HYDROLOGIC AND TOPOGRAPHIC CHANGES IN LONG VALLEY CALDERA, CALIFORNIA, INDUCED BY GEOTHERMAL DEVELOPMENT 1985-1992

M.L. SOREY[1], C.D. FARRAR[2] AND G.A. MARSHALL[1]

[1]U.S. Geological Survey, Menlo Park, California, USA
[2]U.S. Geological Survey, Tahoe City, California, USA

SUMMARY - Long Valley caldera in east-central California has been the site of accelerated geothermal exploration and development and crustal unrest in the form of seismicity and ground deformation since 1980. These factors have contributed to changes observed in the hydrothermal system, including changes in the flow rate and temperature of thermal springs and fumaroles, and changes in pressures and temperatures in wells. The concurrent pattern of ground deformation involves uplift of the resurgent dome and surrounding moat areas in response to magmatic intrusion, and relative subsidence in the area of geothermal development on the south edge of the resurgent dome. Declines in reservoir pressure and temperature in the geothermal well field appear to be responsible for much of the relative subsidence, as well as for decreases in flow rates of thermal springs out to distances of about 5 km and increases in steam discharge from fumaroles within the well field. In spite of these hydrologic changes, the geothermal reservoir appears to have reached a new, relatively stable condition for the current power output of about 40 MW.

1. INTRODUCTION

Long Valley caldera in east-central California formed 0.7 m.y. ago with the eruption of ~600 km^3 of rhyolitic ash referred to as the Bishop Tuff (Fig. 1). Bailey (1989) and Bailey *et al.* (1976) describe the Pleistocene volcanic history of the Long Valley area, including intermittent eruptions of rocks of rhyolitic to basaltic composition. Holocene volcanic activity has occurred along a 26 km-long north-south alignment of rhyolitic domes and phreatic craters, including a southern segment referred to as the Inyo Craters volcanic chain that extends into the caldera from the north, and includes eruptive domes and craters as young as 550-650 years. Phreatic craters on the north flank of Mammoth Mountain were also formed during this most recent eruptive period. In contrast, no eruptive activity has occurred on or around the resurgent dome in the west-central part of the caldera for the past 100,000 years. This observation, along with results from well drilling and geophysical investigations, lead Sorey *et al.* (1991) to the conclusion that the magmatic heat source and the source reservoir for the present-day hydrothermal system occur beneath the west moat (Fig. 1).

Earthquakes of M ~6 occurred in the south moat in May 1980 and January 1983. Uplift and extension of the caldera floor in patterns suggestive of magmatic inflation were delineated over the 1980-1984 period (Hill *et al.*, 1985). Accelerated rates of strain over the resurgent dome since 1989 and an associated increase in seismic activity are modeled as resulting from magmatic intrusion at a depth of about 7 km beneath the center of the resurgent dome (Langbein et *al.*, 1993). The cumulative uplift of the dome between 1975 and 1988 was about 0.52 m; between 1988 and 1992 an additional uplift of about 0.1 m occurred.

Drill holes have encountered temperatures as high as 214 C within the volcanic fill in the west moat but lower temperatures in reservoirs located farther to the east. The drill hole data, along with geochemical and isotopic data from hot springs, indicate a continuity of thermal fluid flow southeastward from the west moat across the southern part of the resurgent dome and into the east moat (Sorey *et al.*, 1991). Discharge occurs at hot springs located around the south and east sides of the dome and in the east moat, most noticeably at Hot Creek Gorge (HCG in Fig. 1). The total throughflow of thermal water in the hydrothermal system is approximately 370 kg/s.

At the Hot Creek Fish Hatchery, four groups of springs discharge ground water at temperatures varying from about 16°C on the west (AB in Fig. 1) to 11°C on the east side (H-2,3 in Fig. 1). The temperatures and chemical composition of the westernmost spring groups indicate that they contain variable mixtures of thermal and nonthermal ground water. The Hatchery maintains highly productive fish breeding and rearing operations utilizing combinations of water from the different springs groups.

