Long Valley Caldera

Field Trip
May 27, 2011

California Geothermal Energy Collaborative
Long Valley, California

Mammoth Pacific binary generating plants at Casa Diablo in Long Valley Caldera. View is from the top of a peak within the caldera's resurgent dome looking southwest toward the southern topographic margin of the caldera. The caldera moat in the background is the focus of recent seismicity during the last two decades of caldera unrest. Paleozoic metamorphic rocks in the Sierra Nevada range to the south are the source area for a landslide block that slid into the caldera on a gassy cushion of ash late in the caldera's collapse. Photo by R. Sullivan

LONG VALLEY CALDERA
GEOTHERMAL AND MAGMATIC SYSTEMS

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INTRODUCTION

Long Valley Caldera in eastern California has been explored for geothermal resources since the 1960s. Early shallow exploration wells (<300m) were located around Casa Diablo near the most prominent hot springs and fumaroles on the southwest flank of the Resurgent Dome (Figure 1). Later deep (±2000m) wells explored the southeastern caldera moat and evaluated lease offerings in and around the caldera's Resurgent Dome. Data from these wells revealed that the principal geothermal reservoir in Long Valley is not located directly beneath the Casa Diablo Hot Springs and is not currently related to the Resurgent Dome. Instead, the hydrothermal system appeared to be more complex with shallow production at Casa Diablo supplied by upflow and outflow from a more extensive deeper geothermal source beneath the western caldera moat.

Geothermal development at Casa Diablo occurred in stages under various operating companies. Mammoth Pacific LP currently owns the project, a subsidiary of Ormat Nevada Inc. generating 40 Mw (gross) from three power plants utilizing 6 production wells and 5 injection wells. Until 2005, production of ~750 L/sec (~12,000 gal/min) of moderate temperature (170ºC) fluids for the geothermal plants was limited to ~0.7 km^2 (~165 ac) around Casa Diablo from shallow wells (<200m) completed in permeable Early Rhyolite eruptive units on the southwestern edge of the Resurgent Dome. MPLP drilled deeper (~450m) production wells in 2005 in the southwest caldera moat around Shady Rest in a development area that Ormat refers to as Basalt Canyon. The deeper west moat wells produce 185°C fluids from deep Early Rhyolite units and the upper part of the Bishop Tuff. In 2006, Approximately 225 L/sec (3,600 gal/min) of higher temperature brine from the Basalt Canyon wells began to be piped 2.9 km to sustain production at the Casa Diablo plants allowing several older shallow wells to be shut in. The deeper hydrothermal system in Long Valley sustains current production levels by supplying additional shallow hydrothermal outflow from Shady Rest to Casa Diablo.

GEOLOGIC SETTING

Long Valley Caldera is a 17 X 32 km (10 X 20 mi) depression created by the eruption of an estimated 600 km^3 of Bishop Tuff 760,000 years ago (Bailey and others, 1976). The caldera is the largest feature in the Mono-Long Valley volcanic field that includes Pleistocene-Recent eruptive centers of Mammoth Mountain and the Mono–Inyo volcanic chain. Volcanism associated with Long Valley began ~ 4 Ma ago with widespread

