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The thermal regime in the resurgent dome of Long Valley Caldera, California: Inferences from precision temperature logs in deep wells

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ABSTRACT

Long Valley Caldera in eastern California formed 0.76 Ma ago in a cataclysmic eruption that resulted in the deposition of 600 km^3 of Bishop Tuff. The total current heat flow from the caldera floor is estimated to be ~290 MW, and a geothermal power plant in Casa Diablo on the flanks of the resurgent dome (RD) generates ~40 MWe. The RD in the center of the caldera was uplifted by ~80 cm between 1980 and 1999 and was explained by most models as a response to magma intrusion into the shallow crust. This unrest has led to extensive research on geothermal resources and volcanic hazards in the caldera. Here we present results from precise, high-resolution, temperature–depth profiles in five deep boreholes (327–1,158 m) on the RD to assess its thermal state, and more specifically 1) to provide bounds on the advective heat transport as a guide for future geothermal exploration, 2) to provide constraints on the occurrence of magma at shallow crustal depths, and 3) to provide a baseline for future transient thermal phenomena in response to large earthquakes, volcanic activity, or geothermal production. The temperature profiles display substantial non-linearity within each profile and variability between the different profiles. All profiles display significant temperature reversals with depth and temperature gradients <50 °C/km at their bottom. The maximum temperature in the individual boreholes ranges between 124.7 °C and 129.5 °C and bottom hole temperatures range between 99.4 °C and 129.5 °C. The high-temperature units in the three Fumarole Valley boreholes are at the approximate same elevation as the high-temperature unit in borehole M-1 in Casa Diablo indicating lateral or sub-lateral hydrothermal flow through the resurgent dome. Small differences in temperature between measurements in consecutive years in three of the wells suggest slow cooling of the shallow hydrothermal flow system. By matching theoretical curves to segments of the measured temperature profiles, we calculate horizontal groundwater velocities in the hydrothermal flow unit under the RD that range from 1.9 to 2.8 m/yr, which corresponds to a maximum power flowing through the RD of 3–4 MW. The relatively low temperatures and large isothermal segments at the bottom of the temperature profiles are inconsistent with the presence of magma at shallow crustal levels.

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1. Introduction

The 30×20-km Long Valley Caldera (LVC) in eastern California (Fig. 1) formed 0.76 Ma ago in a cataclysmic eruption that resulted in the deposition of 600 km^3 of Bishop Tuff. By 0.6 Ma ago, uplift of the caldera floor and eruption of rhyolitic lava formed the resurgent dome (Bailey, 2004; Hildreth, 2004). The most recent eruptions in the region occurred outside the caldera along the Mono-Inyo Craters volcanic chain, including 20 small eruptions at intervals ranging from 250 (on Pahoa Island in Mono Lake) to 700 years before present (Miller, 1985; Sieh and Bursik, 1986; Bursik and Sieh, 1989).

In the past few decades, LVC has been the site of extensive research on geothermal resources and volcanic hazards. The caldera hosts an active hydrothermal system that includes hot springs, fumaroles, mineral deposits and active geothermal power production at Casa Diablo (Fig. 1) which began operation in 1985 (Sorey et al., 1978; Sorey, 1985; Sorey et al., 1991; Sorey et al., 1995) and now produces 40 MWe (net). Sorey (1985) estimated the total conductive and convective heat flow from the caldera floor to be 290 MW, which represents an average heat flux of 640 mW/m^2. LVC and its surroundings have experienced volcanic unrest characterized by several periods of moderate earthquake swarms and uplift of the resurgent dome (RD; Fig. 1) by approximately 80 cm between 1980 and late 1999 (Hill et al., 2003; Langbein, 2003).

In the 1970s and 1980s several intermediate depth (100–500 m) and deep (>500 m) holes were drilled on the RD for geothermal exploration. Some of the proprietary data acquired after drilling was released and published previously (Sorey et al., 1991; Farrar et al., 2003). The deep (~3 km) Long Valley Exploratory Well (LVEW) drilled on the summit of the RD in the 1990s was designed to investigate both the potential for near-magmatic temperature energy extraction and the occurrence of

