PROCEEDINGS, Thirty-Second Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 2007
SGP-TR-183

THE SHALLOW HYDROTHERMAL SYSTEM OF LONG VALLEY CALDERA, CALIFORNIA

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ABSTRACT

Long Valley caldera produces 40 Mw of geothermal power from a shallow (<200m) reservoir in a ~165 acre area around Casa Diablo Hot Springs. Deep drilling during the 1980s established that the shallow geothermal system is sustained by outflow from a larger deep hydrothermal source in the western caldera moat. Recent exploration drilling has identified a hydrothermal outflow zone near Shady Rest that represents input to the shallow geothermal reservoir in the southern caldera moat confined predominantly to Early Rhyolite reservoir rocks at Casa Diablo. Three exploration wells in the southern moat penetrate Sierran metamorphic rocks that slid into the collapsing caldera from the southern caldera rim on a cushion of gassy, frothing Bishop Tuff late in the caldera's collapse sequence. Fluid inclusion data from core samples indicate that the Bishop Tuff within the southern caldera was pervasively fractured by hydraulic overpressures as a post-collapse hydrothermal system developed and the Tuff began to weld within the caldera beneath the impermeable confining landslide block. The landslide effectively directs and confines the current active hydrothermal outflow into shallow Early Rhyolite units that overlie the landslide block in the southern caldera.

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INTRODUCTION

Long Valley caldera in eastern California has been explored for geothermal resources since the 1960s. Early exploration wells (<300m) were located around Casa Diablo near the most prominent hot springs and fumaroles on the west flank of the Resurgent Dome (Figure 1). Early deep wells explored the

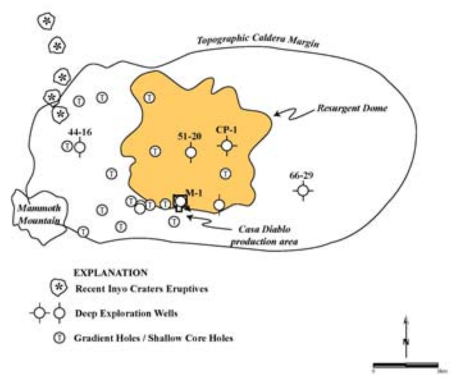

Figure. 1. Shallow and deep wells drilled within Long Valley caldera.

southeastern caldera moat (Rep 66-29) and evaluated lease offerings in the northern Resurgent Dome (Clay Pit-1) and at Casa Diablo (Mammoth-1). Data from these wells revealed that the principal geothermal reservoir in Long Valley was not located directly beneath the Casa Diablo Hot Springs and did not appear to be related to the Resurgent Dome. Instead, the hydrothermal system appeared to be more complex and the shallow production at Casa Diablo appeared to be supplied by upflow and outflow from a distant geothermal source.

Geothermal development within Long Valley caldera has thus far been limited to ~165 ac around Casa Diablo where shallow (<200m) production wells have been drilled to produce a moderate temperature 170ºC shallow aquifer in permeable Early Rhyolite eruptive units on the southwestern edge of the Resurgent Dome (Figure 1). The current development, managed by Mammoth Pacific LP, occurred in stages, eventually reaching an installed capacity of 40 Mwe (gross). Production at this rate has continued since 1991 without drilling make-up wells. The deeper hydrothermal system in Long Valley appears to sustain current production levels by supplying additional shallow hydrothermal outflow to Casa Diablo. Mammoth Pacific LP has continued to evaluate the geothermal potential of the southern caldera moat, drilling intermediate-depth exploration wells 66-31 and 38-32 in 1992, BC 12-31 in 2002 and production wells 57-25 and 66-25 in 2005, adjacent to the Shady Rest core hole drilled in 1984 by the USGS and the DOE (Figure 1). This paper summarizes the results of those wells and revises the general hydrothermal model of Sorey and others (1991) for the southern part of the caldera.

GEOLOGY

Long Valley caldera was created by the eruption of an estimated 600 km^3 of Bishop Tuff 760,000 years ago (Bailey and others, 1976). A large portion of the Tuff filled the 17 X 32 km caldera depression and smaller but significant post-caldera eruptions have continued to fill the caldera over the last 600,000 years. The most recent eruptions occurred along the Mono-Inyo volcanic chain (Figure 1) approximately 600 years ago, providing the most prominent surface evidence of an active magmatic system in Long Valley.

Hydrothermal circulation in Long Valley has varied through time (Bailey and others, 1976, Sorey and others, 1978; 1991). Different mineral assemblages in and around the Resurgent Dome and differing age dates indicate that mineralization occurred in two separate phases (Sorey and others, 1991). The caldera supported an intense hydrothermal system from 300,000 to 130,000 years ago producing widespread hydrothermal alteration in and around the Resurgent Dome. The current hydrothermal system has probably been active for only the last 40,000 years, but prominent surface manifestations occur in many of the older system's established outflow zones at comparatively low elevations in the south central portion of the caldera. As much as 80% of the current hydrothermal outflow occurs at Hot Creek on the southeastern edge of the Resurgent Dome and geochemical estimates of source reservoir temperatures range from 200 ^oC – 280^oC (Sorey and others, 1978; 1991; Mariner and Wiley, 1976).