Geothermal development in Long Valley caldera currently consists of three binary-electric power plants at Casa Diablo. Power production began in this area in 1985 at 10 MW and in late 1990 two additional plants went on line bringing the total power output to approximately 40 MW. The total flow rate through the

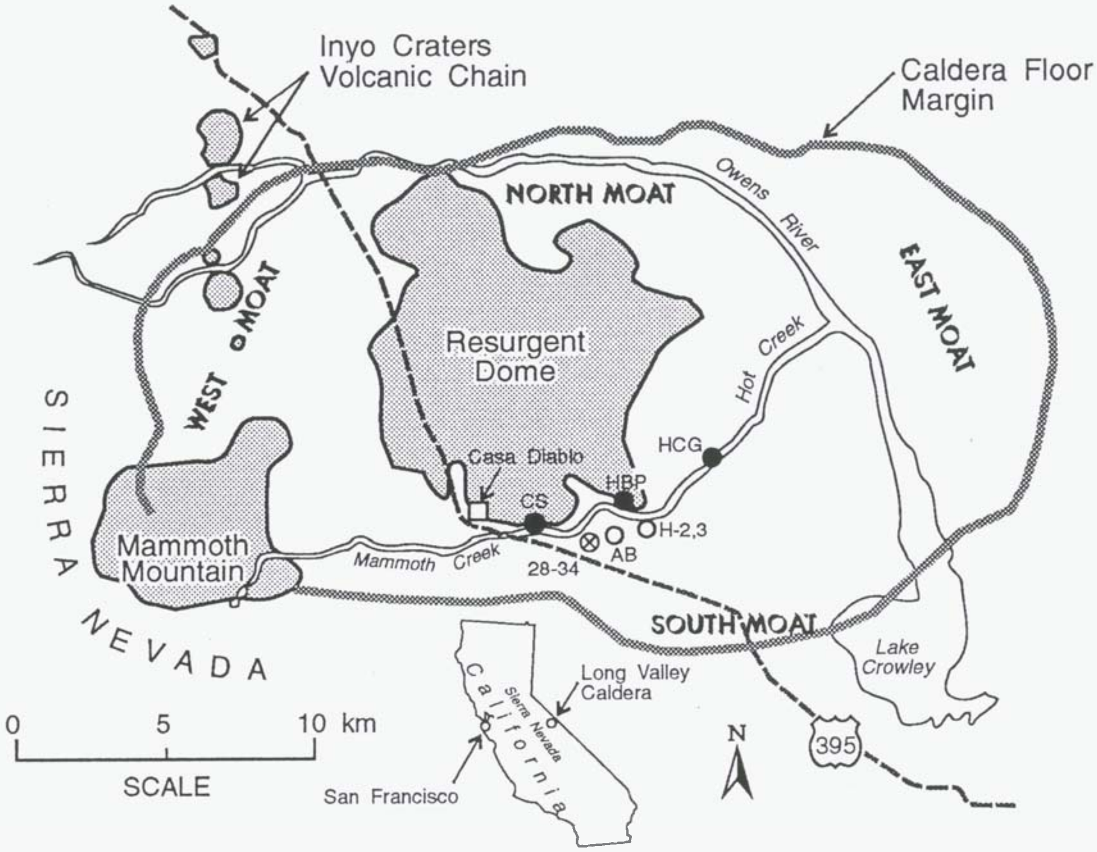

Figure 1. Map of the Long Valley caldera showing locations of the current site of geothermal power production (Casa Diablo) and other sites of hydrologic interest discussed in text. Hot springs are shown as filled circles; an observation well drilled in 1992 (28-34) is shown with a circle and cross; springs containing a small thermal-water component at the Hot Creek Fish Hatchery are shown as open circles.

three plants is approximately 900 kg/s; geothermal water is produced at temperatures near 170°C from 9 wells situated on the western side of the field and injected at 85°C in 4 wells on the eastern side of the field (Fig. 2). The production reservoir is in rhyolite flows and tuffs at depths of 120-150 m; the cooled geothermal fluid is currently injected into fracture zones in the welded Bishop Tuff at depths greater than 500 m. Prior to July 1991, however, the top of the injection zone was as shallow as 335 m.

