California Geothermal Energy Collaborative Meeting
May 27, 2011
Long Valley Caldera Field Trip Log

The trip leaves from the Mammoth Mountain Inn in Long Valley Caldera for a gondola ride to the summit of Mammoth Mountain. Exit the gondola house and visitor center at the lower doors and turn left (east) to the summit sign at top of the mountain.

Stop 1 – Caldera Overview, Mammoth Mountain Summit

The view from the summit of Mammoth Mountain encompasses Long Valley Caldera, the northern Owens Valley and the Sierra crest. The topographic margin of the caldera extends from the Palisades below San Joaquin Ridge on the west, Bald Mountain on the north, the Glass Mountain eruptive complex on the northeast, Lake Crowley to the east and Laurel Mountain and the Sierra front to the south. The White Mountains, on the distant eastern skyline beyond the Glass Mountain complex represent the eastern side of the Owens Valley rift with elevations of 4373m (14347ft) ~ 300m (1000ft) higher than local Sierran peaks.

Long Valley Caldera formed when the roof of the caldera magma chamber ruptured 760,000 years ago erupting 600 km^3 of Bishop Tuff. The roof of the partially emptied magma chamber collapsed to form the 17 x 32 km (10x20 mi) depression of Long Valley Caldera. Drilling data confirms that the structural margin of the caldera and the inherited faults that controlled the caldera collapse can be as much as 2 km (1.2 mi) inboard of the current topographic rim of the caldera. As pressures recovered within the Bishop Tuff magma chamber, the roof of the chamber began rising and lifting the overlying caldera fill. The low hills in the west central part of the caldera are the composite Early Rhyolite eruptive centers of the Resurgent Dome that began erupting at ~600,000 years ago. The caldera moat is the space between the caldera's topographic rim and the Resurgent Dome. Smaller Moat Rhyolite eruptions began in the north around 500,000 years ago, southeast near the airport approximately 300,000 years ago and in the western moat around 100,000 years forming a rhyolite plateau above the Town of Mammoth Lakes. Most eruptive events over the last 160,000 years have occurred in the western caldera varying from mafic to silicic compositions suggesting a complex mixture of contemporaneous magma sources (Hildreth, 2004; Mahood and others, 2010). Mammoth Mountain on the western caldera rim is a composite of a dozen dacite/rhyolite centers that erupted between 120,000 and 58,000 years ago. Mammoth Mountain and Lincoln Peak were erupted between 68,000-58,000 years ago. The summit dome where we stand is dated at 68,000 years and detailed age dating indicates that the main bulk of the mountain was formed by dacite eruptions in less than 2,000 years (Mahood and others, 2010).

The Mono-Inyo volcanic chain extends from the Inyo Domes in the northwestern caldera moat to the Mono Craters and Mono Lake to the north. Eruptions began in the Mono Craters approximately 40,000 yrs. The Inyo Domes erupted approximately 600 years ago and provide the most prominent surface evidence of an active magmatic system in Long Valley. Phreatic explosions related to the Mono-Inyo dike intrusion excavated explosion pits on the north face of Mammoth Mountain ~600 yrs ago (Sorey and others, 1998).

Many of these features have been modified by construction of the mountain's recreational facilities but one side of an explosion pit remains at the base of Chair 19 west of the lodge and stratified eruption deposits are found in drainages eroded between ski runs.