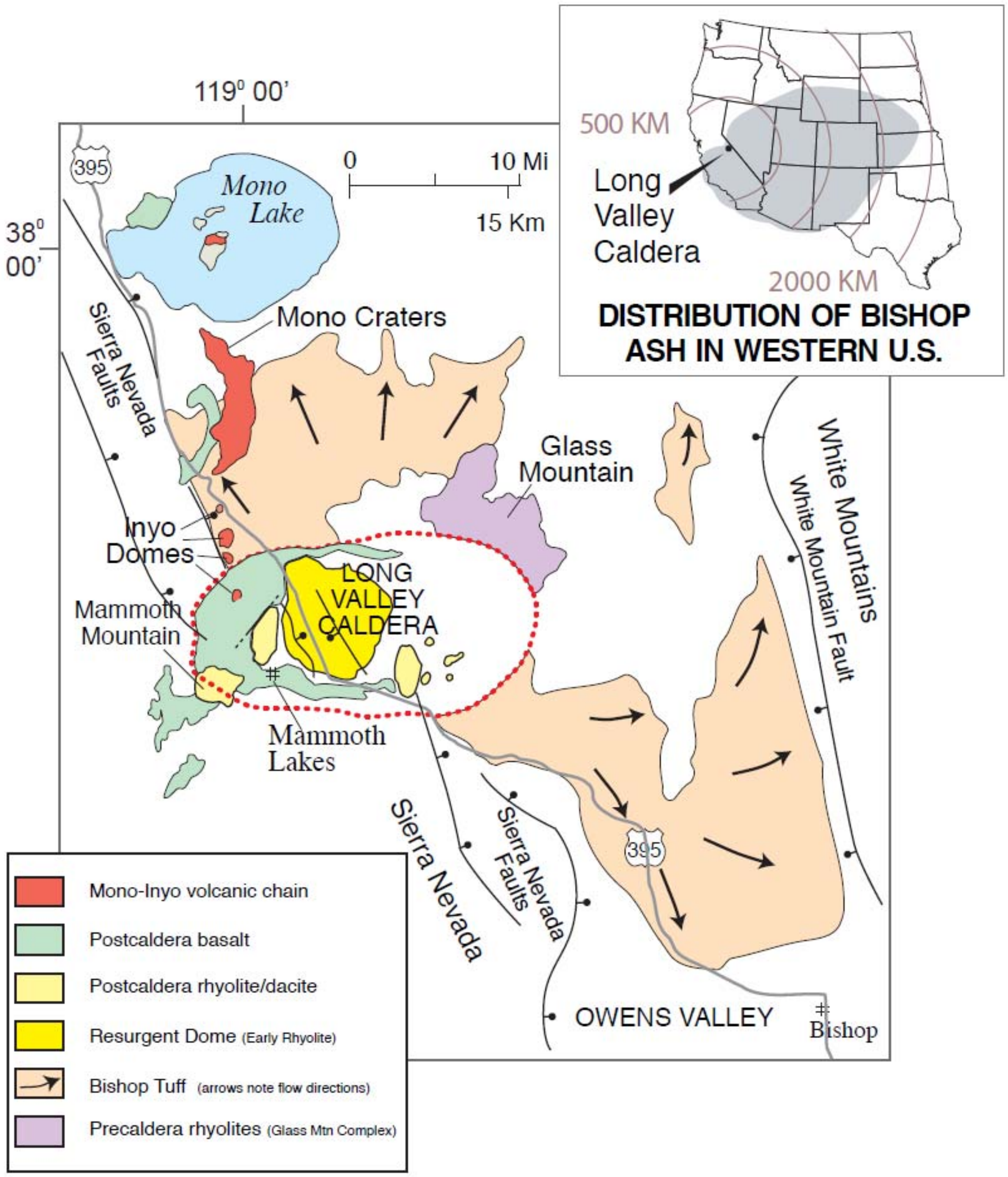

Figure 1. *Simplified geologic map of Long Valley Caldera and the Mono-Inyo volcanic chain showing the principal volcanic units (after Bailey and others, 1976), major faults and locations discussed in text (adapted from USGS).*

eruptions of intermediate and basaltic lavas accompanying the onset of large-scale transtensional faulting that formed the eastern front of the Sierra Nevada and the Owens Valley graben (Figure 1). Discontinuous erosional remnants of precaldera extrusive rocks are scattered over a 4000 km^2 area around the caldera suggesting an extensive mantle source region (Bailey and others, 1989). Rhyolitic eruptions began ~ 2 Ma ago from multiple vents of the Glass Mountain eruptive complex along the northeast rim of the present-day caldera (Metz and Mahood, 1985) (Figure 1). These more silicic eruptions suggest the initiation of magma accumulation and differentiation in the shallow crust (Bailey and others, 1989; Hildreth, 2004). The caldera-forming eruption partially evacuated the underlying magma chamber and the floor of the caldera subsided up to 2 km in segments separated along pre-existing inherited basement faults (Suemnicht and Varga, 1988). Approximately 350-400 km^3 of the Bishop Tuff filled the caldera depression. Post-collapse eruptions have continued to fill the caldera over the last 600,000 years (Bailey and others. 1976; Bailey 2004; Hildreth 2004). A series of rhyolite flows and tuffs (Early Rhyolite) mark the onset of resurgence in the west-central part of the caldera approximately 600,000 years ago (Figure 1). Coarsely porphyritic Moat Rhyolites erupted later around the Resurgent Dome beginning in the north approximately 500,000 years ago progressing to the south around 300,000 years ago and approximately 100,000 years ago in the west (Bailey and others, 1976; 1989). The western Moat Rhyolites erupted during a period of more voluminous basaltic and andesitic flows that began approximately 200,000 years ago in the western caldera extending beyond the caldera margins to the south and west. These more mafic eruptions include basalts in the southwestern caldera moat (Casa Diablo flow of Bailey and others, 1976), eruptive events such as the 100,000 year-old Devil's Postpile basaltic andesite and more recently, the 8,000 year-old Red Cones vents south of the caldera. A series of rhyodacitic eruptions also occurred in the western caldera moat 110,000 – 50,000 years ago (Mahood and others, 2010); the most prominent of these is Mammoth Mountain on the southwestern topographic rim of the caldera (Bailey 2004). Hildreth (2004) suggested that the mixed mafic-rhyodacitic volcanism represented a separate magmatic system outside the caldera's ring-fracture system.

The most recent eruptions in the area occurred along the Mono-Inyo volcanic chain extending from the western caldera moat northward to Mono Lake (Figure 2). Eruptions along the chain began approximately 40,000 years ago and have continued to historic times. Bursik & Sieh (1989) identified 20 small eruptions (erupted volumes <0.1 km3) within the chain over the past 5000 years occurring at intervals ranging from 250 to 700 years. The most recent dome-forming eruptive events began at the north end of the Mono Craters about 600 years ago and culminated with phreatic eruptions in the south at the Inyo Craters and the north flank of Mammoth Mountain (Bursik & Sieh 1989; Mahood and others, 2010). The magma source for these eruptions is an 8–10-km-long dike that trends north out of the caldera. In 1987, the DOE funded several core holes that penetrated the dike at Obsidian Dome north of the caldera and at the Inyo Craters in the caldera's west moat. Petrologic studies of the core indicate that the eruptions may have tapped magmas of three different compositions venting at several places along strike (Eichelberger, 2003). A shallow intrusion beneath Mono Lake approximately 200 years ago lifted lake-bottom sediments to form Pahoa Island erupting a small volume of andesitic lava from vents on the island's north side (Bursik & Sieh, 1989). The progression of eruptions over the past 2 Ma from Glass Mountain on the eastern caldera margin to Mammoth Mountain on the west and the Mono–Inyo volcanic chain to the north suggests that the magmatic system that erupted to form Long Valley Caldera has declined with time and has been supplanted by complex mixtures of magma erupting contemporaneously from the active Mammoth Mountain–Inyo Domes magmatic system at times triggered by the intrusion of more mafic magma into the shallow crust (Hildreth, 2004; Mahood and others, 2010).

