Southern Extent of The Geysers High Temperature Reservoir Based on Seismic and Geochemical Evidence

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Keywords

The Geysers, seismicity, injection, geochemistry

ABSTRACT

In the northwest part of The Geysers steam field, the "normal", 240 ºC vapor dominated reservoir is underlain by a "high temperature" vapor dominated reservoir (HTR) at 260 to 360 ºC. The southeastern extent of the HTR is unknown. A sharp, vertical boundary, the "M≥4 Divide", partitions The Geysers reservoir such that all but one of 26 historic M≥4.0 and over 90% of M≥3.0 earthquakes are located to its northwest. The same boundary coincides with an abrupt 2000 m (6600 ft) increase in the maximum depth of seismicity to the northwest. Steam enriched in volatile acid chloride, believed to originate in the HTR, is essentially restricted to the northwest of this line. Coincidence of this boundary for reservoir characteristics as disparate as earthquake magnitude distribution, earthquake depth and steam chloride chemistry may indicate that the M≥4 Divide represents the southeastern boundary of the HTR. An alternative possibility, supported by the geometry of the "seismic floor", is that a second, smaller HTR, as yet unidentified by drilling, exists immediately to the northwest of the M≥4 Divide. Assuming that a younger intrusive heat source is required for HTR formation than for the normal reservoir, this may further imply that a separate young igneous intrusion underlies the area immediately to the northwest of the M≥4 Divide.

Introduction

In the northwest Geysers the "normal", 240 ºC steam reservoir is underlain by a high temperature reservoir (HTR), also vapor dominated, with temperatures as high as 360 ºC (Walters et al., 1992). The known extent of the HTR, shown by the contours of Figure 1 (Walters and Beall, 2002), has been primarily determined by running maximum-reading thermometers with directional survey tools during drilling operations. A reading of 260 ºC assures that the well bore has penetrated beyond the normal reservoir and into the HTR (Walters et al., 1992). The cross section of Figure 2 shows a gentle southeast dip to the top of the HTR, such that beyond its southeastern known extent it is deeper than overlying wells. The HTR possibly exists as a consequence of a younger intrusive heat source than is responsible for the normal reservoir (Williams et al., 1993). Stark (2003) has shown that deep injection, traced by seismic activity, has penetrated the HTR and suggests that for many years injection-derived steam from the HTR has supported steam production.

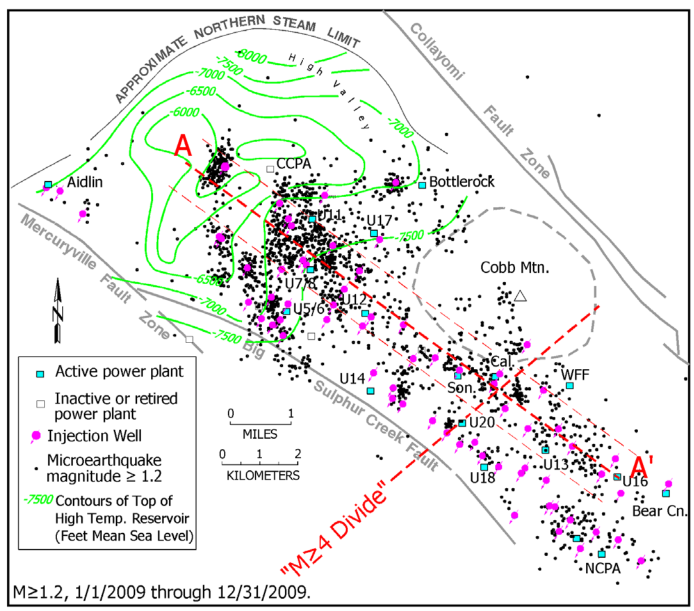

Figure 1. Map of 2009 Geysers earthquakes with M≥1.2 (NCSN data), contoured top of the high temperature reservoir, cross section line A - A′, and the "M≥4 Divide".

