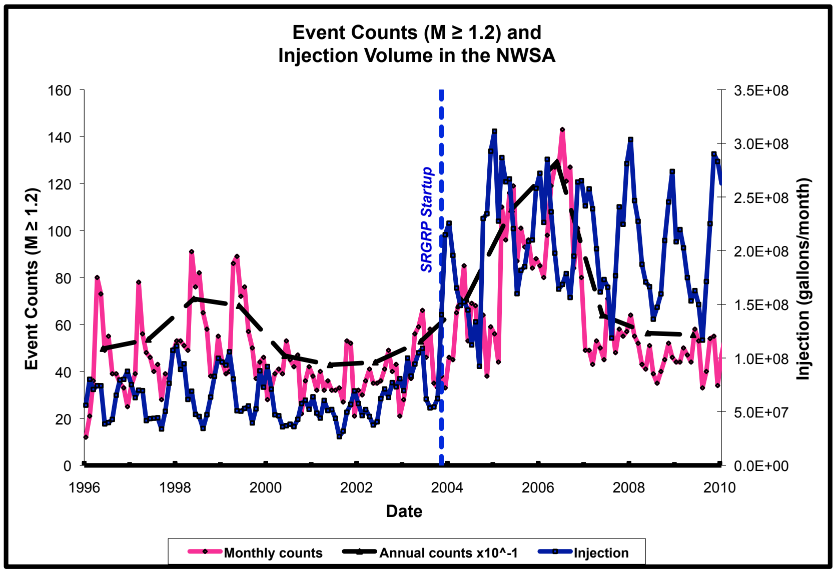

Figure 5. Monthly and annual earthquake count (M≥1.2) and monthly injection volume in the NWSA.

though peak injection rates have remained high and relatively constant (Figure 5). Moreover, since 2007 the M≥1.2 count has averaged below 50 per month and apparently is no longer influenced by injection rates. This may have implications regarding the current state of the reservoir in the NWSA.

1998 Fieldwide Peak in M≥1.2 Events

As noted above, in 1998, following the start up of SEGEP injection in late 1997, the fieldwide count of M≥1.2 events reached a new all time high (Figure 1). This might be assumed to result from earthquakes induced in the SEGEP injection area. An investigation of seismic activity within the SEGEP injection area indicates, however, that 90% of the earthquakes comprising the new high count were actually located outside the southeast Geysers.

As a supplement to the SEGEP Lake County Use Permit, the Seismic Monitoring Advisory Committee (SMAC) was formed to monitor the effect on seismicity of augmenting injection with reclaimed waste water (Dellinger, 1995). A rectangular area was established by SMAC to encompass SEGEP injection and, inside of which, careful observation of injection induced seismic activity would be conducted (dashed line, southeast corner, Figure 3). Until 2009, all SEGEP water was injected into the southeast Geysers. Figure 6 is similar to Figure 1 except that it covers only the time span from 1996 through 2009 and includes an annual count of M≥1.2 events in the SMAC area. SEGEP injection began in November 1997 as indicated by the vertical, dashed line in Figures 1 and 6. The fieldwide annual M≥1.2 count (NCSN data) increased by 641 (from 1602 to 2243 events) between 1997 and 1998. The increase in annual M≥1.2 count in the SMAC area amounted to only 65 events (10% of the total increase) over the same period, increasing from 175 in 1997 to 240 in 1998. If the assumption were to be made that a temporal and a spatial correlation are necessary to establish injection induced seismicity, the data might imply that the 1998 fieldwide increase in seismicity attributed to SEGEP start up did not result from SEGEP injection. In Figure 5, the NWSA (where no SEGEP injection occurred) annual count of M≥1.2 is shown (x10^{-1} in order to use the primary y-axis scale) indicating a 32% increase (536 to 709 events) from 1997 to 1998.