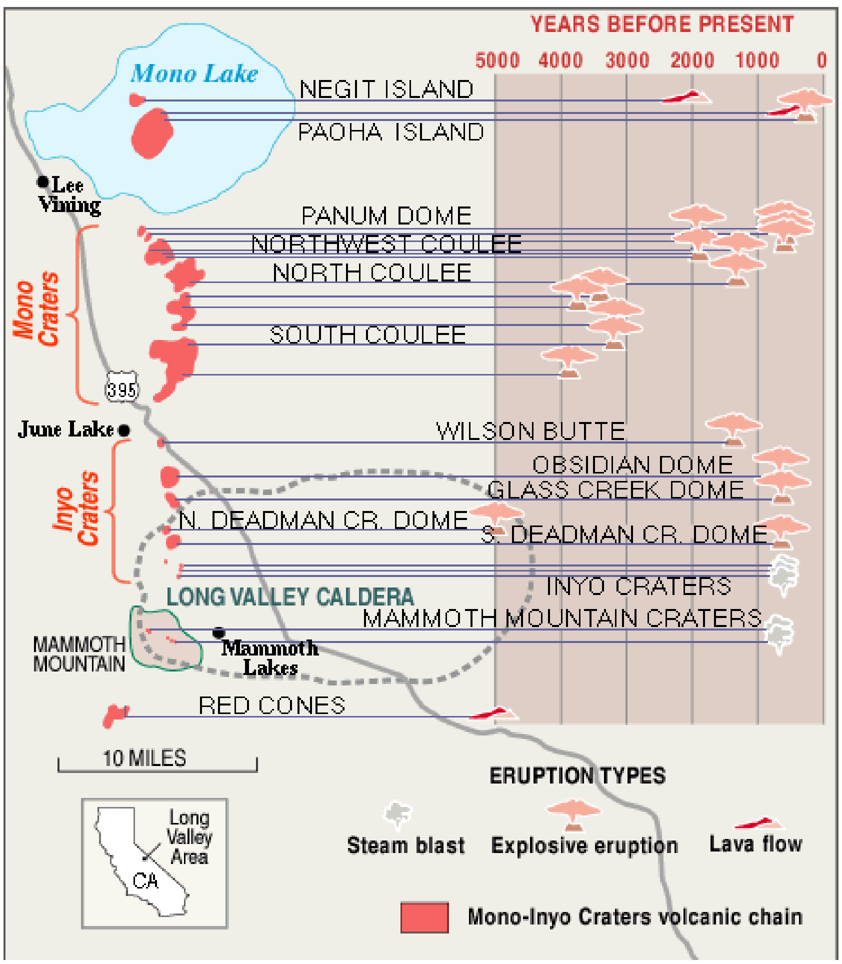

Figure 2. *Locations ages and types of eruptive events in the Mono-Inyo volcanic zone (from USGS)*

Tectonics

Long Valley Caldera lies within an east-west embayment or offset in the northwest trending Sierran escarpment (Mayo, 1934). The east-dipping normal faults that form the escarpment mark the western edge of crustal extension in the Basin and Range Province. The caldera is located at the northern end of the Owens Valley graben, part of the Eastern California Shear Zone, a region of transtensional deformation along the western edge of the Basin and Range that extends to the north along the Walker Lane in western Nevada (Figure 2) (Hill, 2006). Transtensional deformation and active magmatism within the Eastern California Shear Zone and the Walker Lane reflect the combined influence of dextral slip along the San Andreas Fault transform boundary between the Pacific Plate and North American Plates and the westward progression of crustal extension across the Basin and Range Province. Right-lateral slip distributed across this transtensional zone accounts for 15 - 25% of the relative motion between the Pacific and the North American plates (Dixon and others. 2000, Faulds, 2004). Active magmatic processes in the region are generally attributed to upwelling of the underlying asthenosphere as the crust stretches, thins and fractures in response to transtensional extension across the Eastern California Shear Zone - Walker Lane corridor (Hill, 2006).

The tectonic interaction between the Eastern California Shear Zone and the Walker Lane system localizes volcanism at transtensional pull-apart sections in the Mono-Long Valley region. Long Valley Caldera is located at the western end of the Mina Deflection, a broad zone of northeast-trending left-lateral faults that form a right jog in the regional right-lateral fault system of the Owens Valley providing a link to the Walker Lane to the northeast (Figure 3). Crustal extension in the Mono Basin is the result of left lateral shear across the Mina Deflection and the extension increases southward into Long Valley Caldera. Extensional strain is complexly resolved within the caldera because of the faulting and fracturing that defined the pre-existing Sierran range front embayment. The western and central parts of the caldera are superimposed over several pre-existing fault systems that defined the pre-caldera eastern Sierra range front. The floor of the caldera, rather than being a simple planar feature, is segmented into a number of discrete blocks with varying offsets that accommodated 1-2 km of subsidence as the caldera's floor foundered. The basement structure of Long Valley, buried under nearly 400 km^3 of Bishop Tuff and later volcanic fill, has been interpreted from detailed mapping, regional geophysical surveys and drilling data (Bailey, 1976; Suemnicht and Varga, 1988; Bailey, 2000). The Discovery Fault Zone in the western caldera is a prominent surface feature that is a direct extension of the Mina Deflection and an expression of the original range front embayment before the caldera collapsed. The pre-existing tectonic framework controlled the configuration of the caldera floor and, through faults and fault intersections, controlled the location of postcollapse eruptive centers. The inherited deep basement structures of the western caldera provide the high fracture density and deep permeability for the source of the present geothermal system in Long Valley.

