Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

GEOTHERMAL DEVELOPMENT AND CHANGES IN SURFICIAL FEATURES: EXAMPLES FROM THE WESTERN UNITED STATES

Michael L. Sorey[1]
[1]U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

Key Words: geothermal development, hot springs, impacts, monitoring

ABSTRACT

Changes in surficial thermal features and land-surface elevations can accompany development of geothermal reservoirs. Such changes have been documented to varying extents at geothermal fields in the Western United States, including Long Valley caldera, Coso Hot Springs, and Amadee Hot Springs in California, and Steamboat Springs, Beowawe, Dixie Valley, and Brady Hot Springs in Nevada. The best-documented cases are for the Casa Diablo area in Long Valley caldera, California and for Steamboat Springs, Nevada where hydrologic monitoring programs have delineated some combination of declines in thermal-water discharge, increases in fumarolic steam discharge, and subsidence. At other areas noted above, similar types of changes have occurred but existing monitoring programs do not permit the same level of analysis of cause-and-effect relationships between such surficial changes and contributing factors.

1. INTRODUCTION

In most respects, geothermal energy offers considerable advantages over other forms of electrical and direct-use energy development in terms of minimizing adverse environmental effects. However, exploitable geothermal reservoirs are commonly associated with surficial thermal features such as hot springs and fumaroles, and some level of change in such features can be expected to accompany subsurface pressure changes associated with the production and injection of reservoir fluids. Geothermal reservoir pressure and temperature declines can also result in subsidence of the land surface. Perhaps the best-documented examples are from the Wairakei and Broadlands geothermal fields in New Zealand (Allis, 1981; Glover et al., 1996).

Most areas of existing or potential geothermal development in the Western United States include natural thermal features such as hot springs, geysers, spring-fed thermal pools, and steam-heated features such as fumaroles and hot pools. The extent that these features may be impacted by geothermal development depends on many factors, including both the properties of the subsurface and the details of the development (production and injection) scheme. The hydrologic and mechanical properties of the subsurface are usually not sufficiently known before development begins to predict the distribution and magnitude of surficial changes. Ideally, a hydrologic monitoring program should be in operation before and during development in order to delineate changes from both natural and man-made influences. For a variety of institutional, economic, and engineering reasons, this ideal is rarely met. Even when monitoring data are available, it is often difficult to quantify the relative effects of different factors that can influence surficial conditions, e.g. variations in precipitation and groundwater recharge, pumpage of groundwater aquifers, and crustal unrest (earthquakes and deformation).

The following list (see Figure 1 for locations) includes areas for which some degree of documentation exists for changes in surficial thermal features and land-surface elevations, followed by references to background information.

- Amadee Hot Springs, California: Land subsidence (Unpublished consultant's reports available from Lassen County Planning Department and California Division of Oil, Gas, and Geothermal Resources)
- Beowawe, Nevada: Cessation of geyser discharge (Layman, 1984; Faulder et al., 1997)
- Brady Hot Springs, Nevada: Cessation of hot-spring discharge and onset of boiling and steam upflow from shallow aquifers (Garside and Schilling, 1979)
- Coso Hot Springs, California: Increased activity of steam-heated features (Combs and Rotstein, 1975; Moore and Austin, 1983)
- Dixie Valley, Nevada: Increased activity of steam-heated features and subsidence (Benoit, 1997; Bergfeld et al., 1998)
- Long Valley caldera, California: Increased steam discharge in the well field, decreased thermal-water discharge at sites downstream from the well field, and subsidence (Sorey and Farrar, 1998)
- Steamboat Springs, Nevada: Cessation of geyser discharge (Sorey and Colvard, 1992)

In this paper, we describe the hydrologic monitoring program and the evidence for changes in surficial features associated with ongoing geothermal development in the Casa Diablo area of Long Valley caldera. We also compare and contrast the Long Valley development experience with that at Steamboat Springs, Nevada, and comment on situations at the other development areas listed above.