Concern over possible impacts to thermal springs at Hot Creek Gorge and the Hot Creek Fish Hatchery from geothermal development led to formation of a Hydrologic Advisory Committee in 1987 to oversee the collection and interpretation of hydrologic monitoring data (Farrar and Lyster, 1990). Collection of data on ground deformation, while not specifically part of the hydrologic monitoring program, have also proven useful in delineating changes in geothermal reservoir conditions in response to development.

2. CHANGES OVER THE 1988-1992 PERIOD

2.1 Casa Diablo Area

Changes in reservoir conditions at Casa Diablo are monitored continuously in each production well and in an observation well (65-32) located near the southeastern side of the field (Fig. 2). Quarterly sampling of fluid chemistry and measurements of well temperature profiles are also carried *out* by the geothermal operator. The Casa Diablo production reservoir is highly transmissive (kh values of 1,500 darcy-meters are commonly measured in interference tests), and pressures have declined more-or-less uniformly over both the production and injection sides of the well field. The cumulative pressure decline in observation well 65-32 between 1985 and 1990 amounted to about 0.6 bars. An additional decline of approximately 2.3 bars occurred between 1991 and 1992 in response to increased production to supply the two additional plants and deepening of injection wells. The latter change was made to lessen the amount of injection water breakthrough in production wells. The increased rate of pressure decline that occurred following the deepening of the injection wells is thought to be related to lessening of pressure support provided to the production reservoir by injection. Since mid-1992, reservoir pressure and temperature have remained relatively constant.

Thermal fluids formerly discharged in the Casa Diablo area in high-chloride hot springs situated on or near the fault along the western side of the well field (Fig. 2) and in boiling-point steam vents were clustered along the