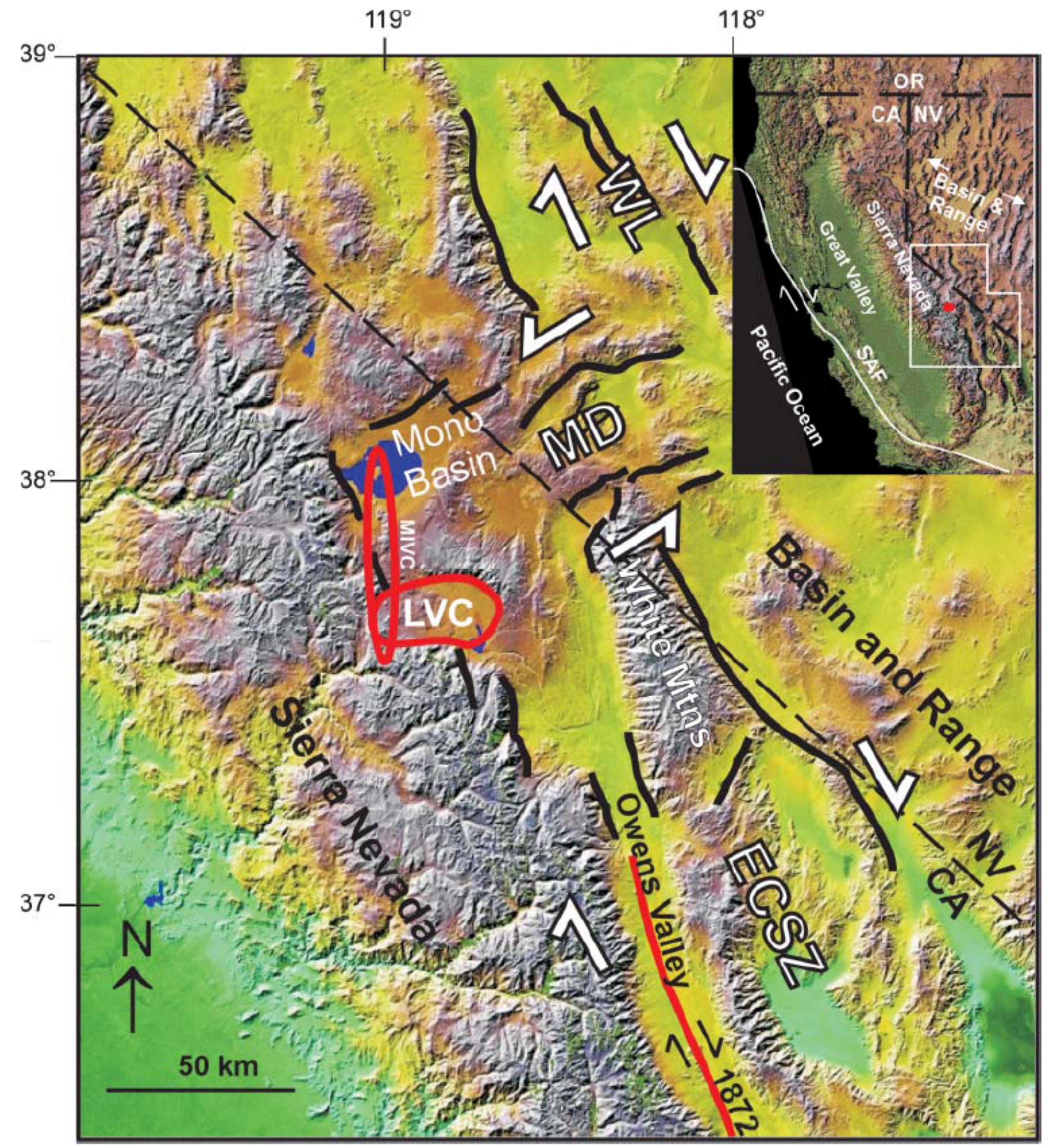

Figure.3 *Shaded relief map of east-central California and western Nevada, showing the location of Long Valley Caldera (LVC) and the Mono–Inyo volcanic chain (MIVC) outlined by red ovals. Increasing elevation is indicated by colors ranging from dark green (at approximately sea-level) to light grey (>2400 m with maximum elevations reaching c. 4300 m). The transition from yellow-green to brown marks the 1700 m contour. Heavy black lines indicate major Quaternary faults. The red line in the Owens Valley indicates surface rupture from the M ≈ 7.6 Owens Valley earthquake of 1872. White arrows indicate the sense of displacement across the Eastern California Shear Zone (ECSZ), the Mina Deflection (MD), and the Walker Lane (WL). The white outline in the inset shows the map location with respect to the San Andreas Fault (SAF) in coastal California (CA) and the Basin and Range Province in western Nevada (NV) with opposing white arrows indicating the sense of extension.* (After Hill, 2005)

Caldera Unrest

Moderate to strong historical earthquakes occur regularly in the eastern Sierra Nevada and the Owens Valley south of Long Valley Caldera (Ellsworth, 1990). The northern end of the rupture zone of the M ~ 7.6 Owens Valley earthquake of 1872 extended to within 60 km of Long Valley Caldera (Figure 4) and earthquakes M>5 occurred outside the caldera before 1970 (Cramer & Toppozada 1980; Ellsworth 1990).