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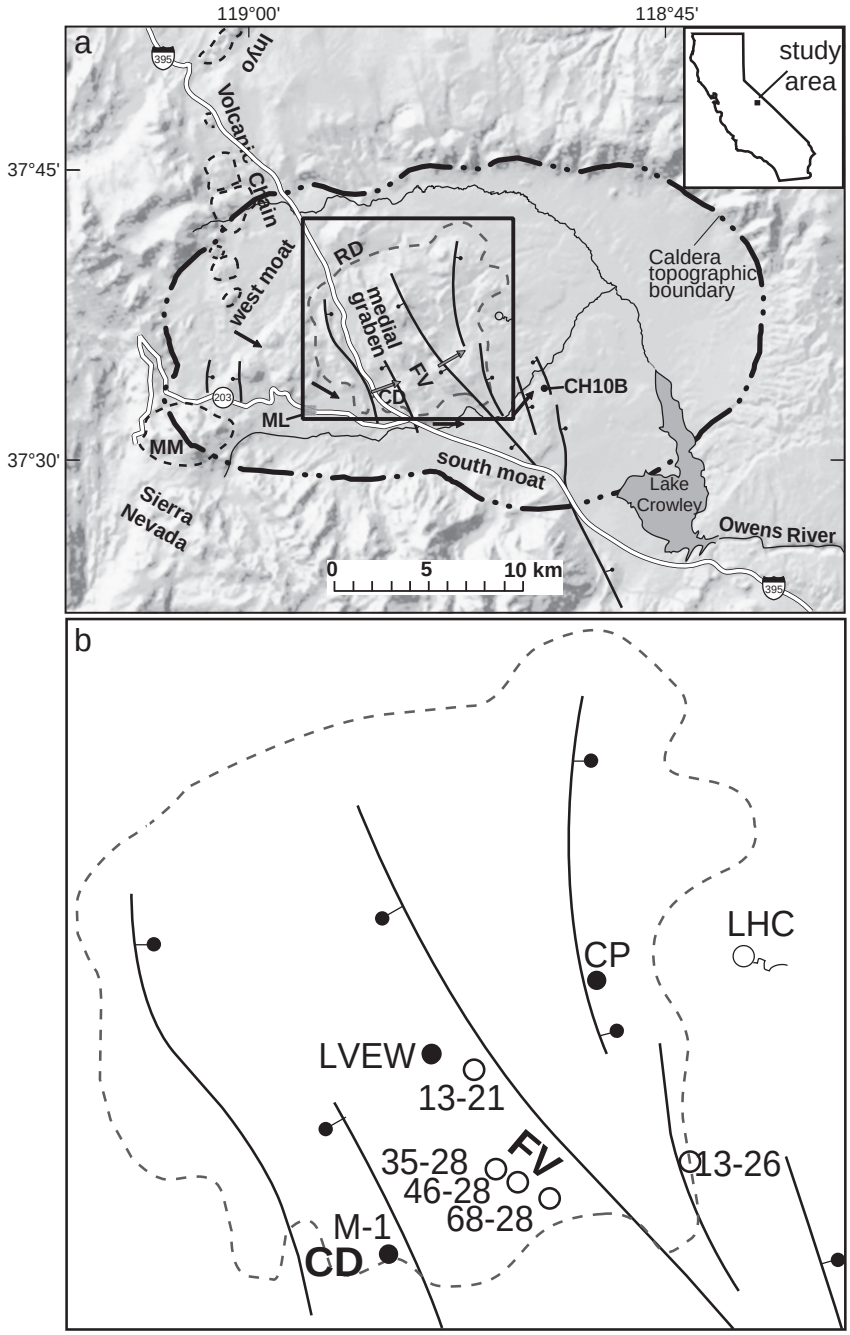

Fig. 1. a. Shaded relief map of Long Valley Caldera (LVC) and surrounding region showing topographic boundary of the caldera (dot-dash line), the resurgent dome (RD), Fumarole Valley (FV), Mammoth Mountain (MM), the town of Mammoth Lakes (ML), Casa Diablo (CD) is the location of the geothermal power plant, rhyolite domes forming the Inyo Volcanic Chain, and borehole CH-10B. Also shown are major northwest-trending faults traversing the resurgent dome and forming the Medial Graben. The rectangular line in the center outlines the area shown in part b. The black arrows represent the direction of hydrothermal flow from the west moat of the caldera, and the grey arrows represent direction of hydrothermal flow as inferred from temperature profiles in Fumarole Valley. b. Plan view of the resurgent dome (RD; dashed line) showing locations of boreholes from this study (open circles), other deep wells on the RD (filled circles), and Little Hot Creek (LHC) spring.

magma (Rundle et al., 1986; Chu et al., 1990). However, temperature at a depth of ~3 km was only 103 °C (Table 1), typical of a near-normal geothermal gradient (Farrar et al., 2003; Pribnow et al., 2003).

In recent years, several additional wells drilled by the industry on the RD were released for scientific research and volcanic monitoring. In June 2005 and July 2006, the U.S. Geological Survey acquired precise, high-resolution temperature–depth profiles in five deep wells on the RD and its vicinity, including three wells in the Fumarole Valley (Fig. 1) for which data was not previously published (Table 1). With the new temperature data (Farrar et al., 2010), we assess the thermal state of the RD with the following specific goals: 1) provide bounds on the advective heat transport through the RD as guidance for future geothermal exploration, 2) provide constraints on the occurrence of magma beneath the RD and 3) provide a baseline for measurement of transient thermal phenomena in response to large earthquakes, volcanic activity, or geothermal production.

2. The dynamics and thermal regime of the resurgent dome

The RD is a structural uplift in the center of LVC that forms a topographic high ~500 m above the surrounding caldera floor. Most of the RD was formed within the 150 ky following caldera formation

Table 1
Properties of wells on the resurgent dome and vicinity.

Well	Lat.[1]	Long.[1]	Altitude (m)[2]	Depth (m)	Well diameter (cm)	Max. temp. (°C)	Bottom temp. (°C)	Water level alt.[3]
13-21 (2005)	374030	1185407	2340	1111	7.32[4]	124.8	99.5	2146
13-21 (2006)						124.7	99.4	
13-26 (2005)	373936	1185134	2258	1158	5.08	135.3	109.6	2147
46-28 (2005)	373920	1185330	2291	342	3.81	127.4	123.2	
46-28 (2006)						127.3	123.2	
68-28 (2005)	373905	1185312	2249	607	3.81	129.5	129.5	2194
35-28 (2006)	373927	1185335	2234	327	3.81	129.0	123.0	
35-28 (2007)						128.1	123.2	
M-1 (1983)	373849	1185440	2227	1605		169.0	100.0	
CP-1 (1982)	374120	1185149	2224		24.45	147.8	147.8	
LVEW(2001)	374048	185428	2367	2997	5.08	102.7	100.7	2103

[1] Latitude and longitude in degrees, minutes, and seconds NAD1927.
[2] NGVD29 datum.
[3] Measured after casing was perforated.
[4] Inside a 9-in. open hole.

760 ky ago and was contemporaneous with eruption of voluminous post-caldera rhyolite eruptions (Bailey et al., 1976). The stratigraphy of the RD revealed from LVEW drillcore consists of 650 m of rhyolite flows underlain by 1,180 m of Bishop Tuff, and a metamorphic section of the Paleozoic basement to the bottom of the hole at 2,996 m (Sackett et al., 1999). The Bishop Tuff varies within the RD from unwelded to strongly welded, and at LVEW the Early Rhyolites comprise a complex sequence of silicic extrusive rocks with zones of obsidian and perlite. Zones of extensive fracturing and faulting are common in the Early Rhyolites, and within these zones argillic and kaolinitic alteration are pervasive. Oxygen isotopes of LVEW core samples indicate that intrusive activity on the RD was initiated soon after caldera collapse (760 ka) and subsequently migrated toward the western margin of the caldera (McConnell et al., 1997).