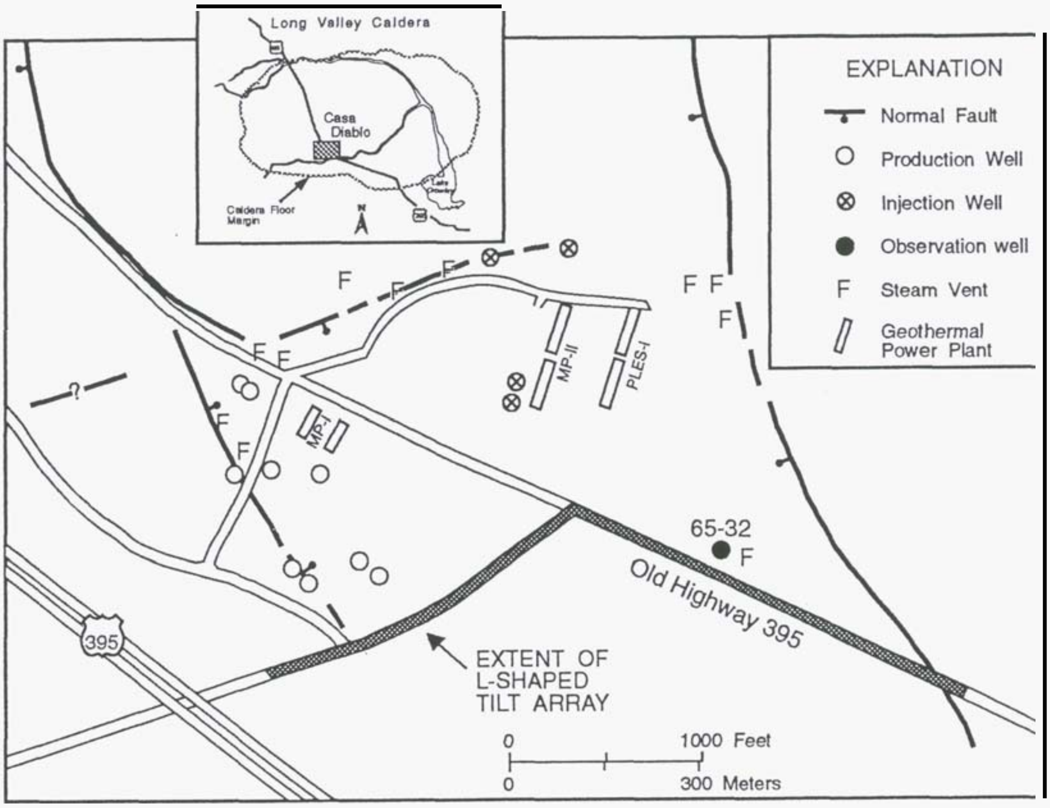

Figure 2. Map of the Casa Diablo area in Long Valley caldera showing the geothermal well field, power plants MP-1, MP-2, and PLES-1, and other sites discussed in text.

fault at the eastern side of the field (Fig. 2). Hot spring flow began to decline in 1985 and by 1986 was replaced by weak emanations of steam along the west-side fault. Steam discharge increased dramatically in 1991 from these vents and from vents within the eastern side of the field. Superheated fumaroles and acid-sulphate seeps currently occur along the fault bordering the eastern side of the field and along an inferred fault along the northern side of the well field. These changes are clearly related to reductions in reservoir pressure accompanying geothermal development; the accelerated rate and increased temperature of steam discharge in 1991 reflects the onset of boiling conditions within the shallow ground-water system resulting from the additional pressure reduction accompanying increased power production. The total rate of steam discharge at present was estimated by Sorey ***et a/.*** (1993) at about 3.6 kg/s.

Beginning in 1986, leveling data collected along Old Highway 395, which merges with the current state highway outside the Casa Diablo area, show a dip in the vicinity of Casa Diablo superimposed on the general pattern of uplift begun in 1980 (Fig. 3). This effect of local subsidence near Casa Diablo is even more significant over the 1988-1992 period when Casa Diablo subsided 0.12 m relative to benchmarks outside the area of subsidence, which had risen about 0.10 m. The corresponding subsidence estimate for the 1985-1988 period is only about 0.04 m. Data from an L-shaped array of bench marks located just south of the well field (Fig. 2) show the time-history of subsidence and resultant tilt in this area (Fig. **4)**. Northward tilt, which began in 1985, appears to have stabilized by 1990 but then increased again over the 1990-1992 period. Additional bench marks were installed at several well pads in 1988. Leveling data from the network of bench marks in the Casa Diablo area show that the area of maximum subsidence now extends across the production and injection sides of the well field near the inferred fault that marks the northern edge of the well field (Farrar ***et*** *al.*, 1993). These data also indicate local offset on the northwest-trending faults that border the field.

2.2 Thermal Springs East of Casa Diablo

Changes have been observed at thermal springs located to the east of Casa Diablo over the 1991-1992 period. Colton Spring, a boiling temperature vent located approximately 2.5 km southeast of Casa Diablo (CS in Fig. 1), began a sharp decline in flow in the winter of 1991 and by mid-1991 was dry. Water-level reductions in a hot pool and an adjacent unused geothermal well at the Hot Bubbling Pool site (HBP in Fig. 1), located approximately 5 km east of Casa Diablo, have also been recorded since early 1991. The cumulative decline in water level at this site is –1.2 m, equivalent to –0.1 bar of pressure drop.