Long Valley Caldera began a period of unrest in the late 1970s that included earthquake swarms, approximately 80 cm of inflation within the resurgent dome, changes in the outflow from hot springs and fumaroles and increased CO_2 emissions around the flanks of Mammoth Mountain (Figure 1). The gas emissions on Mammoth Mountain have been accompanied by rising $^3He/^4He$ ratios interpreted as potential indicators of magma moving to shallower crustal levels. The largest magnitude earthquakes occurred within the Sierran block south of the caldera while caldera activity was marked by earthquake swarms, long-period (LP) and very-long period (VLP) volcanic earthquakes. An intense earthquake sequence that included four M>6 earthquakes within and around the caldera on May 25, 1980 occurred within days of the May 18, 1980 eruption of Mount St Helens and in that context, raised strong concerns about the eruptive potential of a large active magma chamber beneath the caldera.

Volcanic hazard concepts related to the continuing unrest within the caldera evolved rapidly as research progressed on the Mono-Long Valley magmatic system (Hill, 2006). Based on Long Valley data and a better understanding of restless calderas worldwide, large silicic calderas can go through sustained periods of episodic unrest, separated by years to decades of relative quiescence, all without producing an eruption (Newhall & Dzurisin 1988; Newhall, 2003). Caldera unrest can also be more intense and may extend beyond the comparatively short restless periods associated with central vent volcanoes. Volcanic earthquakes, increased magmatic gases and changes in geothermal manifestations have all occurred in Long Valley Caldera without an eruption.

Long Valley remains on an active volcanic hazard alert status although the US Geological Survey states that earthquake activity within and adjacent to the caldera has remained at a comparatively low level since 1999. The caldera is probably not underlain by a laterally extensive, upper-crustal magma body capable of feeding a major eruption (Eichelberger, 2003), but none of the current data exclude the possibility of smaller (<1 km3) eruptions from smaller magma sources or a series of phreatic explosions similar to the historical eruptions that occurred along the Inyo-Mono dike (Miller, 1985). The 1978-2004 period of unrest most likely was associated with the addition of ~0.3 km^3 of magma and hydrous fluids at a depth of 6-7 km beneath the resurgent dome. Seismic tomography studies might resolve a 1–2 km diameter magma body but not the smaller melt volumes noted above (Hill and Prejean, 2005). The dacitic magma chamber beneath Mammoth Mountain has probably crystallized because the last eruption occurred 52,000 years ago (Hildreth, 2004). Hill & Prejean (2005) ascribed the 1989 earthquake swarm beneath Mammoth Mountain that included mid-crustal long-period earthquakes and