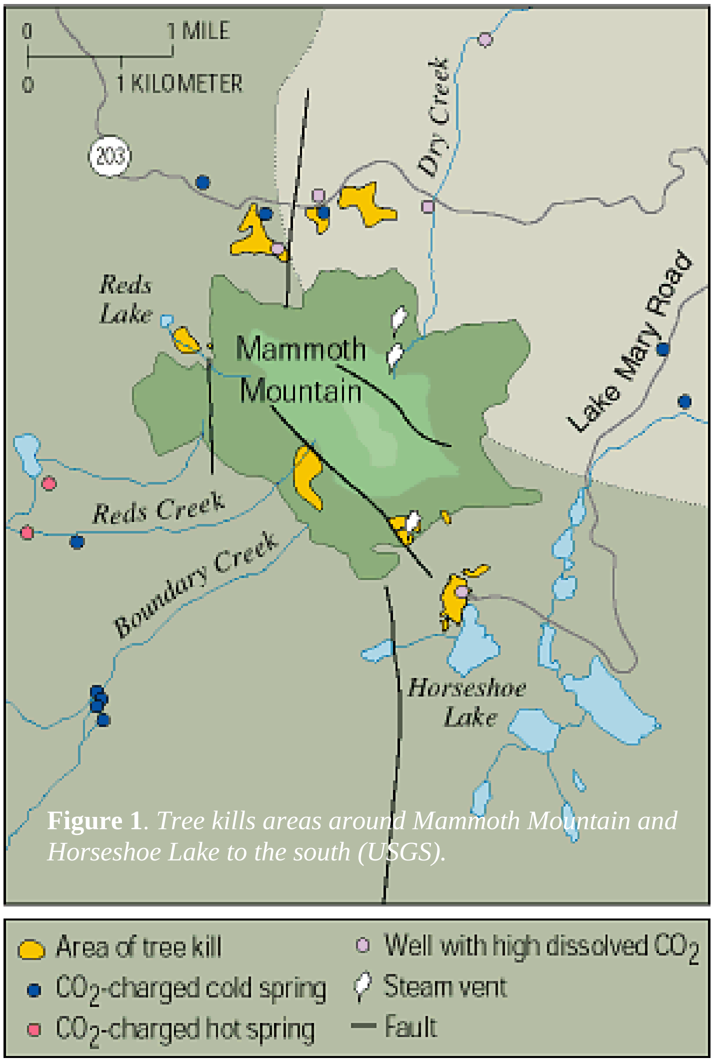

Figure 1. *Tree kills areas around Mammoth Mountain and Horseshoe Lake to the south (USGS).*

Areas of dead trees began to appear where high levels of CO_2 soil gas were noted following a six-month period of seismic swarms beneath the mountain in 1989 (Sorey and others, 1998)(Figure 1). Elevated soil gas flux and tree-kill areas occur along faults or fault intersections around all but the eastern flank of Mammoth Mountain, most notably along the northern flank near Chair 12 and along the southern flank at Horseshoe Lake just outside the southwestern margin of the caldera. The cold CO_2 discharge does not contain ^{14}C but is accompanied by elevated levels of magmatic helium ($^3He/^4He$ ratios ~ 5 times the atmospheric ratio). Groundwater with the same inorganic carbon and helium isotopic compositions flows off the flanks of the mountain. The source of these inorganic carbon and helium emissions appears to be a long-lived gas reservoir formed above a region of magmatic intrusion, sealed at the top by hydrothermally altered volcanic and metasedimentary rocks that are periodically penetrated by intrusions of basaltic magma (Sorey and others, 1998).

Ride down the gondola for vehicle part of the trip. Reset odometer before leaving the ski area parking lot. All distances are from the Main Lodge at Mammoth Mountain. Exit the ski area parking lot and head east toward Mammoth Lakes on Minaret Summit Rd (Hwy 203). Look for the US Forest Service sign for Earthquake Fault and turn left (north) into the parking lot stopping near the display sign at the far northwestern end of the lot.

Incremental Distance *–2.0 mi / 3.2 km* **Cumulative distance** *– 2 mi. / 3.2 km*

Stop 2 – Earthquake Fault

Figure 2. *Earthquake Fault view north.*

The Earthquake Fault is the best known dilational ground crack in the western part of Long Valley Caldera (Figure 2). A more appropriate name for the nearly straight fracture would be Earthquake Fissure because there is scant evidence that the rocks on either side of the fracture have moved vertically or laterally relative to one another. Irregularities in the joint faces across the fissure nearly match perfectly with some suggestion of right-lateral pull-apart separation. The fissure is up to 10 feet wide and 60 feet deep and cuts through 113,000 year old dacites or 81,000 year old rhyodacites of Mammoth Mountain (Mahood and others, 2010). Snow from the winter months commonly lasts all year round in deep bottom protions of the fissure. Local Native Indians would store their food at the bottom of the fissure during the warmer summer months.