2. LONG VALLEY CALDERA, CALIFORNIA

2.1 Geothermal Development

The geothermal system in Long Valley involves upflow from a source reservoir in the west moat of the caldera and lateral outflow of thermal water in a generally west to east direction (Sorey et al., 1991). Reservoir temperatures range from 214°C beneath the west moat, to 170°C at Casa Diablo, and 110°C near Hot Creek gorge in the east moat of the caldera (Figure 2). Hot springs discharge primarily within Hot Creek gorge. Geothermal development currently consists of three binary power plants on a combination of private and public lands located at Casa Diablo. The plants produce a total of about 40 MW from wells that tap the shallow, 170°C, reservoir at depths of ~150 m. Plant MP-1 has been in continuous operation since 1985; plants MP-2 and PLES-1 began operations in 1991. In this single-phase, closed system, cooled geothermal water at ~80°C is reinjected in the well field at depths of about 600 m. Total flow rate through the plants is about 900 kg/s.

Inadvertent leaks of isobutane working fluid into the injection wells at Casa Diablo have provided a useful chemical tracer within the geothermal system. Isobutane has been detected in fumaroles at and near Casa Diablo and in the Hot Bubbling Pool 5 km to the east. Fluorescein tracer tests and isobutane data indicate that less than 10% of the fluid injected at Casa Diablo moves into the production zone. Instead, most of it flows away from the well field within the injection reservoir. The appearance of isobutane at distant thermal features, however, indicates a higher degree of connection between these two zones outside the well field.

2.2 Hydrologic Monitoring Program

The Long Valley area, which includes the resort town of Mammoth Lakes, has numerous features of geologic, hydrologic, and recreational significance. Concerns over possible impacts of geothermal and water-resources developments on surficial thermal features led to establishment of the Long Valley Hydrologic Advisory Committee (LVHAC) in 1987. LVHAC membership includes the U.S. Bureau of Land Management, U.S. Forest Service, U.S. Geological Survey (USGS), Mono County, California State Department of Fish and Game, Mammoth Community Water District, geothermal developers, and various environmental organizations. As described by Farrar and Lyster (1990), the purpose of the LVHAC was to implement a hydrologic monitoring program focused on early detection of changes in surficial features that could be influenced by water-resource developments within the caldera. The LVHAC provides information to permitting agencies on such changes and recommends mitigation alternatives for specific development projects. The committee is advisory and as such its recommendations do not create legal obligations. The USGS, as a non-voting member of the LVHAC, is responsible for collecting and compiling hydrologic monitoring data, and has on occasion been requested to prepare interpretive reports based on these data.

In addition to the hydrologic monitoring program conducted by the USGS, each resource developer is required to monitor conditions in and around their well fields. Thermal and nonthermal subcommittees of the LVHAC meet with specific developers to discuss both public and proprietary monitoring and development data and interpretive analyses of such information. Findings and/or recommendations are conveyed to the LVHAC. Experience has shown that this full and open disclosure and discussion of public and proprietary monitoring data has allowed a more complete understanding of changes accompanying development and promoted an attitude of trust that has helped to avoid litigation. One example of this process is the planning and completion of a numerical model of the response of the geothermal field to development. The modeling was funded by the developer and carried out by one of its consultants, but input and review were sought from members of the thermal subcommittee.

The LVHAC monitoring program includes thermal springs east of Casa Diablo (Figure 2), streamflow measurement sites along Mammoth and Hot Creek, and both thermal and nonthermal wells (e.g. CH10B, and M-14, respectively). Areas of environmental concern include thermal springs at the Hot Creek Fish Hatchery and in Hot Creek gorge. The Hatchery springs discharge at a composite temperature near 16°C, considered optimum for trout-rearing operations. These springs contain a small (~5%) component of thermal water. Springs in Hot Creek gorge discharge at temperatures up to boiling (93°C), and provide a popular environment for bathing in heated creek water.