Triggering Mechanism for Injection Induced Events

Stark (2003) presented a conceptual model of a triggering mechanism for deep earthquake clusters in the north Geysers. In the model, a large contrast between injectate and rock temperature triggers seismicity as a consequence of thermal contraction. We propose that the triggering mechanism is related to the amount of heat extracted from the rock. Heat is extracted from the rock by two processes, (1) heating the water to the boiling point and (2) boiling the water to create injection-derived steam. During periods of peak (i.e. winter) injection, the volume of saturated fracture porosity expands as the water front moves outward into hot, dry rock fractures and away from the wellbore. Movement of the water front is rapid (t_0-t_1, Figure 7) causing boiling associated with the movement of water into hot, dry rock to take place mostly along the leading edge of the water front. While the water front is expanding the saturated volume of rock, most of the heat flow from the rock is being absorbed in raising the temperature of the water to the boiling point (1 cal/gm/ ºC). During this period, boiling is inhibited within the injectate plume by increased hydrostatic pressures. At the outset of the dry season, due to lower injection rates the water front stabilizes, then begins to recede as a result of boiling (t_1-t_2, Figure 7). The rate of boiling increases as hydrostatic pressures decline within the plume. Much of the saturated volume reaches the boiling temperature and the rate of boiling peaks. The

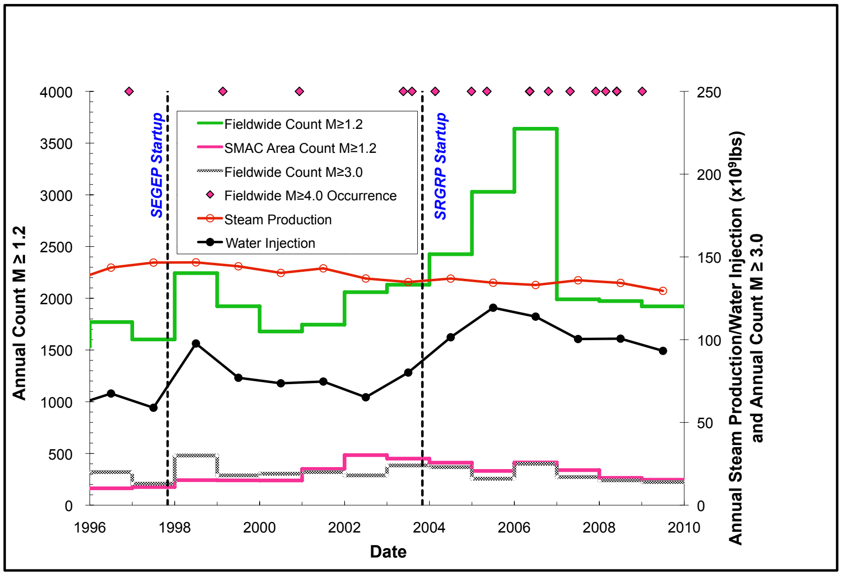

Figure 6. Expansion of Figure 1 with the addition of SMAC area counts of M ≥ 1.2.

average injection water temperature entering the formation, based on many pressure and temperature logs of injecting well bores, is about 66 ºC. At an average reservoir pressure of 1034 kPa (150 psi), the boiling point is 185 ºC. On average, the heat required to raise the temperature of injection water to the boiling point would therefore be 119 cal/gm. At a boiling point of 185 ºC, the heat of vaporization is 476 cal/gm. It therefore requires about four times as much heat to boil a quantity of injection water as it takes to raise its temperature to the boiling point. Eventually, the rock is sufficiently cooled from heating and boiling of injectate that thermal contraction increasingly triggers MEQs. We therefore hypothesize that the timing offset in injection and seismicity peaks reflects a rapid increase in boiling activity at the conclusion of the winter injection peak. The heat sink afforded primarily by boiling extracts heat from the rock until thermal contraction reaches a threshold value at which MEQs are increasingly triggered. Seismic activity decreases when the rock volume recently cooled from reservoir temperatures (especially in the HTR) is relieved of stress by slippage along fracture surfaces.

