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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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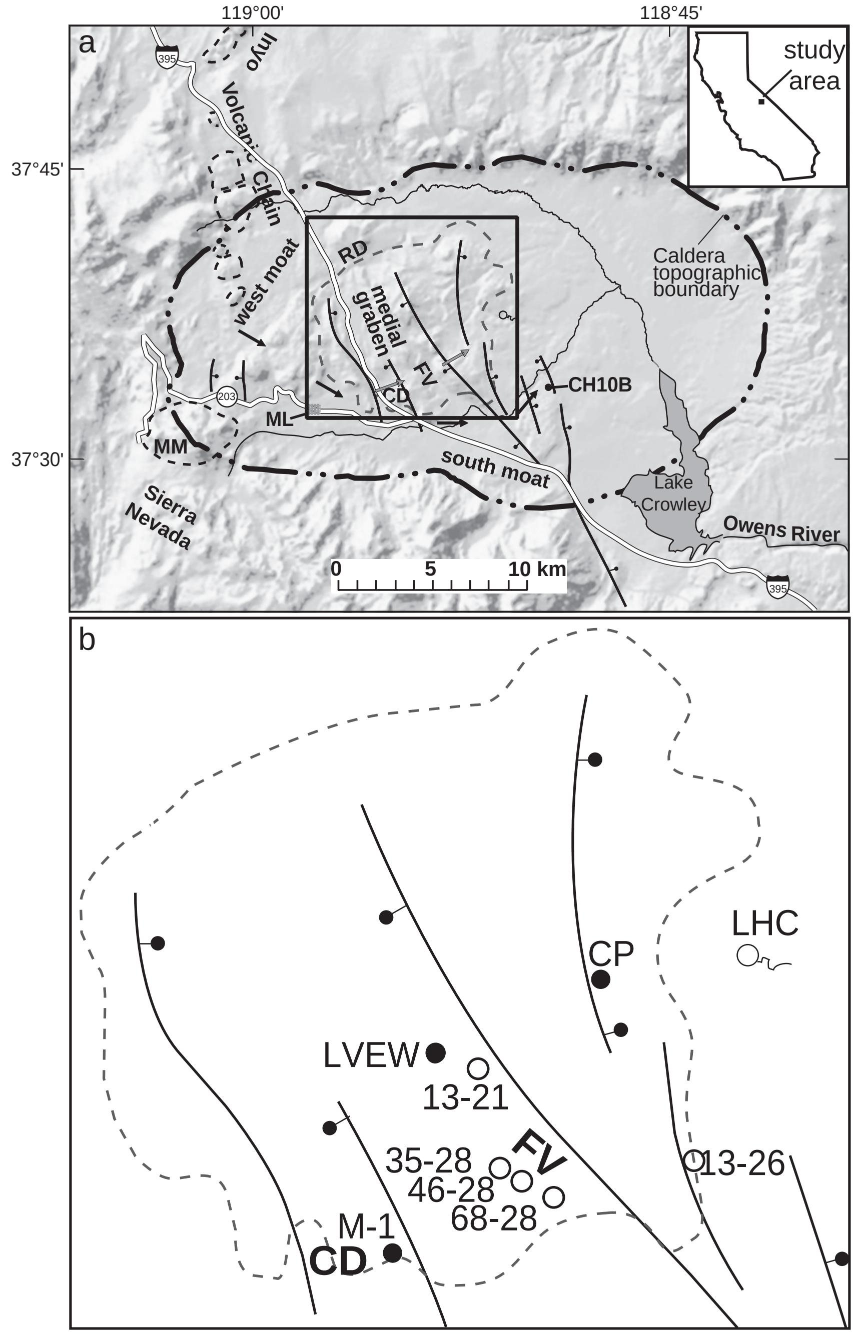

Fig. 1. a. Shaded relief map of Long Valley Caldera (LVC) and surrounding region showing topographic boundary of the caldera (dot-dash line), the resurgent dome (RD), Fumarole Valley (FV), Mammoth Mountain (MM), the town of Mammoth Lakes (ML), Casa Diablo (CD) is the location of the geothermal power 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