Earthquake Fault is one of a series of western caldera fissures and faults (see stop #9) in aligned with the Inyo-Mono Craters volcanic chain that, in a regional senseare part of the east-west stretching that is gradually widening the entire Basin and Range. Early studies (Benioff and Guttenberg, 1939; Rinehart and Ross, 1964; Bailey and others, 1976) concluded that these features are tectonic in origin and suggested that at least some of the cracks and faults might represent the southern extension of the Harley Springs Fault. Subsequent work on the Inyo-Mono eruptive sequence (Mastin and Pollard, 1988) led to the conclusion that the faults and fissures in the western part of Long Valley Caldera are part of crustal dilation above the southern portion of 8–10-km-long dike that strikes north out of the caldera that supplied the most recent dome-forming eruptive events at the north end of the Mono Craters about 600 years ago (Bursik & Sieh 1989) and here along the south end of the Inyo Domes at about the same time interval (Sorey and others, 1998). Both interpretations are compatible because the Inyo-Mono dike is probably controlled at greater depths by preexisting faults that allowed magma into the shallower crust similar to previous intrusive events in the western caldera while the cracks and fractures in the ground surface are related to shallow uplift and extensional stresses immediately above a rising Mono-Inyo dike (Mastin and Pollard, 1988).

The age of Earthquake Fault is unknown or at least poorly constrained. Trees growing in the crack are ~160 years old, indicating that the crack is at least that old. The crack lacks pumice fill so the fissure formed after the eruption of the Inyo Craters 600 years ago. Indian legends recount a massive earthquake in the area ~ 200 years ago causing among other things, the Earthquake Fault rift to open. Separating fact from myth is often difficult but the age and cause are tantilizing since the legendary event roughly corresponds to a shallow intrusion beneath Mono Lake ~200 years ago that pushed up lake-bottom sediments to form Pahoa Island and produced a small volume of andesitic lavas from vents on the island's north side (Lajoie, 1968; Bursik & Sieh 1989) (see Stop #7).

Benioff and Guttenberg (1939) placed stainless steel pins in opposite walls of the fissure and they or CalTech colleagues periodically measured the distance between the pins with a steel rod to determine strain over time. Through the 1940s,measurements showed the fissure widened by approximately a millimeter but after a 20-year break, a measurement in1967 found that the crack had closed enough that the steel caliper bar would no longer fit between the fixed steel pins. Unsubstantiated rumors persisted during the 1980s Mammoth Lakes earthquakes that the Earthquake Fault crack was reactivated but no firm evidence was ever presented. Soil settling noted at the bottom of the rift was probably related to consolidation of loose material during the series of M 6 earthquakes in May 1980 and M5 events in January 1983. A number of collapse pits up to 5 m in diameter also formed along the northern extensions of this and other ground cracks in the western caldera because of ground settling during the Mammoth Lakes earthquake sequence. The US Forest Service restricted access to the fissure during the seismic unrest of the 1980s and removed damaged ladders that had previously allowed tourist access to deeper levels of the rift.

Exit the Earthquake Fault parking lot and turn left (east) on Minaret Summit Road (Highway 203). BEWARE OF TRAFFIC! Turn left at the intersection with Main Street and Minaret Summit Road (Highway 203) and continue east through the Town of Mammoth Lakes. At the eastern edge of town, turn left (northeast) at the Sawmill Cutoff Road just before the Mammoth Ranger Station (USFS sign reads Shady Rest Campground). Drive northeast past the Shady Rest camping area and turn right (east) onto Sawmill Road leading to Shady Rest Community Park. Continue east around the park facilities and turn right to drive through a gap in the log barriers at the eastern side of the parking lot. Continue east on the Sawmill dirt road to the fenced Mammoth Pacific 57-25 well pad on the left. Park on the south side of the location. Access to the well pad or wellhead is only by permission of Ormat and Mammoth Pacific LP.