2.3 Changes in Surficial Features

Geothermal development at Casa Diablo has resulted in declines in reservoir pressure and temperature over the 1985-1998 period. As exemplified by data from observation well 65-32 on the edge of the well field (Figure 3), a cumulative pressure change of 0.1 Mpa between 1985 and 1990 was followed by an additional drop of 0.25 Mpa during 1991 in response to increased production and deepening of injection wells. Between 1991 and 1999, reservoir pressures have declined by about 0.1 Mpa, for a total decline of 0.45 Mpa (4.5 bars). The reduction in reservoir temperature amounts to 10-15°C, compared with localized reductions of ~80°C in the deeper injection zone. Boiling conditions in the heated groundwater system above the production reservoir have resulted in significant steam occurrences at and near the land surface, including fumaroles occupying former hot-spring vents, steam collecting beneath building foundations, and steam flowing upward through the roots of trees.

Data from the USGS monitoring program outside the Casa Diablo area (Sorey and Farrar, 1998a, b) show cessation of spring flow at Colton Spring (2 km east of Casa Diablo) and declines in water level in Hot Bubbling Pool (HBP, 5 km east of Casa Diablo). The water-level record for thermal well CW-3 adjacent to HBP correlates with the pressure record from well 65-32, indicating that the 0.25 Mpa pressure decline in the well field in 1991 (equivalent to a water-level drop of 25 m) caused a drop of 1.2 m in water level at this distance.

At the Hot Creek Fish Hatchery, chemical-flux measurements show that the thermal-water component in the springs has declined by some 30-40% since 1990. However, temperatures in the Hatchery springs have changed mainly in response to variations in the nonthermal component caused by seasonal and annual variations in groundwater recharge. The apparent lack of observable response in spring temperature accompanying the decline in thermal-water component suggests a moderating influence of conductive heating from rocks within and adjacent to the shallow flow zone containing a mixture of thermal and nonthermal fluids.

Total thermal-water discharge at Hot Creek gorge is calculated from chemical flux measurements at gaging sites on Hot Creek upstream and downstream from the thermal springs. Within a measurement error of ~15%, no decrease in thermal-water flow has been detected over the 1988-1998 period and the presence of isobutane has not been detected in the gorge springs. It appears from this that the current level of geothermal development has not caused detectible hydrologic changes beyond distances of about 5 km from the well field.

Leveling data collected along Highway 395 show subsidences in the vicinity of Casa Diablo beginning in 1986, superimposed on a general pattern of uplift that began in 1980 in response to crustal unrest (Sorey and Farrar, 1998; Sorey et al., 1995). Since 1988, benchmarks at Casa Diablo have subsided approximately 25 cm relative to benchmarks on the resurgent dome, which have risen approximately 20 cm. This perhaps represents a unique situation in that subsidence induced by geothermal fluid withdrawal has allowed the actual land surface elevation to remain relatively constant, while intermittent intrusive activity has cause significant uplift of the surrounding region.

3. STEAMBOAT SPRINGS, NEVADA

3.1 Geothermal Development

The geothermal system beneath the Steamboat Hills, located about midway between Reno and Carson City, Nevada, is currently being developed by two well fields and associated power plants (Figure 4). To the south, the higher-temperature Caithness Power Incorporated (CPI) development involves single-stage steam flash and residual liquid injection. To the north, the lower-temperature Far West Capital (FWC) project involves production and injection of pressurized single-phase liquid and binary power plant conversion. Electrical production totals about 15 MW at the CPI plant and 85-90% of produced fluids are reinjected north of the production well field. The generating capacity of the FWC plants totals about 40 MW and 100% of produced fluids are reinjected in wells adjacent to the production well field.

Between the two development areas is a silica terrace through which hot springs and geysers discharged until 1987, when sustained testing of geothermal wells began and water levels in the spring vents began falling (Sorey and Colvard, 1992; Collar and Huntley, 1990; Collar, 1990). Analyses of available hydrologic and geochemical data have led various authors to conclude that a single, interconnected, geothermal system exists in the Steamboat Springs area (Sorey and Colvard, 1992; Mariner and Janik, 1995, and White, 1968). Hot water flows upward beneath the Steamboat Hills and then laterally toward the north and northeast. In addition to the main terrace described above, the ultimate point of discharge of thermal water under pre-development conditions was Steamboat Creek.