Hydrothermal manifestations are notably absent in the western caldera moat (Bailey and others, 1976); however, detailed mapping (Suemnicht and Varga, 1988) and remote sensing studies of the western caldera (Martini, 2002) identify many high-temperature alteration mineral assemblages <100,000 years old that are related to vigorous hydrothermal outflow along penetrative faults in the western caldera. The alteration mineralogy shows that significant surface manifestations occurred at higher elevations in the western caldera in the early phases of the current hydrothermal system and the current pattern of outflow to the southeast toward Casa Diablo may have resulted from active fracturing and faulting opening older hydrothermal flow zones, allowing outflow along permeable zones at lower elevations.

DRILLING AND PRODUCTION DATA

Early exploration drilling in Long Valley focused on the central part of Long Valley caldera. Wells in the 60s evaluated shallow production around Casa Diablo's fumaroles and hot springs. The first deep well (66-29) was drilled in 1976 to evaluate the resource potential in the southeast moat (Figure 1). Numerous shallow gradient holes evaluated the heat flow associated with the Resurgent Dome in the 1970s and geothermal lease sale opportunities in the late 70s and early 80s prompted shallow and intermediate drilling to assess lease blocks within the Resurgent Dome.

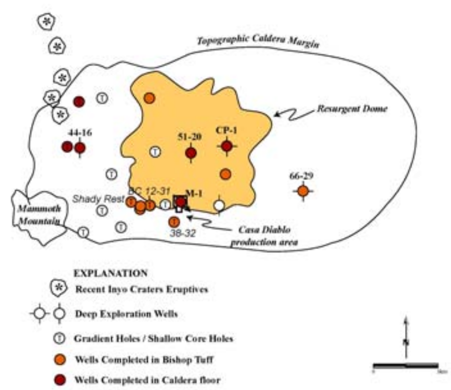

Figure. 2. Long Valley wells penetrating the Bishop Tuff (orange) or the caldera floor (red).

Clay Pit-1 and Mammoth-1 drilled in 1979 were the first deep wells drilled in the Resurgent Dome of Long Valley and the first deep tests to penetrate the entire section of the caldera fill (Figure 2). Mammoth-1 drilled through 390m of Early Rhyolite, 863m of Bishop Tuff and 230m of metasedimentary rocks that correlate with the Convict Lake roof pendant to the south, bottoming at 1605m. Mammoth-1 was also the first well within the caldera to encounter a block of chaotically mixed metapelite and granite at 466m in the upper section of Bishop Tuff that was interpreted as a landslide block based on cuttings alone (Suemnicht, 1987).

Drilling to evaluate federal lease offerings during the 1980s and scientific drilling to evaluate eruptive units expanded the understanding of the western part of the caldera. Unocal's deep well IDFU 44-16 penetrated the caldera fill, Tertiary volcanic rocks and metamorphic rocks to a depth of 2000m near the Inyo Craters (Figure 2). The well encountered the highest temperatures yet measured in Long Valley but proved unproductive because of a limited thickness of reservoir rocks and the incursion of cold water beneath the production zone (Suemnicht, 1987). Later scientific drilling by Sandia National Labs approximately 1 km west of 44-16 (Figure 2) established that a kilometer of vertical offset on the caldera's western ring fracture system occurs within a kilometer distance between the two wells identifying the location of the western structural margin of the caldera (Eichelberger and others, 1990). Additional scientific drilling in Long Valley included a core hole at Shady Rest (Figure 2) (Wollenberg and others, 1989), and an ultra-deep (3 km) well intended to test the presence of magma near the center of the Resurgent Dome (Finger and others, 1995).

The results of deep drilling on the Resurgent Dome indicate that present-day thermal conditions are controlled in places by vertical flow of relatively cold water in steeply dipping faults that formerly provided channels for high-temperature fluid upflow (Sorey and others, 2000). In the central caldera, current temperatures and gradients are relatively low and show little evidence of possible magmatic temperatures at depths of 5-7 km postulated on the basis of recent deformation, seismic interpretations and shear-wave attenuation of teleseismic waves. Drilling results establish that magmatic activity beneath the central part of the caldera has waned over the past ~100,000 years while similar activity in the western caldera has increased.