The ~80 cm of RD uplift between 1980 and 1999 occurred mainly in a few intense pulses rather than through uniform displacement (Hill et al., 2003). Since 1998, deformation of the RD has slowed substantially and rates of seismic activity within the caldera since 2000 have remained low. Seismicity beneath the RD in the past three decades was concentrated in the southern half with essentially no earthquakes in the northern part.

Most models of RD deformation invoked magma intrusion into the shallow crust as the cause of uplift (e.g. Savage et al., 1987; Battaglia et al., 1999; Fialko et al., 2001; Langbein, 2003; Newman et al., 2006). Based on gravity data, Battaglia et al. (2003) proposed that the volume of the crustal source increased by 0.105–0.187 km^3 from 1982 to 1999 with a material that has a density of 1180–2330 kg/m^3, suggesting intrusion of silicic magma or the addition of a mixture of silicic magma and an aqueous-rich fluid beneath the RD. These values were recently modified to a volume change of 0.068 km^3 and a density of 2,192–3,564 kg/m^3 at a depth of 6.6–8.7 km, suggesting supply of basaltic magma to the shallow crust (Tizzani et al., 2009). However, Hildreth (2004) argues that the formerly vigorous sub-caldera rhyolitic reservoir has largely crystallized and the presence of magma in the shallow crust is unlikely. Several studies have suggested that some of the RD dynamics could be related to pressure increases in a liquid- or gas-filled volumes that receive inputs from deeper sources under the south moat of the caldera, instead of beneath the resurgent dome (Hill et al., 2003).

Early studies of the hydrothermal regime in LVC showed that upwelling hot water in the west moat mixes with meteoric water recharged along the eastern front of the Sierra Nevada and this mixed water flows to the east and southeast to discharge areas along and to the east of Hot Creek (Lachenbruch et al., 1976; Sorey et al., 1978). Wells drilled along the hydrothermal flow path characteristically show zones of temperature maxima and underlying temperature reversals with depth within the volcanic fill. These zones of high temperature are indicative of lateral fluid flow with maximum temperatures decreasing from 220 °C in the west moat, to 70–90 °C in the east moat (Blackwell, 1985; Sorey et al., 1991).

Current knowledge on the deep thermal structure of the RD is mainly derived from temperature measurements in LVEW (Fig. 2). The temperature profile in the well consists of an upper part to a

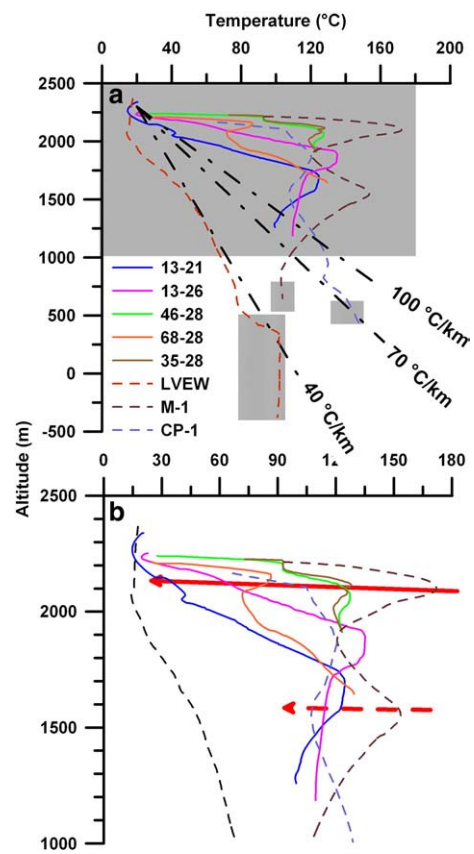

Fig. 2. a. Temperature–elevation profiles in boreholes on the resurgent dome (RD) of Long Valley Caldera. Solid lines are profiles from this study and dashed lines are for the Long Valley Exploratory Well (LVEW) acquired in 2001 (Pribnow et al., 2003; Farrar et al., 2003)). Clay Pit-1 (CP-1) acquired in August 1982 (Gene Suemnicht, EGS Inc.; written communication, March 2010), and M-1 in Casa Diablo acquired in 1983 (Tom Urban, U.S. Geological Survey, unpublished data). Dot-dash lines show temperature gradients extrapolated to depth from an elevation of 2,300 m and a temperature of 20 °C. The dark shaded region shows the section presented in part b and the shaded rectangles show segments of the profile that are within the metamorphic basement (from Farrar et al., 2003). The solid red arrow in part b shows the proposed elevation of the active hydrothermal flow system and the dashed arrow shows the deeper and probably extinct hydrothermal flow system.

depth of approximately 650 m (within the volcanic fill) with generally conductive gradients averaging about 35 °C/km. Within the underlying metamorphic basement, however, temperatures become isothermal at 103 °C below depths of 2000 m. Other deep wells drilled on or around the RD to depths that pass through all, or most of the Bishop Tuff section and into the pre-caldera metamorphic basement show isothermal conditions at ~100 °C near their bottoms (with the exception of CP-1; Fig. 2), suggesting an advective flow system that underlies the volcanic fill (Sorey et al., 1991; Farrar et al., 2003).