3.2 Hydrologic Monitoring Program

Regulation and monitoring activities at Steamboat have tended to be more complex and difficult to pursue than at Long Valley. Although there are multiple regulatory jurisdictions involved at each area, the absence of an entity such as the LVHAC at Steamboat has made it more difficult to conduct adequate monitoring and to provide for interpretive studies of changes associated with development. This situation still exists today, in spite of the fact that part of the silica terrace and adjacent areas to the west were designated an Area of Critical Environmental Concern by the Bureau of Land Management (Sorey and Colvard, 1992).

Each developer has been responsible for monitoring conditions in and around their well field. A set of wells drilled for testing and monitoring exists in the FWC well field; in the CPI well field wells drilled for stratigraphic information are monitored. A network of wells drilled into the nonthermal groundwater system surrounding the Steamboat Hills is included in the monitoring program carried out by FWC.

3.3 Changes in Surficial Features

Data on pressure changes in the developed well fields are either not publicly available or are difficult to interpret. Pressures declines in both fields appear to be minimal (~0.05 Mpa, or 0.5 bars). This indicates high reservoir transmissivity and pressure support from injection wells. Indeed, tracer tests at the FWC show that most of the injected water remains within the well field (Rose et al., 1999). This is in contrast to the situation at Long Valley described above.

By the time monitoring programs began in earnest in 1986, the geysers and springs were in decline and by 1987, liquid discharge on the main terrace had stopped. Monitoring of water levels in some spring vents continued through 1989, when water levels in the silica-lined spring conduits fell beyond the reach of measuring equipment. Two measurements were also made in 1989-1990 of thermal-water discharge in Steamboat Creek, using chloride flux techniques, for comparison with similar estimates made in the 1950-1960 period (Sorey and Colvard, 1992). These data suggest declines in total discharge of about 40%.

The analysis by Sorey and Colvard (1992) concluded that declines in hot-spring activity and thermal-water discharge at Steamboat Springs resulted from a combination of (1) successive years of below-normal precipitation and groundwater recharge, (2) groundwater pumpage in the South Truckee Meadows (north of the Steamboat Hills), and (3) geothermal fluid production. It was not possible at that time to adequately determine the relative impacts of each factor. However, precipitation has returned to normal or above-normal levels since 1994 and monitoring records show that groundwater levels have risen significantly since that time and are now at nearly the same levels as in the late 1980's. Although no recent measurements have been attempted of water levels in the spring vents on the main terrace, there is no evidence of any renewed spring flow.

4. OTHER AREAS OF GEOTHERMAL DEVELOPMENT

The scale and type of geothermal development at other noted areas in the Western United States vary widely, ranging from a small binary-electric power plant supplied by two production wells and no injection wells at Amadee Hot Springs in northeastern California to the ~250 Mwe steam-flash power plants at Coso Hot Springs in eastern California (Figure 1). In all but one case, all or most of the development area and surficial thermal features are privately owned. The exception is the Coso Hot springs area south of Long Valley in eastern California, where most of the land under development is part of the federally operated China Lake Naval Weapons Center. Thermal features at Coso Hot Springs, located adjacent to the well field, are traditionally utilized by local Native Americans. Environmental agreements between the Navy, the U.S. Bureau of Land Management, and Native American organizations call for mitigation in the event that geothermal development causes changes that negatively effect future use for religious and ceremonial purposes (Bureau of Land Management, 1980).

In cases where geothermal reservoirs and associated surficial thermal features are on privately owned land, regulations governing geothermal development are usually specified by state or county agencies, rather than federal agencies. Monitoring programs may not include observations of thermal features, so that information about changes in thermal features or land elevations is usually anecdotal or unpublished and often not sufficiently detailed to provide adequate documentation of cause-and-effect relations. Even when thermal features are on public lands, hydrologic monitoring may be deemed unnecessary where expected changes in thermal features or land-surface elevations are judged a-priori to be either mitigatable or insignificant.