Geysers seismicity is recorded by a close-spaced array, installed by Lawrence Berkeley National Laboratory (LBNL), which functions as part of the USGS Northern California Seismic Network (NCSN). Although induced seismicity is common to the entire Geysers steamfield, the "style" of seismicity varies substantially between the northwest and southeast parts of the field. The frequency of earthquakes, the vast majority of which are microearthquakes (MEQs, M<3.0), is much greater in the northwest (Beall et al., this volume), where seismicity extends to much greater depth than in the southeast Geysers. A map and northwest-southeast cross section of 2009 Geysers induced seismicity, including all events of M≥1.2, are shown as Figures 1 and 2, respectively. The line of cross section is indicated on Figure 1, as is the half-width of the section (760 m, 2500 ft). Shown on the cross section are the top of the steam reservoir (based on steam entries of production wells), injection wells within the half-width lines of the section, the top of the 1.1 Ma felsite (granitic intrusion) which underlies much, if not all, of the reservoir (Thompson, 1991), and the top of the HTR. The tops of the felsite and HTR are shown only where they have been identified by drilling. Several relationships are apparent from the cross section. In the southeastern Geysers, seismicity extends only slightly (300-600 m, 1000-2000 ft) into the felsite. To a close approximation, this "seismic floor" correlates with the deep limit of steam production. While some steam is produced from fractures within the felsite, deep drilling into the felsite has generally failed to encounter steam beyond this seismic floor. In the northwest Geysers, as shown by Stark (2003), the top of the HTR separates deep, injection-induced seismicity from shallower seismic activity and a "seismic gap" exists between the two clusters of events. The cross section shows two zones of deep (relative to The Geysers) seismicity, the one previously identified by Stark in the northwest Geysers steamfield and a second area in the central part of the field. These two deep seismic zones are identifiable in a northwest – southeast cross section ("B") by Priess, et al. (2002) using pre-1996 data (prior to the addition of LBNL stations to the NCSN).

We hypothesize that the southeastern extent of the HTR is coincident with a reservoir boundary which segregates on its northwest side, the preponderance of the higher magnitude induced seismicity, deeper induced seismicity and, as discussed below, the production of steam with elevated concentrations of volatile acid chloride.

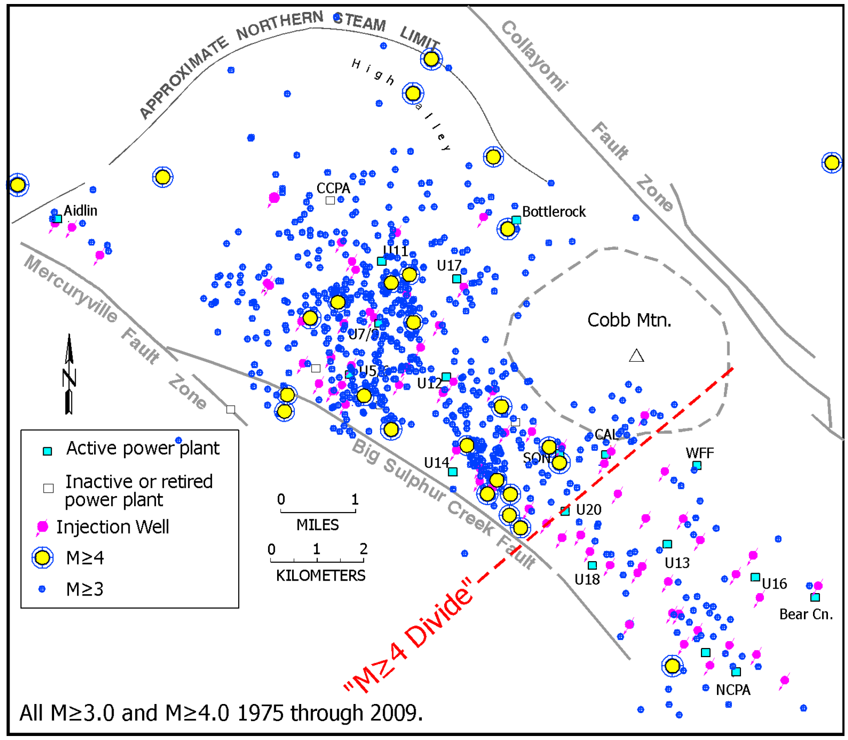

Figure 3. Map of Geysers M≥3.0 epicentral locations for the period 1975 through 2009 (NCSN data). Large symbols indicate M≥4.0.