3. Temperature logging methods

All the reported temperature measurements were made in cased boreholes with diameters that vary from 3.81 cm (1.5 in.) to 7.32 cm (2.88 in.) (Table 1). The new temperature data is included as part of a new database of temperature measurements in LVC (Farrar et al., 2010). Boreholes 13-21, 13-26, 68-28, and 46-28 were originally constructed for temperature gradient measurements and had no openings for hydraulic communication with the formation. Temperatures measured in June 2005 were done before the casings were perforated. The measurements were made with the U.S. Geological Survey's heat flow logging truck, using a precision Platinum RTD element suspended on a calibrated four-conductor cable (Sass et al., 1971). Temperature measurements were obtained every foot (0.3048 m) while lowering the cable at a constant rate of approximately 6 m/min. The temperature probes are calibrated against a NIST-traceable Platinum Resistance Thermometer to a laboratory accuracy of better than 0.01 °C.

In September 2005, boreholes 13-21, 13-26, and 68-28 were perforated to establish a hydraulic connection between the wellbore and the surrounding rocks and allow sampling formation water and gases. Unfortunately, the perforation process damaged the casing of these wellbores so that access to the deeper parts of wells 13-26 and 68-28 is not possible. In July 2006, we repeated the temperature measurements in 13-21 that was perforated at a depth of 670 m and in well 46-28 that was not perforated.

Because of access problems with the logging truck, temperature in borehole 35-28 in Fumarole Valley was measured with a portable device in July 2006 and May 2007 using a precision thermistor suspended on a calibrated four-conductor cable. Temperature measurements were made with the "stop and go" method (Harris and Chapman, 2007) at either 6.10 m (20 ft.) or 3.05 m (10 ft.) intervals in 2006 and 2007, respectively. Electrical resistivity at discrete depths was recorded after the thermistor output stabilized and the recorded resistance was converted to temperature using a polynomial calibration curve. This resulting accuracy (considering errors in depth and temperature measurements) of the system is estimated to be better than 0.5 °C.

4. Temperature–depth profiles

The new high-precision temperature profiles display substantial non-linearity within each profile and variability between the different profiles (Figs. 2–8). All profiles display temperature reversals (Fig. 3) and temperature gradients <50 °C/km at their bottom (Figs. 4–8) where temperatures range between 99.4 °C in 13-21 (Fig. 4) and 129.5 °C in 68-28 (Fig. 5). Maximum temperature in the individual boreholes range from 124.7 °C in 13-21 to 129.5 °C in 68-28 (Table 1). All the metadata is available online (Farrar et al., 2010).

There is a strong correlation between the temperature distribution with depth and the lithology of the three Fumarole Valley wells (Figs. 5, 7, 8), for which logs obtained from cuttings are available (unpublished records at the Bureau of Land Management in Bishop, CA, reviewed in 2004). In these wells, zones of high temperature overlying temperature inversions are within the Early Rhyolite units. Elevated temperature gradients within the profiles, which are likely indicative of active groundwater flow, occur either at the contact between volcanic flow and tuff units (Figs. 5 and 7) or in fractured zones within the volcanic flow units (Figs. 5 and 8). In wells 46-28 and 35-28, the negative gradients also coincide with the zones that display the largest temperature difference between 2006 and 2005 in well

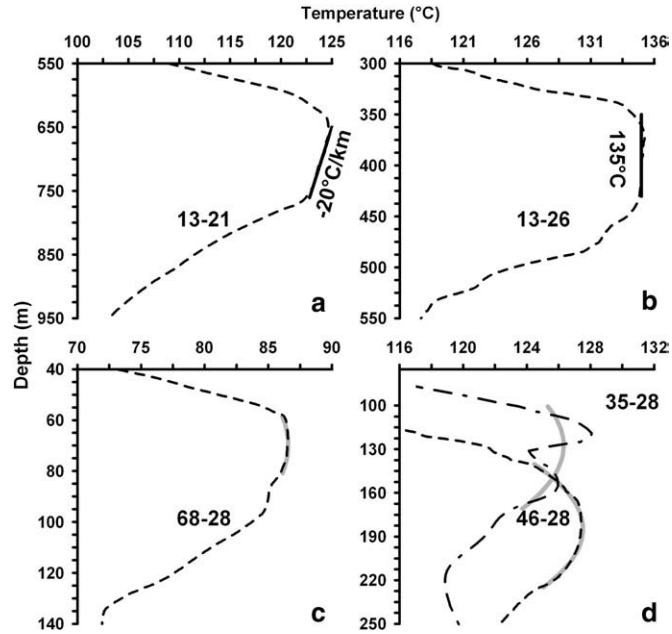

Fig. 3. Sections of the temperature profiles with elevated temperatures above temperature inversions (dashed curves) and calculated best fits to the profiles obtained from the solution to Eq. 3 (thick gray curves in the three Fumarole Valley wells) in a. 13-21, b. 13-26, c. 68-28 and d. 46-28 and 35-28 (dash-dot curve). The solid line in part a shows a negative linear gradient of 20 °C/km between a depth of 650 m and 760 m and the vertical solid line in part b shows an isotherm of 135 °C between a depth of 350 m and 430 m. Calculation results are presented in Table 2.