RECENT DRILLING

Mammoth Pacific LP has continued to assess the productive potential of the southern and western part of the caldera. A similar section of metapelite/granite was encountered at the top of the Bishop Tuff in both the 38-32 corehole drilled to 353m less than a kilometer south of Casa Diablo (Bailey, pers. com.) and in corehole BC 12-31 drilled in 1992 to 600m approximately 2 km west of the production facilities in 2002 (Figure 3). Successful wells 57-25 and 66-25 drilled in 2005 near Shady Rest produce fluid from the intracaldera Early Rhyolite and the upper part of the Bishop Tuff but, like the earlier Shady Rest well, neither well encountered metamorphic rocks at the top of the Tuff.

Based on drilling results, the intracaldera landside block is relatively coherent and covers approximately 3 km^2 of the southern moat between Mammoth-1 on the north, and BC 12-31 on the west (Figure 4). The landslide block is absent in surrounding wells that penetrate into the Bishop Tuff on the Resurgent Dome and near Shady Rest, approximately 1 km northwest of BC 12-31. The landslide lies at or near the top of the Bishop Tuff. Lithologic interpretations of cuttings from Mammoth-1 indicate that the well penetrated an upper ash-rich section of highly altered Bishop Tuff before passing through a 43m thick section of landslide breccia and then back into highly altered ash-rich Bishop Tuff.

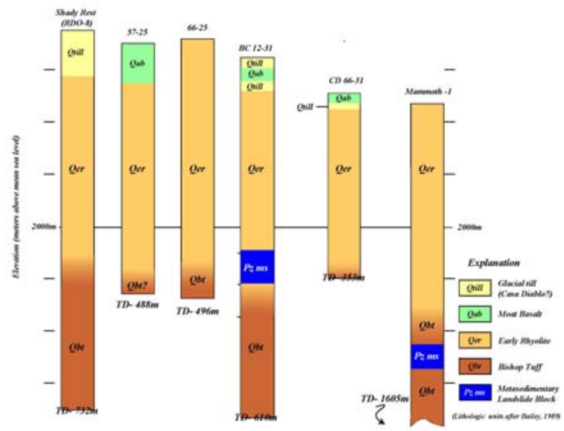

Figure. 3. Lithology of southern caldera wells.

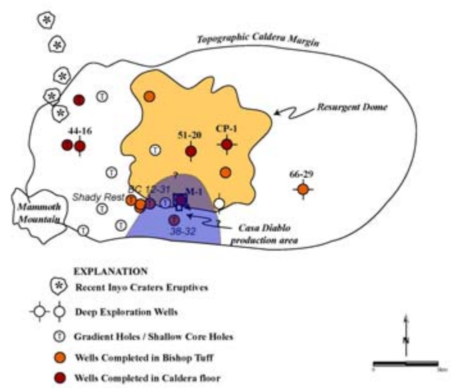

Figure.4. Distribution of the landslide block of Paleozoic metasedimentary rocks from the southern rim of Long Valley caldera.

Core from 38-32 and BC 12-31 indicate the landslide block is a highly indurated relatively undisturbed meta-breccia or conglomerate with a dense grey matrix of rock fragments and larger rounded or subrounded clasts of granite, hornfels, metapelite and metaquartzite typical of lithologies that crop out in the southern topographic wall of the caldera (Figure 3). The landslide block does not contain pumice or phenocrysts from the Bishop Tuff and the southern wall lithologies and indurated metamorphic matrix preclude the possibility that the block might be glacial till. Based on the excellent core samples from 38-32 and BC 12-31, the Bishop Tuff below the landslide block is lithic rich with an intensely altered glassy matrix permeated with gas void spaces. The landslide block lies entirely at the top of the Bishop Tuff in both 38-32 and BC 12-31 and the underlying remarkably undisturbed soft ash probably represents the upper ash cloud at the top of the Bishop Tuff that acted as a gas cushion beneath the landslide block (Figure 5). Intense clay alteration has obscured many of the primary features of the ash but much of the porous tuff matrix appears to be a gassy froth that retains doubly terminated quartz crystals diagnostic of the Bishop Tuff.

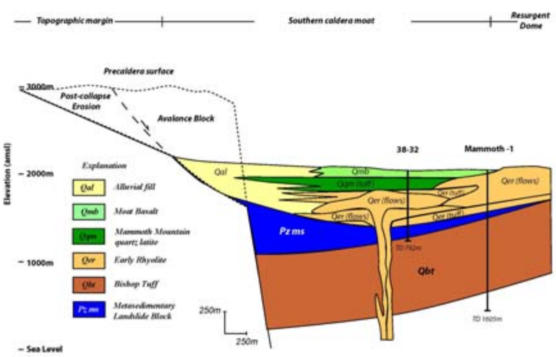

Figure. 5. Structural cross-section of the southern caldera showing the landslide block encountered in exploration corehole 38-32 and the Mammoth-1 deep test well at Casa Diablo.