The "M≥4 Divide"

As noted above, the northwestern part of the producing Geysers reservoir is more active seismically than the southeastern Geysers. This relationship is even more apparent when attention is focused on the larger earthquakes. At the time of this writing, 26 earthquakes of M≥4.0 have been recorded in The Geysers since development began in 1960. The locations of all the M≥4.0 events are shown in Figure 3. The largest was M4.6 in 1973. All but one of the M≥4.0 earthquakes occurred northwest of the dashed line, the "M≥4 Divide" (Figure 3). Moreover, over 90% of historic M≥3.0 events occurred to the northwest of this line. As viewed in cross section A-A' (Figure 2), the M≥4 Divide also coincides with an abrupt increase of about 2000 m (6600 ft) in the maximum depth of induced seismicity.

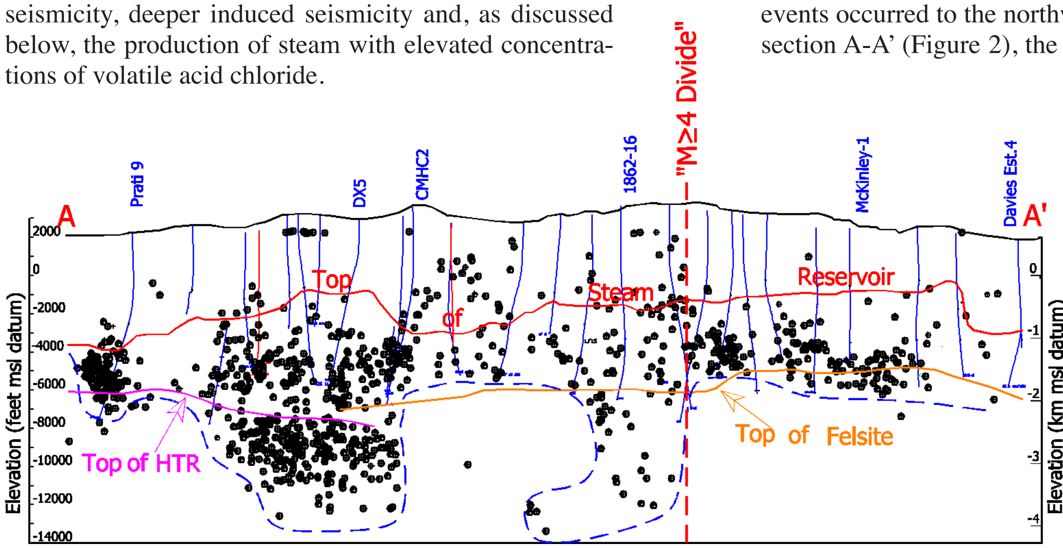

Figure 2. Cross section A to A' of Figure 1, showing 2009 events with M≥1.2 (NCSN data), top of the high temperature reservoir, top of steam reservoir, top of felsite, injection wells along the section line and the "M≥4 Divide".

HCl-Bearing Steam

Early production from The Geysers reservoir consisted entirely of saturated steam with generally low concentrations of noncondensible gas which varied systematically throughout the field (Gunderson, 1989; Beall, et al., 2007). Production of saturated steam was not associated with corrosion problems in well casings and surface piping. Corrosive steam with relatively high concentrations of volatile acid chloride has been produced from many wells since reservoir steam transitioned from saturated to superheated in the latter half of the 1980's. Chloride concentrations measured in steam produced throughout the field now range from <0.025 ppmw to over 100 ppmw. Calpine considers chloride concentrations ≥ 0.40 ppmw to be "elevated" and chloride ≥ 1.0 ppmw to be "high". Hirtz et al. (1991) noted that it is not clear whether the volatile chloride is transported in the vapor phase as NH_4Cl or as HCl, although most authors have preferred the latter.