The flow of hot springs located at greater distances from Casa Diablo, for example at Hot Creek **Gorge**

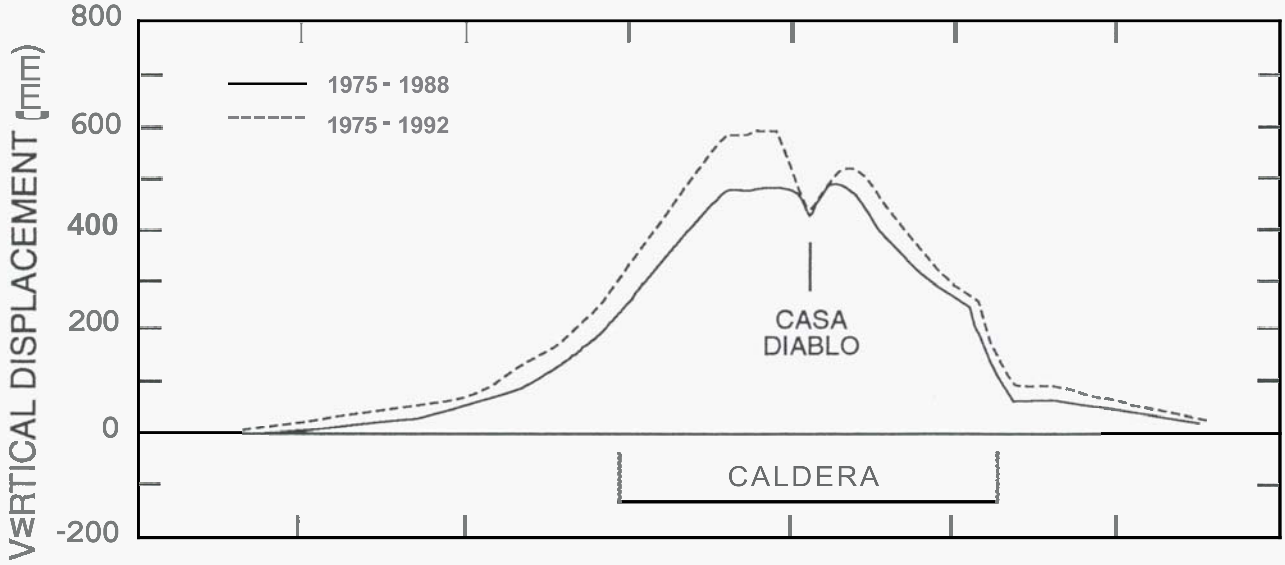

Figure 3. Vertical displacement of the land surface along Highway 395 across Long Valley caldera since 1975. Lines fitted to data points at individual bench marks, based on data from D. Dzurisin, U.S. Geological Survey Cascades Volcanic Observatory, Vancouver, Washington.