A common aspect of changes induced by development of hot-water reservoirs is the reduction of liquid discharge in springs and geysers and the increase in steam discharge in fumaroles and other steam-heated features. Available information indicates that such changes have occurred at Long Valley, Steamboat, Beowawe, Amadee Hot Springs, and Brady Hot Springs, while at Coso Hot Springs and Dixie Valley naturally occurring steam discharge has increased during development. At Amadee Hot Springs, Brady Hot Springs, Dixie Valley, and Long Valley, reductions in reservoir pressure have also induced significant levels of land subsidence and ground cracking. As pointed out previously, documentation of such changes and determinations of the influence of various factors on the thermal features is adequate only for Long Valley. At Beowawe and Steamboat Springs, reductions and cessation of geyser activity accompanied the pre-development testing of production wells in the 1970's, at a time when monitoring efforts were inadequate. Some of the previously cited references contain information on thermal features at the "other" areas of geothermal development discussed in this section; additional pertinent references are listed below:

- Beowawe: Zoback (1979); White (1998); Layman (1984); Olmsted and Rush (1987)
- Brady Hot Springs: Ettinger and Brugman (1992); Harrill (1970), Osterling (1969); Olmsted et al. (1975)
- Coso Hot Springs: Monahan and Condon (1991a,b); Erskine and Lofgren (1989); Fournier et al. (1980); Fournier and Thompson (1982)
- Dixie Valley: Williams et al. (1997); Waibel (1987)

5. CONCLUSIONS

Changes in surficial thermal features and land elevations accompanying geothermal development should be viewed as the rule, rather than the exception. This follows from the nature of geothermal reservoirs within flow systems that commonly include discharge of fluids at the land surface. In the absence of fluid injection in locations proximal to such discharge areas, reductions in reservoir pressure will cause some degree of reduction in fluid upflow feeding the thermal features. Natural geyser activity should be expected to be most sensitive to such changes because of the unique combination of processes and characteristics typically required for geyser discharge. Where hot fluids occur at relatively shallow depths, either within a developed reservoir or in the overlying groundwater system, pressure reduction can also induce boiling conditions that result in increases in steam discharge at the land surface.

Factors other than pressure reductions in geothermal reservoirs can influence the temperature and flow rate of surficial thermal features. Information gained from hydrologic monitoring in and around the developed well fields, both during and prior to the development period, can allow quantification of the timing and magnitude of cause-and-effect relations between various factors that affect surficial thermal discharge and guide attempts to mitigate any adverse impacts caused by development.

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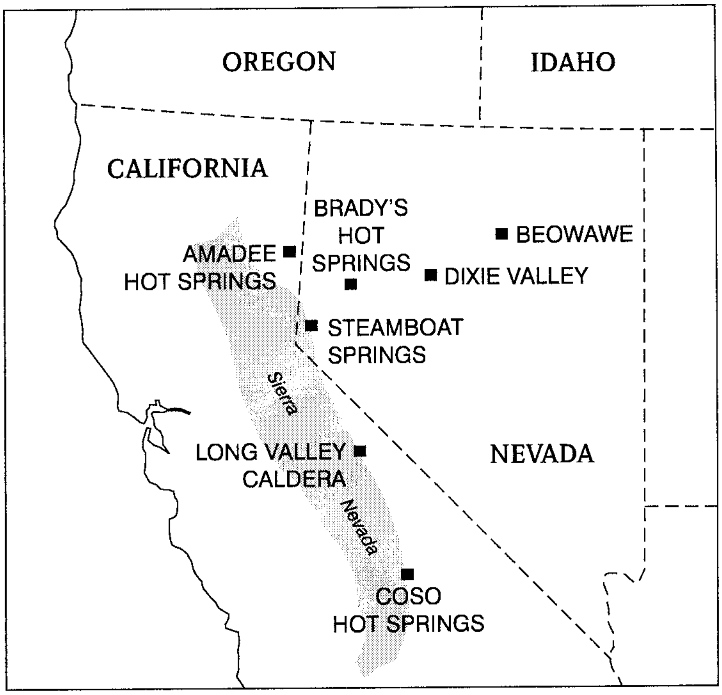

Figure 1. Locations of some geothermal fields where development has been associated with changes in thermal features and/or land subsidence.