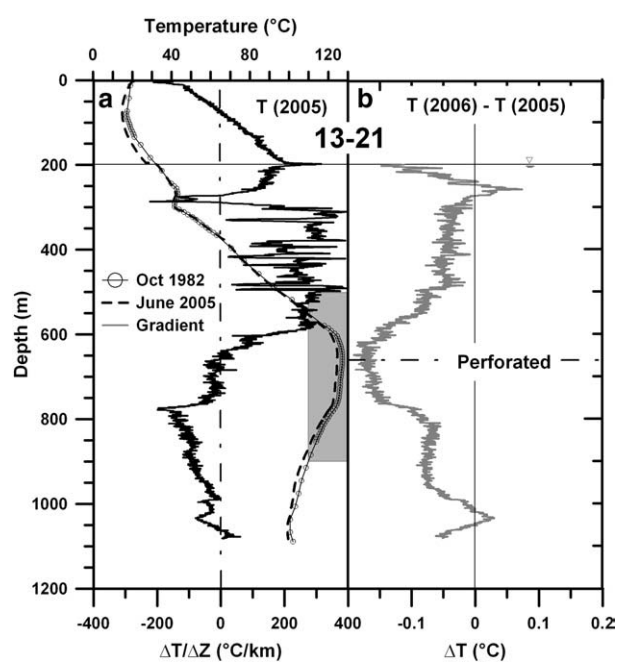

Fig. 4. a. Temperature profiles in borehole 13-21 from June 2005 (dashed line) and October 1982 (thin solid line) (data provided by Gene Suemnicht, EGS Inc.; written communication, March 2010), and the temperature gradient (thick solid line) in 2005. The shaded region shows the section of the 2005 profile presented in Fig. 3. b. Temperature difference between measurements made in July 2006 and June 2005. The horizontal dash-dot line shows the perforation depth and the thin horizontal line shows the depth to water after perforation in September 2005.

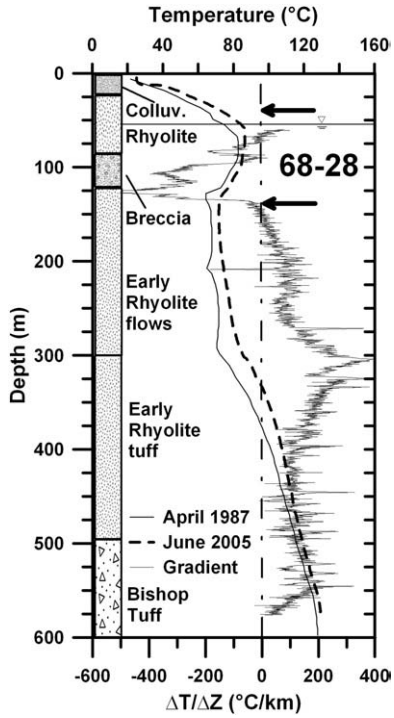

Fig. 5. Lithology and temperature profiles in borehole 68-28 from June 2005 (dashed line) and April 1987 (thin solid line) (acquired by Santa Fe Geothermal, Inc. and retrieved from unpublished records at the Bureau of Land Management in Bishop, CA, 2004) and the temperature gradient (thick solid line) in 2005. The horizontal arrows bracket the segment in the 2005 profile presented in Fig. 3. The thin horizontal solid line shows the depth of the water table after perforation in September 2005.

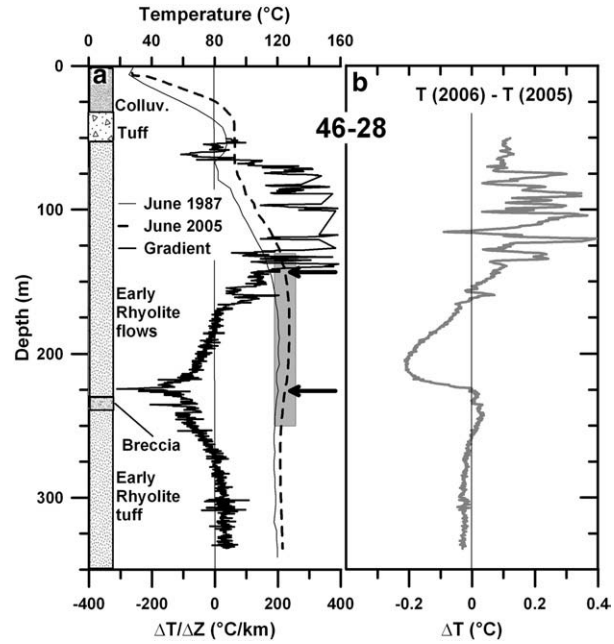

Fig. 7. a. Lithology and temperature profiles in borehole 46-28 from June 2005 (dashed line) and 1987 (thin solid line) (acquired by Santa Fe Geothermal, Inc. and retrieved from unpublished records at the Bureau of Land Management in Bishop, CA, 2004) and the temperature gradient (thick solid line) in 2005. The shaded region shows the section of the 2005 profile presented in Fig. 3c and the horizontal arrows bracket the segment in the June 2005 profile that was used for the groundwater velocity calculations presented in Table 2. b. The temperature difference between measurements made in July 2006 and June 2005.

46-28 (Fig. 7b) and between 2007 and 2006 in well 35-28 (Fig. 8b). These observations suggest probable cooling of the active hydrothermal flow system.

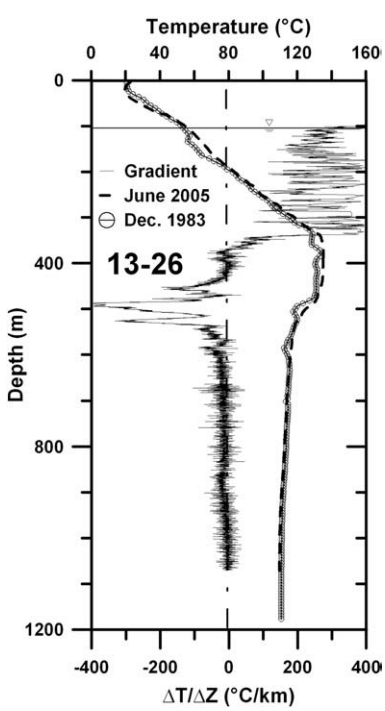

Fig. 6. Temperature profiles in borehole 13-26 from June 2005 (dashed line) and 1984 (thin solid line) (data provided by Gene Suemnicht, EGS Inc.; written communication, March 2010), and the temperature gradient (thick solid line) in 2005. The horizontal arrows bracket the segment in the 2005 profile presented in Fig. 3. The thin solid horizontal line shows the depth of the water table.