FLUID INCLUSIONS

Fluid inclusions within pervasively fractured and densely veined Bishop Tuff core samples from BC-12-31 indicate that the vein formation temperatures exceed the current shallow hydrothermal system temperatures (Figure 6).

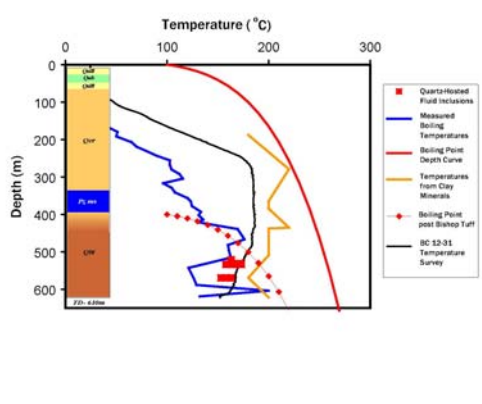

Figure. 6. Fluid inclusion temperatures and measured temperatures in BC 12-31.

Fracturing within the intracaldera Bishop Tuff certainly occurred after welding because brittle failure would not occur if the Tuff were still in an unwelded plastic state. Calculated fluid inclusion temperatures also indicate that temperatures within the evolving hydrothermal system exceeded the boiling point-depth curve at least at relatively shallow depths. The BC 12-31 corehole penetrated 3m of thinly bedded very fine-grained lacustrine clays immediately above the landslide block indicating that a caldera lake probably formed early after caldera collapse. Fracturing within the Tuff probably occurred before it was overlain by thick Early Rhyolite units, and therefore, at relatively low confining pressures. When temperatures exceeded the boiling point, hydrostatic pressures exceeded the strength of brittle cooling Tuff, resulting in pervasive fracturing

INTERPRETATION

Landslide blocks are common features that have been mapped in several eroded collapsed calderas (Lipman, 2003). In Long Valley, a block of metasedimentary rock from the southern caldera rim slid into the southern Long Valley moat on a gassy cushion of Bishop ash late in the eruption and collapse sequence (Figure 5). The temperature distribution within the caldera indicates that the present-day outflow of the deeper hydrothermal system occurs along penetrative NW-SE faults related to the Resurgent Dome and E-W ring fracture faults that control the southern structural margin of the caldera (Figure 7). Upflow at these fracture intersections occurs at comparatively low elevations at the base of the Rhyolite Plateau west of Shady Rest.

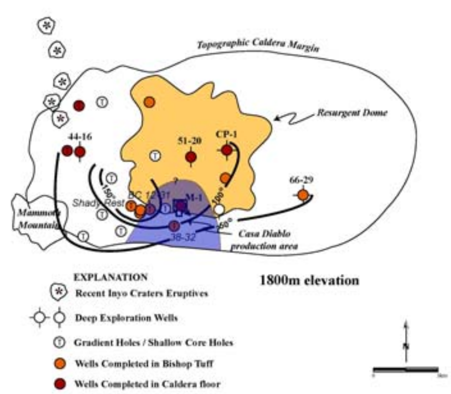

Figure. 7. Temperatures at 1800m above mean sea level in the southern moat of Long Valley caldera.

Within the corresponding shallow hydrothermal system, the landslide block controls the flow of hydrothermal fluids southeast around the Resurgent Dome. Intense alteration of the over/underlying ash froth, the clay-rich lacustrine sediments and the impermeable nature of the landslide block isolates the shallow hydrothermal system from deeper lower temperature flow in the underlying Bishop Tuff and maintains moderate-temperature outflow in shallower Early Rhyolite or lacustrine units east of Shady Rest.

Early proposals used the available temperature data to suggest that hotter outflow was separated from colder recharge water because of density (Blackwell, 1985) and while density separation might prevail for a time, it would be a transient condition. Shallow hydrothermal circulation could only be sustained where hot water is physically separated from the underlying permeable Bishop Tuff. All of the drilling results within the caldera show that the strong head of cold recharging waters from the caldera rim has a significant effect on the hydrothermal system. Sharp temperature reversals of nearly 100 ^{o}C are commonly found on the structural caldera margin where high temperature upflow is affected by cold recharge penetrating into the deeper fractured Bishop Tuff (Suemnicht, 1987).

The physical separation between the Bishop Tuff and the overlying impermeable landslide block in the southern part of the caldera allows the shallow moderate temperature hydrothermal system to survive. Once thermal outflow has made it to the intracaldera fill east of Shady Rest, it is laterally separated from the pervasive influence of cold recharge waters around the rim of the caldera. The impermeable landslide block, lacustrine clays or intensely altered clay-rich upper part of the Bishop Tuff separate differing parts of the shallow hydrothermal system in the southern caldera allowing sustained shallow production at Casa Diablo by isolating warm shallow outflow from deep cold recharge that might quench the system.

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