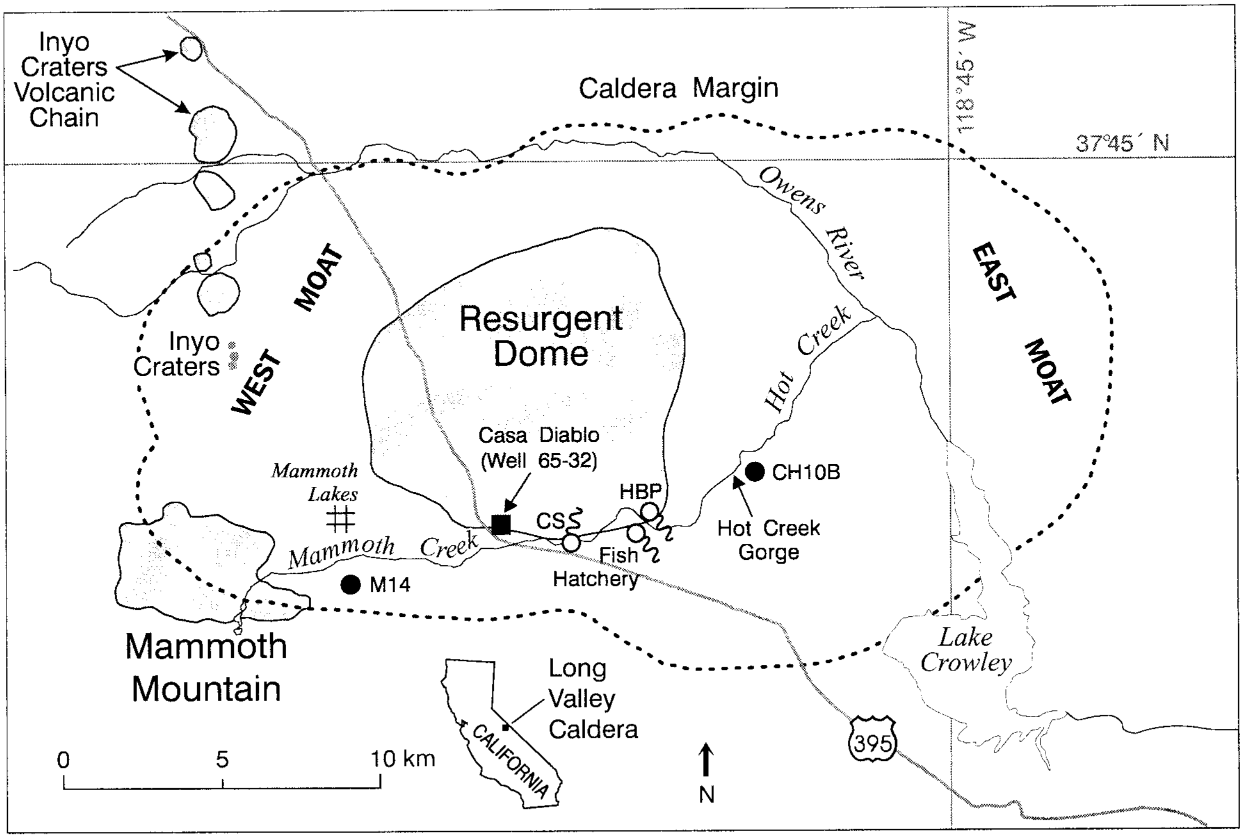

Figure 2. Map of Long Valley caldera showing various geologic and cultural features, and key sites in the hydrologic monitoring program directed by the Long Valley Hydrologic Advisory Committee.