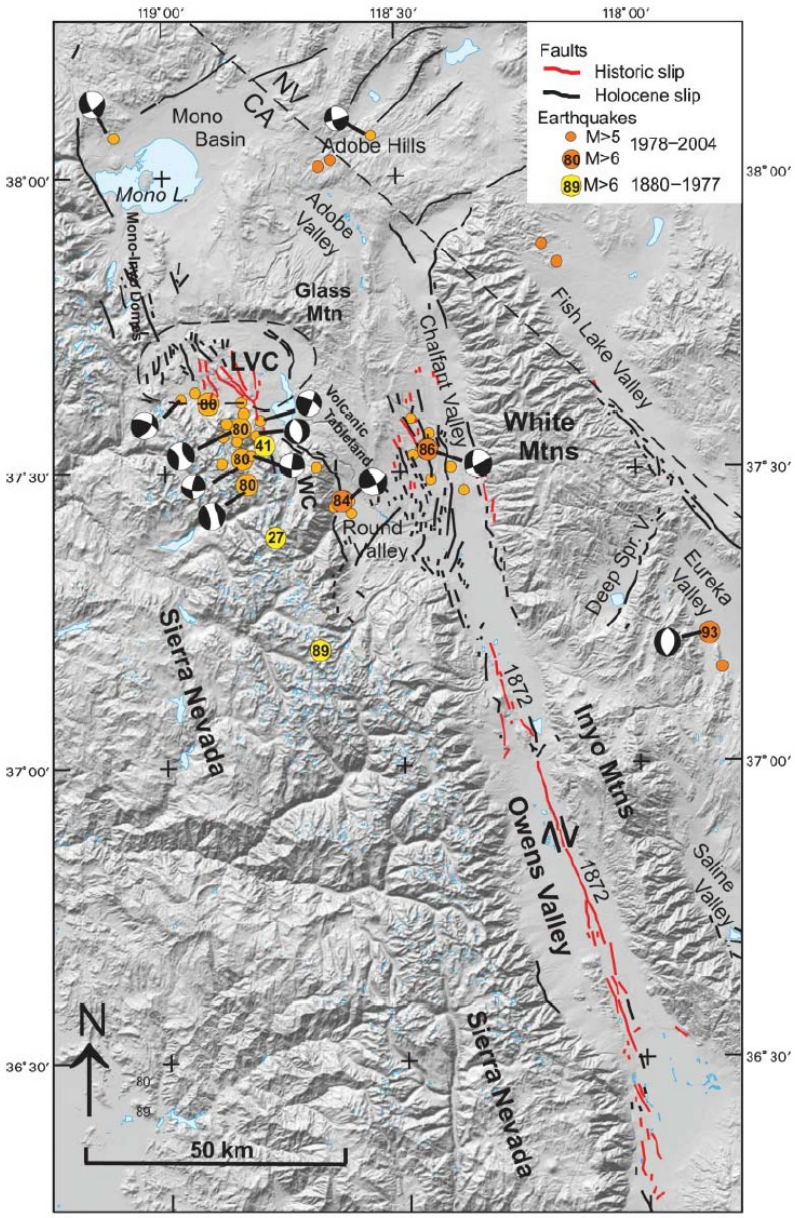

Figure 4. *Shaded relief map illustrating the relation of Long Valley Caldera (LVC) to major tectonic elements and M>5 earthquakes in eastern California (the red rectangle in inset shows the map area). Heavy black and red lines are faults with Holocene slip and historic (post-1870) slip, respectively. The surface trace of the M=7.8 Owens Valley earthquake of 1872, labeled '1872'. Orange circles are post-1977 earthquakes (small for M>5; large with decadal year included for M>6). Yellow circles are 1870–1978 M>6 earthquakes (not including aftershocks to the 1872 main shock with decadal year indicated. WC is Wheeler Crest (from Hill, 2005).*

increased CO_2 venting to a "mid-crustal plexus of basaltic magma (*that*) remains capable of feeding future mafic eruptions. This magma plexus presumably fed eruptions of the mafic field surrounding Mammoth Mountain, including the 8,000 year-old Red Cones vents, and it is the likely heat source for the 700 year-old phreatic explosion vents on the northeast flank of Mammoth Mountain." Some long period earthquakes have occurred west of the Mono Domes (Pitt & Hill 1994) but the area has remained comparatively quiet during the unrest in Long Valley. Based on a geologic history of 20 eruptions over the last 5000 years and the eruption at Pahoa Island approximately 200 years ago (Bailey 2004), the young silicic domes of the Mono–Inyo volcanic chain still have the potential to produce significant eruptive events.

GEOTHERMAL SYSTEM

The geothermal system 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 around the Resurgent Dome (Figure 5). As much as 75% of the current hydrothermal outflow occurs in the thermal springs at Hot Creek on the southeastern edge of the Resurgent Dome and geochemical estimates of source reservoir temperatures range from 200 ^{o}C – 280^{o}C (Sorey and others, 1978; 1991; Mariner and Wiley, 1976).

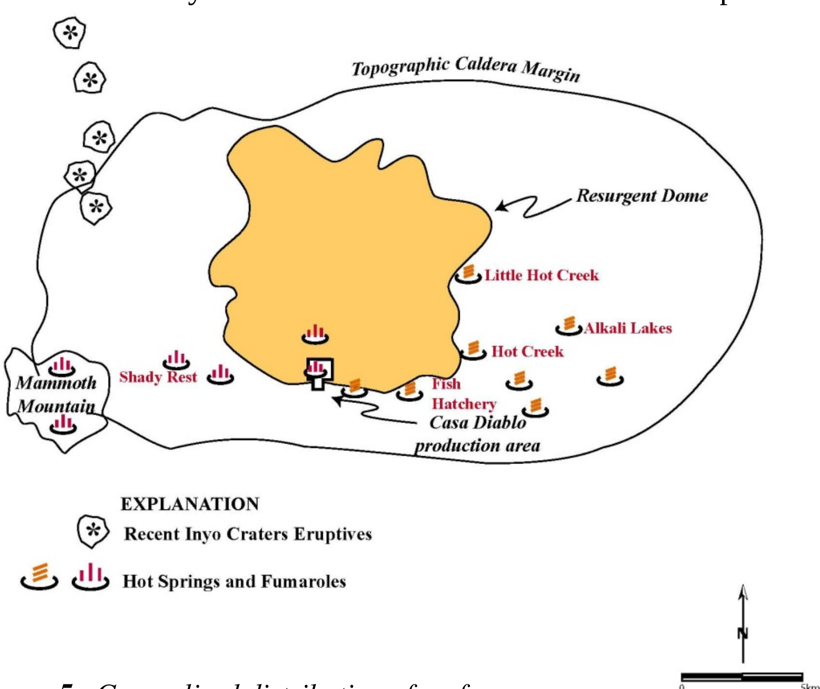

Figure. 5. *Generalized distribution of surface manifestations in Long Valley Caldera*

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.

GEOTHERMAL EXPLORATION

Early exploration drilling in Long Valley focused on the southern and central part of the caldera. Production wells drilled 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 6). 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.

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 6). Mammoth-1 drilled through 390m of Early Rhyolite, 863m of Bishop Tuff and 230m of metasedimentary rocks that correlate with the Mt. Morrison 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 various eruptive processes 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 6). The well encountered temperatures of 218^{o}C at 1100m, the highest 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 west of 44-16 (Figure 6) established that 1000 m of vertical offset on the caldera's western ring fracture system occurs within a kilometer distance between the two wells along the western structural margin of the caldera (Eichelberger and others, 1988). Additional scientific drilling in Long Valley included a core hole at Shady Rest (Figure 6) (Wollenberg and others, 1989), and an ultra-deep (3 km) Long Valley Exploratory Well (LVEW, Figure 6) intended to test the presence of magma near the center of the Resurgent Dome (Finger and others, 1995).