With the limitations of comparing datasets obtained using different methods, each with different accuracies and precisions, the new temperature data show that significant heating occurred in the

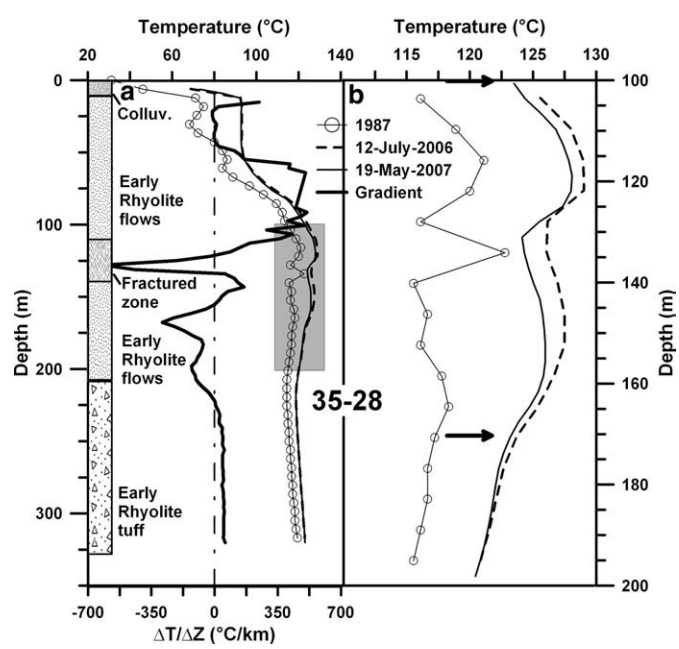

Fig. 8. a. Lithology and temperature profiles in borehole 35-28 measured with a portable device (see text for details) in May 2007 (solid line), July 2006 (dash line), and 1987 (solid line and empty circles) (acquired by Santa Fe Geothermal, Inc. and retrieved from unpublished records at the Bureau of Land Management in Bishop, CA, 2004), and the temperature gradient (thick solid line) in May 2007. The shaded region shows the area presented in part b. The horizontal arrows in part b bracket the segment in the May 2007 profile that was used for the groundwater velocity calculations presented in Fig. 3 and Table 2.

three Fumarole Valley boreholes (35-28, 46-28, and 68-28) compared with data collected in the 1980s, with slightly greater offsets in the shallow sections of the logs (Figs. 4, 5 and 7). In contrast, the new temperature profiles in 13-21 (Fig. 4) and 13-26 (Fig. 6)) vary only slightly from the temperature profiles acquired in the 1980s. In 13-21, temperatures below a depth of 600 m measured in June 2005 were slightly cooler than temperatures in October 1982 (Fig. 4), and in 13-26, temperatures measured in June 2005 between 300 m and 500 m were slightly warmer than in December 1983.

When plotted as a function of altitude, several significant patterns emerge in the temperature profiles on the RD (Fig. 2). The temperatures in LVEW are cooler than temperatures in all the other wells in the RD, supporting the idea that the profile in LVEW is significantly affected by precipitation recharge (Farrar et al., 2003). In the three Fumarole Valley boreholes, the shallow segments of the temperature profiles characterized by high temperatures are at about the same elevation as the upper high-temperature part of the profile in well M-1 (Fig. 2), the unit from which geothermal energy is produced at Casa Diablo (Fig. 1). The thickness of the high-temperature units in the Fumarole Valley boreholes is similar to the thickness of the upper high-temperature unit in M-1.

The temperature measured in 13-21 in July 2006 was obtained 10 months after the well was perforated at a depth of 655 m. The temperatures in July 2006 indicate that since June 2005, large portions of the profile have cooled by 0.15 to 0.2 °C with the most significant changes occurring between 600 m and 750 m (Fig. 4). In borehole 46-28, the temperature differences between June 2005 and July 2006 indicate that active flow in the surrounding rocks is confined to a depth range between ~160 m and 225 m where groundwater has cooled during this period by a maximum of 0.21 °C (Fig. 7).

5. Discussion

The newly acquired high-precision temperature data provide constraints on the thermal regime of the RD and Long Valley Caldera and allow the testing of several hypotheses with implications for geothermal energy resources and the occurrence of magma in the shallow crustal levels.

5.1. Evidence for hydrothermal flow through the resurgent dome

The LVC hydrothermal system is recharged primarily from snowmelt in the western moat of the caldera (Fig. 1a) that is heated by cooling magma beneath the Inyo Craters and Domes where temperatures in nearby wells attain values of ~220 °C (Sorey et al., 1991). The thermal groundwater then flows eastward to discharge along Hot Creek and around Lake Crowley (Fig. 1a). Groundwater temperature decreases eastward to approximately 170 °C at Casa Diablo and to about 50 °C in the springs near Lake Crowley (Sorey et al., 1991). The high-temperature zones encountered in the Fumarole Valley boreholes are approximately at the same elevation as the high-temperature zone in M-1, suggesting hydrothermal flow through the southern part of the RD. The inference is consistent with the occurrence of steam discharge in response to geothermal production in Casa Diablo (Sorey and Farrar, 1998), vegetation kill (Bergfeld et al., 2006), and the occurrence of high concentrations of isobutane. Isobutane is the binary fluid used in the geothermal power plant and occasionally leaks from heat-exchangers into the groundwater (Evans et al., 2004). The higher concentrations of isobutane in Fumarole Valley compared with springs just to the south of the RD and the higher temperature in borehole 35-28 in the northern part of the Fumarole Valley compared with borehole 68-28 in the southern part of Fumarole Valley suggests eastward hydrothermal flow directly from Casa Diablo rather than northward flow from the previously inferred hydrothermal flow path south of the RD. Temperature along the flow path decreases from approximately 170 °C at M-1 in Casa Diablo to 128 °C in boreholes 35-28 and 46-28 in Fumarole Valley.