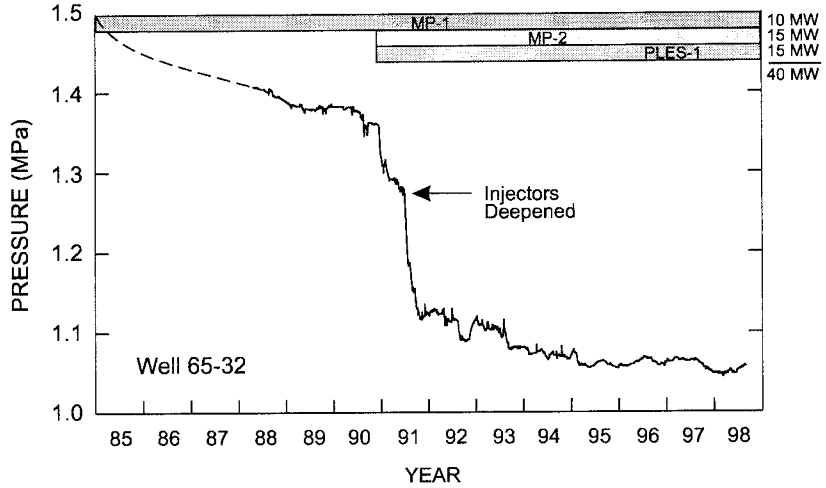

Figure 3. Pressure history in observation well 65-32, located on the edge of the geothermal well field at Casa Diablo, and periods of operation of three geothermal power plants.

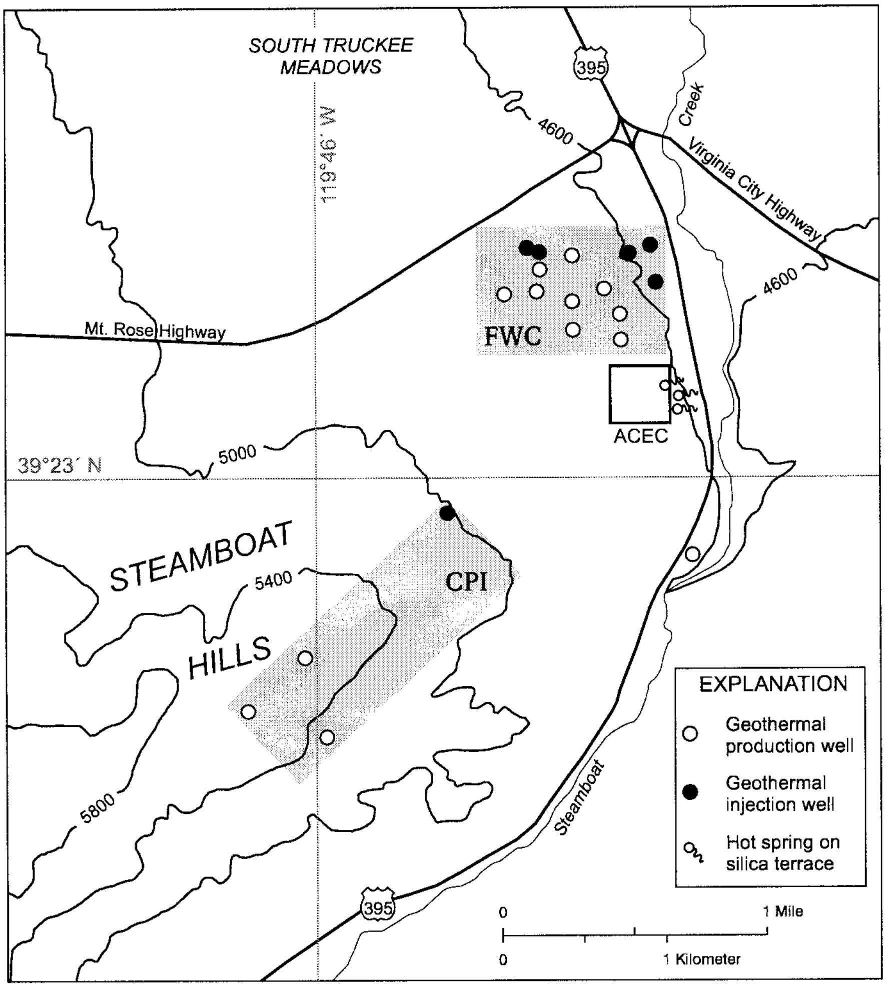

Figure 4. Map of the Steamboat Hills and surrounding region showing approximate wellfield areas for the Caithness Power, Incorporated (CPI) and Far West Capital (FWC) geothermal developments, locations of most of the production and injection wells, some of the vents on the main silica terrace that formerly included active hot springs and geysers, and the outline of the Area of Critical Environmental Concern (ACEC) designated by the Bureau of Land Management.