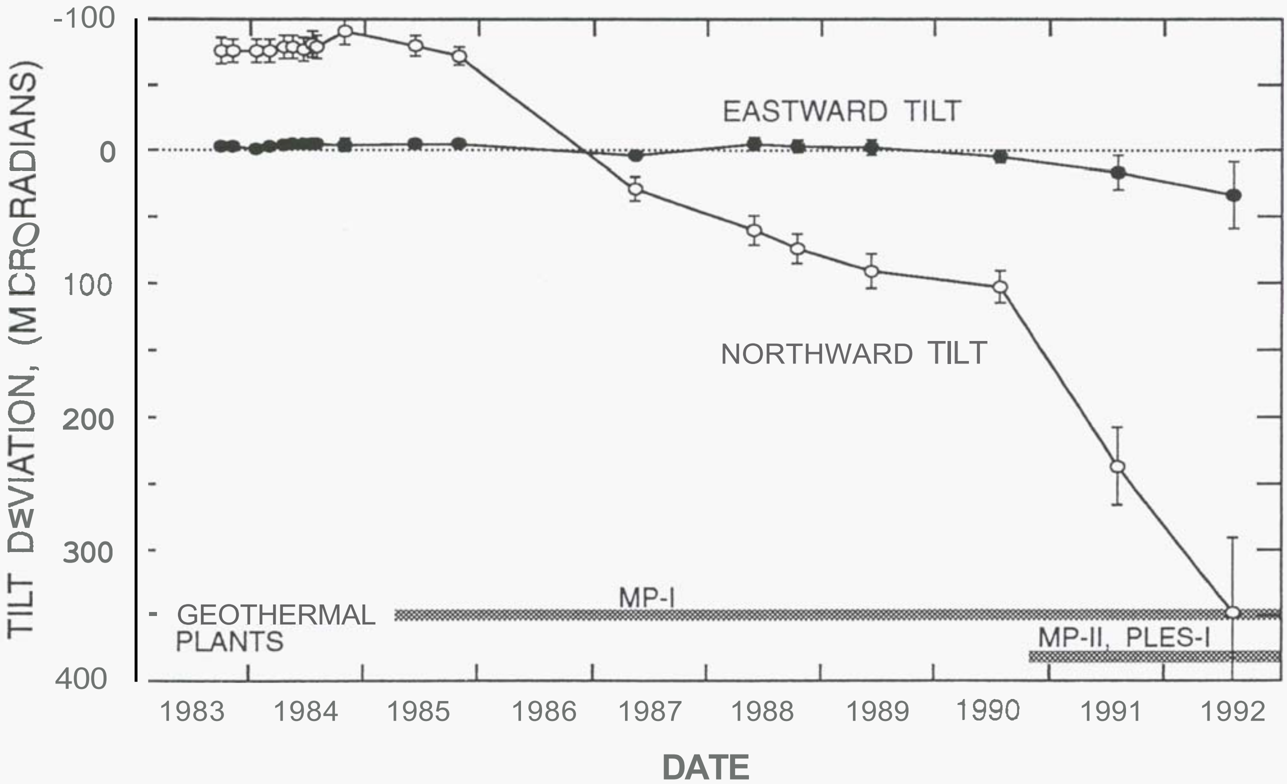

Figure 4. Calculated tilt from elevation changes along L-shaped bench mark array at Casa Diablo in Long Valley caldera (location in Fig. 2). Also shown are the periods of operation of the three geothermal power plants at Casa Diablo. Error bars represent 1 standard deviation.

(HCG in Fig. 1), does not appear to have declined thus far. This may reflect greater error in measuring the combined flow of these springs, as well as attenuation of reservoir pressure decline with distance from Casa Diablo.

Thermal springs at the Hot Creek Fish Hatchery are located approximately the same distance from Casa Diablo as is the Hot Bubbling Pool site (5 km). Monitoring of spring flow and chloride concentration at the westernmost groups of hatchery springs over the past 5 years indicates that the thermal component in these springs could have declined by about 30% since 1991. However, because of a concurrent reduction in the nonthermal component due to several years of below normal precipitation, the composite temperature of these springs has actually increased 1-2°C. Further complicating interpretationsof changes at these springs is the observation that the magnitude of the thermal component increases due to a loading effect following increased recharge of the cold-water aquifer from snowmelt.

3. DISCUSSION

Correspondence between the timing of geothermal power productionand observed changes in land-surface elevation, hot-spring flow, and steam discharge at Casa Diablo, and in spring flow at sites east of Casa Diablo suggest causative relations. Further, the rate of such changes accelerated in 1991, following the increase in geothermal fluid production and deepening of injection wells. Accelerated rates of crustal strain may also have contributed to ground deformation and increased steam flow.

The correspondence between the tilt record and the history of power-plant operation and associated reservoir pressure decline suggests that the relative subsidence at Casa Diablo results in large part from effects associated with geothermal development. Subsidence appears to be localized within a region of –3 km^2 that includes both the production and injection sides of the well field, but extends beyond the well field to the north, south, and west. Offsets along several normal faults that bound the well field are indicated by the leveling data and by visual inspection; such offsets could result from a combination of slippage accompanying magmatic inflation over the resurgent dome and reservoir pressure reductions related to fluid withdrawal.