If flow is continuous between Casa Diablo and Fumarole Valley and perhaps even Little Hot Creek, at the northeastern edge of the RD where springs discharge at 68–82 °C (Fig. 1), it appears that the NNW striking faults of the Medial Graben that traverse the RD (Fig. 1) do not form barriers for hydrothermal flow. This continuity also suggests that uplift of the RD was not sufficient enough to block the flow path, which was presumably initially established ~30,000 years ago (Blackwell, 1985; Sorey et al., 1991).

The high-temperature units that include the temperature maxima in boreholes 13-21 and 13-26 are deeper and thicker than the comparable hydrothermal flow units in the Fumarole Valley boreholes. The shape of the high-temperature zones in these wells also differs from the shape in the Fumarole Valley wells (Fig. 3); in well 13-21 the profile between a depth of 650 m and 760 m is almost linear with a negative temperature gradient of 20 °C/km (Fig. 3a), and in well 13-26 there is a 135 °C isotherm between a depth of 350 m and 430 m (Fig. 3b). These shapes are more consistent with conductive cooling than with active flow (Hurwitz et al., 2002). In addition, very small temperature changes occurred in these wells since the 1980s. In contrast, the high-temperature zones in the Fumarole Valley wells are characterized by more curvature (Fig. 3c,d). Boreholes 13-21 and 13-26 are more likely related to the deeper high temperature unit in M-1 (Fig. 2) with temperatures near 150 °C within the welded Bishop Tuff unit, although at a distinctly lower elevation. If indeed the high-temperature units in 13-21, 13-26, and M-1 are related, they might represent an inactive flow system that was modified by differential vertical movements of the RD.

5.2. Hydrothermal flow rates in the resurgent dome

The differential equation for conductive and groundwater advective heat transport through a discrete unit or a fracture derived by Stallman (1963) is given by:

$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2} = \frac{c_{pw}\rho_w}{k_{ws}} \times \left(\frac{\partial(v_x T)}{\partial X} + \frac{\partial(v_Y T)}{\partial Y} + \frac{\partial(v_Z T)}{\partial Z}\right) + \frac{c_{pws}\rho_{ws}}{k_{ws}}\frac{\partial T}{\partial t} \quad (1)$$

where T is temperature; X, Y, and Z (depth) are rectangular coordinates, c_{pw} and ρ_w are the specific heat and density of water, c_{pws} and ρ_{ws} are the specific heat and density of water saturated rock, k_{ws} is the thermal conductivity of water saturated rock, and v is specific discharge. Several authors (Stallman, 1963; Bredehoeft and Papadopulos, 1965; Lu and Ge, 1996; Ge, 1998; Reiter, 2001) derived analytical solutions for this equation with various simplifying assumptions for specific cases. To derive specific discharge from the measured temperature profiles, we assume steady state, uniform groundwater flow confined to the horizontal direction, $\partial^2T/\partial Z^2 >> \partial^2T/\partial X^2$ and $\partial^2T/\partial Y^2$, and that the values of material properties are constant ($\rho_w = 1000$ kg/m^3; $c_w = 4200$ J/kg/°C; $k_{ws} = 2$ W/m/°C).

With these assumptions, Eq. 1 is reduced to:

$$\frac{d^2T}{dZ^2} = \frac{d}{dZ}\left(\frac{dT}{dZ}\right) = \frac{c_{pw}\rho_w}{k_{ws}} v_x \frac{\partial T}{\partial X} \quad (2)$$

Assuming that $\partial T/\partial X$ is constant, Eq. 2 can be integrated to yield the following expression for the temperature distribution with depth (Reiter, 2001):

$$T = a + bZ + cZ^2 \quad (3)$$

where a and b are constants and

$$c = \frac{1}{2}\frac{c_{pw}\rho_w}{k_{ws}} v_x \frac{\partial T}{\partial X} \quad (4)$$

The horizontal groundwater velocity (v_x) can be approximated by curve-fitting a quadratic equation in the form of Eq. 3 to the measured temperature data.

Following the approach of Reiter (2001; 2005), we match curves in the form of Eq. 3 to segments of the temperature profiles in the three boreholes in Fumarole Valley where discrete zones of elevated temperatures at relatively shallow depths are likely associated with the active hydrothermal system from which energy is generated at the power plant in Casa Diablo (Fig. 1). The value of $\partial T/\partial X$ for each well is based on the difference between the maximum temperature at well M-1 in Casa Diablo and that of the well and the distance of the well from M-1.

Calculated results and the statistics associated with the curve-fitting processes are presented in Table 2 and Fig. 3. These results suggest that groundwater velocities in the hydrothermal flow unit range between 1.9 and 2.8 m/yr. Whereas the calculated fits to the measured profiles in 68-28 (Fig. 3c) and 46-28 (Fig. 3d) were very good (high values of r^2 and F_{stat}), the calculated curve for the temperature profile in 35-28 (Fig. 3d) is a rather poor fit (Table 2). This poor fit results from the much coarser sampling (10 ft. rather than 1 ft. on the other wells) and a major temperature inversion within the high-temperature zone (Fig. 3).