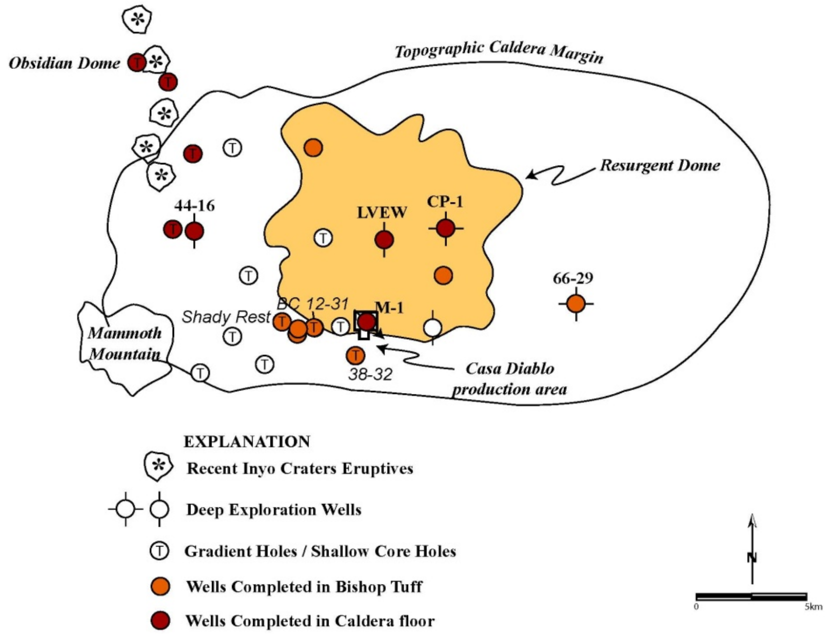

Figure 6. *Caldera outline and locations of temperature gradient holes (T designation), intermediate and deep wells drilled in Long Valley. Wells in orange drilled into intracaldera Bishop Tuff and wells in red have penetrated the intracaldera fill and are completed in the Paleozoic metamorphic rocks of the caldera basement. (Suemnicht and others, 2006)*

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 (Rundle and others, 1986; Rundle and Hill, 1988). 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 caldera's western moat. Shallow test wells confirmed the general temperature distribution within the shallow hydrothermal system and expanded the understanding of the intra-caldera geology. 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.) in 1992 and the BC 12-31 corehole drilled to 600m approximately 2 km west of the production facilities in 2002 (Figure 7).

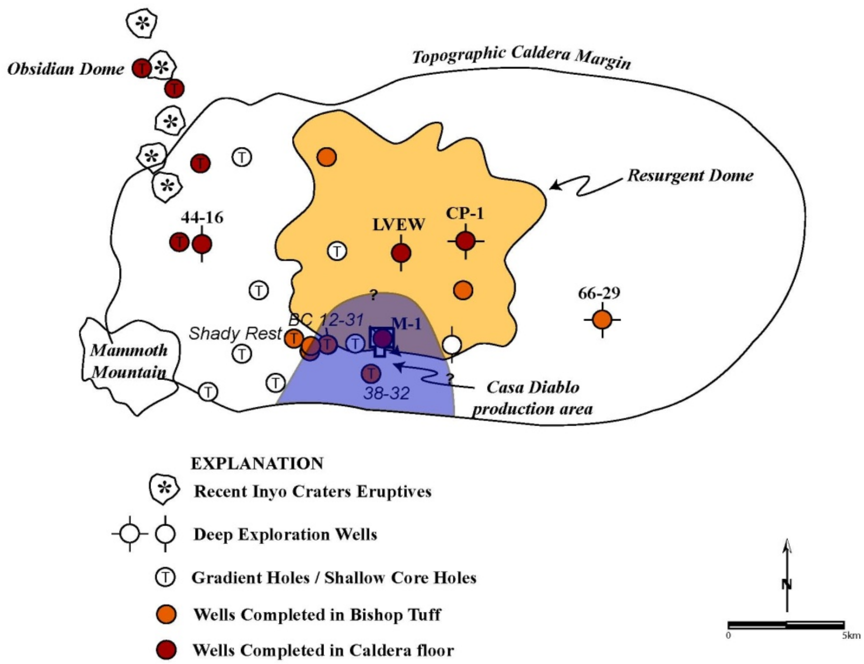

Figure 7. *Distribution of the landslide block (blue) of Paleozoic metasedimentary rocks from the southern rim of Long Valley Caldera (Suemnicht and others, 2006)*

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. The landslide block is absent in surrounding wells that penetrate into the Bishop Tuff on the Resurgent Dome and at 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. 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 8).