Haizlip and Truesdell (1992) and Walters et al. (1992) reported that steam from the HTR tends to have elevated noncondensible gas and volatile chloride concentrations. Hirtz et al. (1991) reviewed the various origins proposed for volatile chloride which include reactions involving concentrated brine and/or solid chloride phases at temperatures above 300 ºC. However, such reactions are not necessary to account for the presence of volatile chloride since HCl gas is a well documented component of many high temperature fumaroles in volcanic environments (White and Waring, 1963). Consequently, HCl gas in Geysers steam may emanate directly from a magmatic heat source. Whatever the genetic origin of the volatile chloride, its occurrence in produced steam signifies a dry (i.e. superheated) path from its source to the production well bore. Otherwise, the volatile acid chloride, whether NH_4Cl or HCl, will ionize, form acid and react with rocks in the reservoir.

Calpine has sampled wells producing high chloride steam with a downhole sampler (DHS) designed by Sandia National Laboratory in collaboration with Thermochem, Inc. (Beall, et al., 2009). The DHS utilizes a eutectic material with a high heat of fusion to condense steam and allow collection of a significant volume of both condensate and noncondensible gas. Samples collected with the DHS show that chloride is at higher concentrations when the sample is taken in the well bore immediately above the deepest steam entries. The high chloride steam is believed to emanate from the HTR. Production of high chloride steam from wells that do not penetrate the HTR is an indication of vertical permeability connecting the HTR and normal reservoir. Figure 4 shows, in a southwest-northeast cross section, the distribution of steam entries (short "ticks" crossing well bores) to producing wells in the Units 5 and 6 area (Figure 1). The surface-sampled concentrations of chloride in the steam produced from these wells

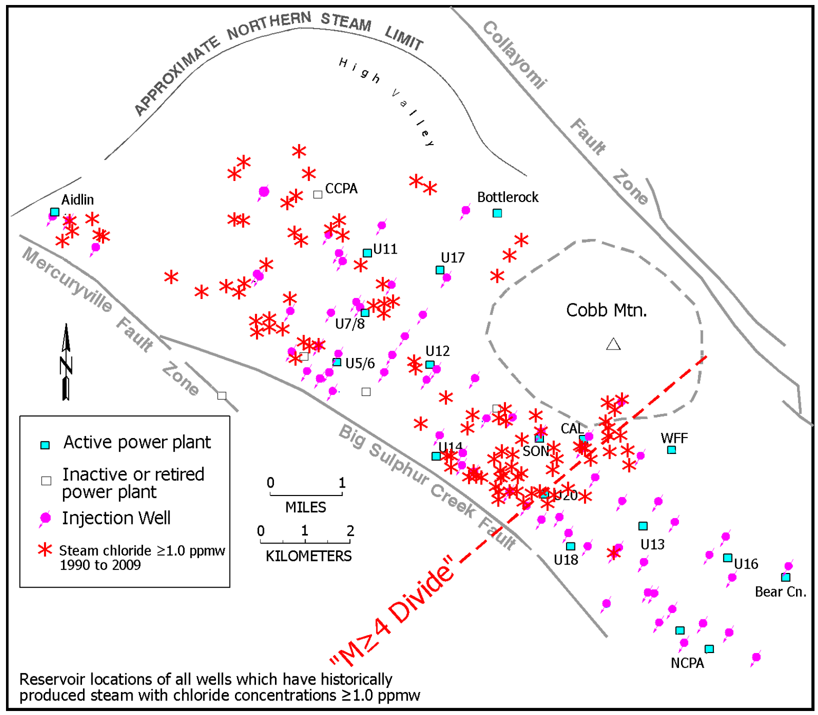

Figure 5. Map showing reservoir locations of all wells known to have produced steam with chloride concentrations ≥ 1.0 ppmw.