Several processes associated with geothermal development could combine to cause relative subsidence in this area: (1) reductions in pore pressure in the shallow production reservoir and in overlying, more compressible formations, (2) reductions in temperature and resultant rock contraction around injection wells, and (3) loss of mass caused by escape of steam from shallow boiling zones. The correspondence between the period of accelerated deformation of the L-shaped tilt array (1991-1992) and the record of increased pressure decline accompanying the start-up of the two additional power plants and the deepening of the injection wells in 1991 indicates that much of the –0.12 m of subsidence during this period was caused by pore-pressure decline and associated formation compaction. Although the relative subsidence at Casa Diablo is significant against a background of uplift of the surrounding region in response to magmatic inflation, no detrimental impacts to structures or roads have resulted from these changes in land surface elevation. Indeed, the net effect of relative subsidence and regional uplift is a rise in land surface at Casa Diablo of **–0.4** m since 1975.

Increases in the rate and temperature of steam discharge in the Casa Diablo area since 1990 are due in large part to the onset of boiling in the ground-water system overlying the geothermal production reservoir. A zone of nearly isothermal, vapor-static conditions has been detected in temperature profiles in some wells. Increases in permeability along faults caused by the concurrent seismic activity and extensional strain may also play a role in increasing the rate of steam discharge at the surface. Steam upflow has heated the soil in places to such an extent that one building had to be abandoned and mature pine trees have died at several locations. Although steam-heating of shallow ground-water aquifers in response to pressure reductions in geothermal reservoirs has caused hydrothermal eruptions in some developed geothermal fields (Scott and Cody, 1982; Allis, 1986; Bixley and Browne, 1988), no such eruptive activity has occurred at Casa Diablo. The relative ease with which steam can escape along fault conduits may provide a margin of safety in this regard.

Decreased spring flow at two thermal areas located ≤**5** km east of Casa Diablo followed the accelerated reservoir pressure decline over the 1991-1992 period. As part of the hydrologic monitoring program accompanying geothermal development, a second observation well was drilled by the developer in 1992 at a site between Colton Spring and the Hatchery (28-34 in Fig. 1). Because the well was completed after the effects of the most recent reservoir pressure reductions at Casa Diablo occurred, its pressure record thus far contains little useful information about hydrologic connections between Casa Diablo and thermal aquifers farther to the east. The new observation well did encounter a permeable zone at depths of 140-200 m containing 150 C, high chloride fluid, thus lending support to the conceptual model of Sorey ***et a/.*** (1991) of lateral flow of thermal fluid from Casa Diablo to thermal springs farther to the east.

Conditions of the use permits under which the various geothermal power plants were permitted require that thermal springs in Hot Creek Gorge and at the Hot Creek Fish Hatchery do not suffer negative impacts. In this context, negative impacts require that reductions in spring flow or temperature caused by geothermal development result in an identifiable degradation of the current use of these features. Such degradations have not occurred; and because reservoir conditions at Casa Diablo are now relatively stable, no mitigation to reverse the hydrologic changes discussed above has been required. Continued monitoring is needed, however, to assess additional changes that may result in negative impacts to thermal springs if further changes occur at Casa Diablo as a result of additional fluid production or some unexpected drop in reservoir pressure or temperature.

4. ACKNOWLEDGEMENTS

Results of leveling data along Highway 395 over the 1975-1992 period were provided by D. Dzurizin, U.S. Geological Survey, Vancouver, WA. Assistance in the collection of the tilt data was provided by J.F. Howle, U.S. Geological Survey, Tahoe City, CA. Permission to publish information about pressure changes in the production reservoir at Casa Diablo was given by Pacific Energy, Commerce, California.

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