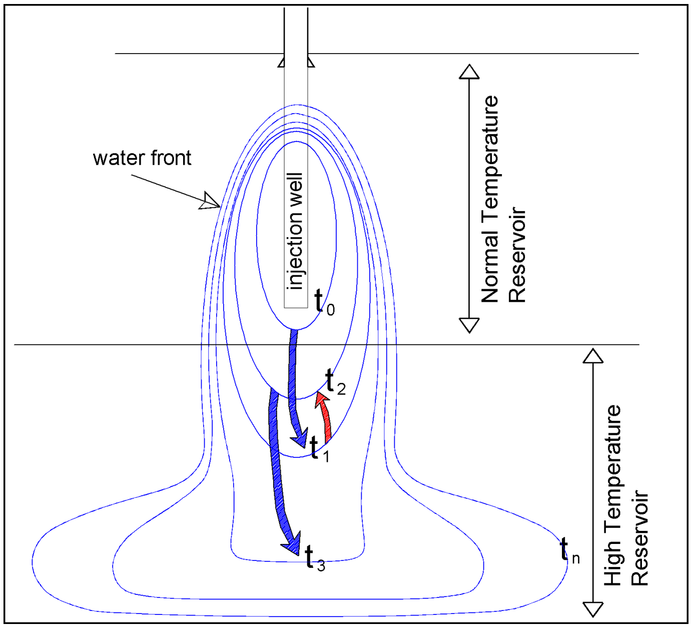

Figure 7. Schematic cross section of injection well with saturated zone expanding over time into high temperature reservoir.

Reservoir Implications of Injection-Seismicity "Uncoupling"

The "uncoupling" of injection and seismicity that is evident in the NWSA since early 2007 may indicate that saturated zones associated with various injection wells have begun to coalesce, thereby deactivating the triggering mechanism described above. Wright and Beall (2007) described the formation of deep, saturated reservoir in the southeast Geysers. Because the southeast Geysers lacks a deep high temperature zone underlying the "normal" reservoir a saturated interval (i.e. water table) developed in the lower part of the production zone, quenching the steam flow to the deepest steam entries of some wells. Calpine is in the process of shifting a substantial portion of injection from the northwest production area, which includes the NWSA, to the former (currently nonproductive) CCPA area, which Calpine is redeveloping. The Prati-9 injection well is part of this program. In addition, future injection plans include slim hole, low rate injection into the upper reservoir to "mine" the heat from this still very superheated zone. These measures may prevent the formation of an extensive, deep, saturated reservoir zone such as was documented in the southeast Geysers and help to maintain production of injection-derived steam.

Conclusions

Large scale injection augmentation in The Geysers has resulted in very different induced seismicity responses in the northwest and southeast parts of the field. Following SEGEP startup in late 1997 a gradual increase from about five to 20 events per month occurred in the SESA over a five year period, subsequently declining to about 10 events per month. No correlation was seen between annual injection peaks and the frequency of M≥1.2 events.

In the northwest Geysers, where the HTR (up to 360 °C) underlies the normal 240 °C reservoir, seismicity extends deep into the HTR. Annual winter peaks in injection have for decades been followed a few months later by peaks in seismicity. An approximate tripling of injection rate in the NWSA in late 2003 by startup of SRGRP was followed by a commensurate increase in seismicity. We suggest that the cooling of reservoir rock, particularly in the HTR, by injectate heating and boiling eventually results in sufficient thermal contraction to trigger MEQs. Since 2007 NWSA annual injection peaks have not been followed by peaks in seismicity, even though peak injection rates have remained high and relatively constant. Moreover, since 2007 the monthly M≥1.2 count has fallen dramatically and apparently is no longer influenced by injection rates. This may indicate that plumes of injectate have begun to coalesce in the reservoir, effectively disabling the triggering mechanism.

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