Assuming an average thickness of 70 m and a width of 1,500 m (in an approximately N–S direction) for the hydrothermal flow unit under the RD, the calculated groundwater velocities (1.9–2.8 m/yr), and fluid enthalpies of 356 kJ/kg for 68-28 (86 °C) and 535 kJ/kg for 46-28 and 35-28 (127 °C) translates to a power of 3–4 MW. This is an order of magnitude less than the current power generation at the power plant in Casa Diablo (~40 MW). This calculated value should be considered as maximum, because the temperature profiles can represent low flow rates in a zone that was dominated in the past by lateral advective heat transport and currently by slow conductive cooling following permeability reduction, rather than steady state hydrothermal flow (Hurwitz et al., 2002). Time-dependent temperature measurements are required in order to evaluate the steady state assumptions and the resulting calculated flow rates. Indeed, sporadic temperature measurements in CH-10b southeast of the RD (Fig. 1a) indicate that between 1991 and 2004, temperatures at a depth of 40 m in the well, where temperatures are at maxima, increased from 93 °C to 101 °C (Farrar et al., 2007), followed by cooling since 2007 (Chris Farrar, U.S. Geological Survey, unpublished data). These changes suggest active hydrothermal flow and temperature changes that reflect either long-term precipitation trends, changes in geothermal production rates at Casa Diablo, or a response to the large seismic swarm in the south moat of the caldera in 1997 (Prejean et al., 2002). If the apparent warming in the Fumarole Valley wells and 13-21 since the 1980s (Figs. 4–8) is real and not due to differences in acquisition methods, they could have resulted from the same processes. The U.S. Geological Survey has established a program to measure temperatures in several wells on the RD and its surroundings continuously that will enable a quantitative determination of flow rates and heat transport through the southern part of the RD (Chris Farrar, US Geological Survey, unpublished information).

Table 2
Results of curve-matching to temperature profiles using Eqs. (3) and (4).

Well	Depth (m)	a	b	c	r^2	F_{stat}	$\partial T/\partial X$ (°C/m)	Max T (°C)	v_x (m/yr)
68-28	58–125	69.23	0.50	-0.0035	0.99	20471	0.038	87	2.8
46-28	140–225	74.93	0.57	-0.0015	0.98	8294	0.022	127	2.1
35-28	100–170	103.92	0.35	-0.0013	0.27	4	0.021	128	1.9

5.3. Thermal constraints on the occurrence of magma underneath the RD

It is debatable whether magma resides at, or was recently intruded to shallow crustal levels beneath the RD. The ~80 cm of RD uplift episodes between 1980 and 1997 were attributed to magma intrusion into a crustal reservoir at depths of 6 to 10 km (Battaglia et al., 1999, Langbein, 2003; Newman et al., 2006). In contrast, a range of geological evidence has led Hildreth (2004) to argue against magma intrusion into the shallow crust. Extrapolation of the measured conductive gradients in the upper 2 km of wells LVEW and CP to a depth of 6 km yields temperatures of 170 °C and 300 °C, respectively, which are inconsistent with the presence of shallow magma (Sorey et al., 1991; Farrar et al., 2003). Extrapolation of the conductive segment of the temperature profile in CP-1 on the eastern margin of the RD to a depth of 6 km is high enough (300–400 °C) to suggest the possible presence of ductile conditions at such depths. This in turn is consistent with an apparent bottom to the seismogenic zone beneath the resurgent dome of 6–7 km (Hill, 1992). It should be noted that experimental studies have shown that under realistic geological strain rates, the temperatures at which different rock types undergo transition from brittle to ductile rheology can range from 230 °C for wet granite at 50 MPa to ~690 °C for dry orthopyroxene at 10 MPa. Further, at periods of elevated strain rates such as during episodes of RD uplift, the temperature at which crystalline ductile flow occurs increases (Simpson, 2001).

The new temperature profiles in the three Fumarole Valley wells attain higher temperatures than those previously reported for the RD (Fig. 2). Nevertheless, these higher temperatures are more likely associated with horizontal hydrothermal flow originating in the west moat of LVC. The Fumarole Valley wells also confirm that there is a major thermal difference between the warm southern part of the RD and the cold northern part (Farrar et al., 2003). These thermal differences are consistent with the occurrence of abundant seismicity in the southern part of the RD compared with the lack of seismicity under the northern part of the RD (Prejean et al., 2002). These sharp boundaries in thermal structure and seismicity are not consistent with the existence of a magma reservoir beneath the RD.

6. Conclusions

- The new high-precision temperature profiles in five boreholes on the resurgent dome of Long Valley Caldera display substantial non-linearity within each profile and variability between the different profiles. All profiles display significant temperature reversals with depth within the volcanic and sedimentary fill and temperature gradients <50 °C/km at their bottom. The maximum temperature in the individual boreholes ranges from 124.7 °C (13-21) to 129.5 °C (68-28). Bottom hole temperatures range from 99.4 °C (13-21) to 129.5 °C (68-28). None of the wells have a positive linear temperature gradient at the bottom.
- The temperatures in all five wells are higher than the temperatures in the deep (>3 km) Long Valley exploratory well (LVEW), suggesting that the temperature profile in LVEW is significantly affected by recharge to significant depths.
- Temperature reversals in the Fumarole Valley (FV) wells are at the approximate same elevation as temperature reversals in borehole M-1 in the Casa Diablo geothermal well field, indicating lateral or sub-lateral hydrothermal flow through the resurgent dome.
- Small differences in temperature between measurements in consecutive years in 13-21, 46-28, and 35-28 suggest slow cooling of the shallow hydrothermal flow system.

- By matching theoretical curves of steady state heat transport to segments of the measured temperature profiles, we calculate groundwater velocities in the hydrothermal flow unit under the RD that range between 1.9 and 2.8 m/yr. Based on these velocities and the temperatures in Fumarole Valley boreholes, we estimate the maximum power flowing through the RD to range between 3 and 4 MW, which is an order of magnitude less than rates of current production at the nearby geothermal power plant at Casa Diablo (~40 MW).
- The relatively low temperatures and large isothermal segments at the bottom of the temperature profiles are inconsistent with the occurrence of a magma reservoir at shallow crustal levels, in agreement with several previous studies (Sorey et al., 1991; Farrar et al., 2003; Hildreth, 2004).
- The new measurements serve as baselines for monitoring future temperature transients that may be associated with changes in energy production at the geothermal plant, magma intrusions, or seismic activity.

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