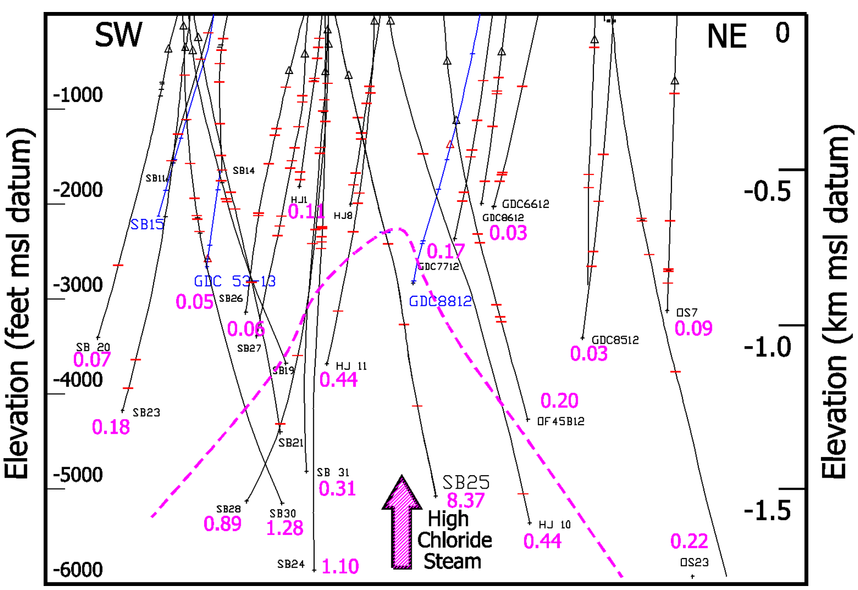

Figure 4. Southwest to northeast cross section through the Units 5/6 area. Red ticks represent steam entries to wells. Produced steam chloride concentrations are shown next to bottom-hole locations of wells. Dashed line represents an upwelling of high chloride steam originating in the HTR.

are shown adjacent to the bottom-hole locations in the cross section. In this area of the steamfield, although wells have a wide range of depths and steam entries, none are believed to penetrate the HTR. The cross section indicates that, in general, the concentration of chloride is controlled by an upwelling "dome" of high chloride steam in the vicinity of SB25. None of the shallow wells in the area surrounding SB25 production well produce steam with elevated chloride. The implication is that high chloride steam is migrating upward from the HTR along a steep fracture zone.

The locations of wells producing steam with chloride in excess of 1.0 ppmw (40 times the detection limit) during the period from 1990 – 2009 are shown in Figure 5. It is apparent that the M≥4 Divide also serves as a close approximation of the southeast limit of high chloride steam production.

Summary and Conclusion

A sharp boundary, the M≥4 Divide, separates The Geysers field into two areas in terms of magnitude distribution, with all but one of the historic M≥4.0 and over 90% of M≥3.0 events located to the northwest of this line. The same boundary, as shown in the cross section of Figure 2, coincides with an abrupt 2000 m (6600 ft) increase in the maximum depth of seismicity to the northwest. High chloride steam, believed to originate in the HTR, is essentially restricted to the northwest of this line. A coincident boundary for reservoir characteristics as disparate as earthquake magnitude distribution, earthquake depth and steam chloride chemistry may indicate that the M≥4 Divide represents the southeastern boundary of the HTR. An examination of the cross section suggests an alternative possibility, supported by the geometry of the "seismic floor", that a second, smaller HTR, as yet unidentified by drilling, exists immediately to the northwest of the M≥4 Divide. Assuming that a younger intrusive heat source is required for HTR formation than for the normal reservoir, this may further imply that a separate young igneous intrusion underlies the area immediately to the northwest of the M≥4 Divide.

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