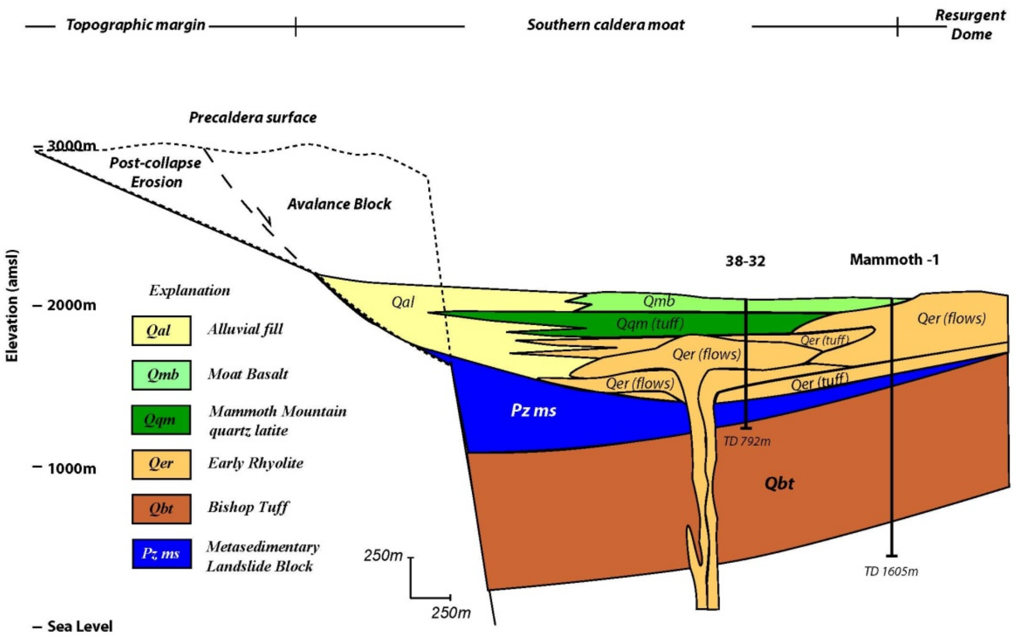

Figure 8. *Structural cross-section of the southern caldera margin showing the landslide block encountered in exploration corehole 38-32 and the Mammoth-1 deep test well at Casa Diablo (Suemnicht and others, 2006).*

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 cushion beneath the landslide block (Figure 7). 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.

SHALLOW HYDROTHERMAL SYSTEM

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. 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. Upflow at these fracture intersections occurs at comparatively low elevations at the base of the Rhyolite Plateau west of Shady Rest. Within the corresponding shallow hydrothermal system, the landslide block controls the flow of hydrothermal fluids southeast around the southern part of the Resurgent Dome (Figure 9). Intense alteration of the over/underlying ash froth, overlying clay-rich lacustrine sediments and the impermeable nature of the landslide block isolates the shallow hydrothermal system from deeper flow and maintains moderate-temperature outflow in shallower Early Rhyolite or lacustrine units east of Shady Rest.

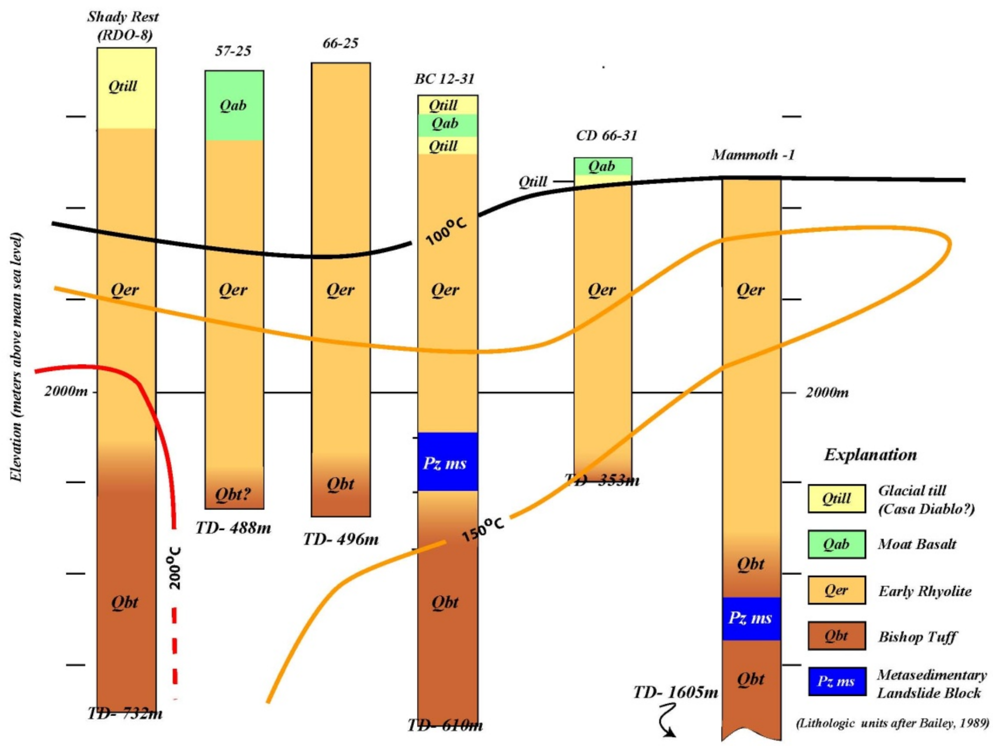

Figure. 9. *Lithology and temperatures (°C) from wells in the southern moat of Long Valley caldera. Wells extend from the projected outflow zone of he current geothermal system at Shady Rest to existing production area at Casa Diablo represented by the deep Mammoth-1 well (Suemnicht and others, 2006) .*

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 °C are commonly found on the structural caldera margins 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 into the shallow permeable Early Rhyolites east of Shady Rest, it is effectively separated from underlying rocks and the pervasive influence of cold recharge waters around the rim of the caldera (Figure 10). Production wells at Casa Diablo are completed in an upper 170^{o}C zone in Early Rhyolites while injection wells are completed in the deeper (~700m) permeable Bishop Tuff below the landslide block. The impermeable landslide block, lacustrine clays or intensely altered clay-rich upper part of the Bishop Tuff control shallow hydrothermal circulation 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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