***Incremental Distance** – 3.2 mi / 5.2* km ***Cumulative distance** – 5.2mi.* / *8.4 km*

Stop 3 – Recent Production Wells, Shady Rest

Figure 3. Drilling BC 12-31 exploration corehole in *Basalt Canyon (photo by R. Sullivan)*

The USGS and DOE drilled a core hole (RDO-8) to 732 m (2401 ft) near the Shady Rest campground in the southern caldera moat in 1984 (Wollenberg and others, 1989). The lower portion of the well was lost because of wellbore instability but measured temperatures at 400m(1312 ft) were 203°C (397°F) and appeared to persist at depth based on extrapolated survey temperatures. This scientific effort and exploration wells drilled in the western caldera added to understanding the Long Valley geothermal system. Drilling established that the principal geothermal reservoir in Long Valley was not located directly beneath Casa Diablo 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 is supplied by upflow from a western geothermal source and outflow at or near Shady Rest.

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 (Figure 3) in 2002 and production wells 57-25 and 66-25 in 2005, ~1km (0.6 mi) east of the Shady Rest core hole. The production wells are nearly 500 m (1640 ft) deep and produce from the upper fractured portion of the Bishop Tuff. Approximately 225 L/sec (3,600 gal/min) of brine from these wells is piped to Casa Diablo and commingled with production from earlier wells.

Return to Sawmill Road and continue east to the intersection with Highway 203. Turn left (east) on Highway 203 heading toward Highway 395. Cross beneath the freeway and continue east ~300m (0.2 mi). Turn left (north) on Casa Diablo Cutoff Road passing production wells on the right (east) side of the road. Turn right at the power plant control gate at the top of the hill. Access to the geothermal development is by permission of Ormat and Mammoth Pacific LP. After entering the gate, drive downhill to the east and stop at the power plant control facilities on the right.

Incremental Distance *– 4.7 mi / 7.6* km ***Cumulative distance –*** *9.9 mi. / 16.0* km

Stop 4 – Mammoth Pacific Production Facilities, Casa Diablo

Casa Diablo Hot Springs is an active thermal area on the southwestern side of the caldera's Resurgent Dome (Figure 4). Most of the prominent hot springs within the caldera including Hot Creek (Stop 5) occur in the southern caldera moat or are localized along faults around the southern edge of the Resurgent Dome. The springs at Casa Diablo were an early gathering place for local Paiute Indians, settlers and prospectors. During the late 1800s, the site was a way station on the Bodie-Mammoth City stage line and later an automobile rest stop on Old Highway 395. The old highway route survives as a paved roadway dividing the east and west portions of the geothermal field (Figure 5). Historical records and photographs recount the erratic discharge of the thermal features that varied from relatively quiet outflow to fumaroles to sporadic geysering.

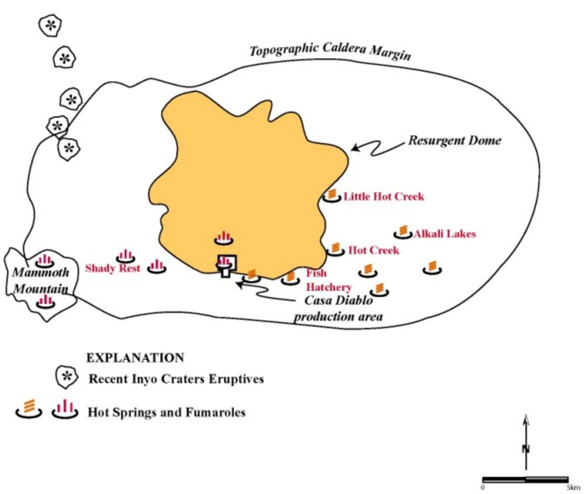

Figure 4. *Generalized distribution of surface manifestations in Long Valley Caldera.*

Active and relict fumaroles, mudpots and hot springs at Casa Diablo are localized along major northwest trending normal faults that form a graben within the Resurgent Dome. Hydrothermal alteration marks the trace of a fault that cuts 600,000 year-old Early Rhyolite of the Resurgent Dome on the northeastern side of the field. Younger 129,000-62,000 year-old postcaldera mafic lavas flood the southwestern caldera moat and lap against the Resurgent Dome. Active fumaroles on the western side of the geothermal field are aligned along a fault scarp that uplifts and exposes these moat basalts. Casa Diablo was the location of several seismic swarms that occurred during the initial phases of caldera unrest and Resurgent Dome uplift from 1980 to 1983. Some of these events were marked by ground cracking, changes in spring discharge, and vigorous reactivation of a previously dormant fumarole immediately east of the old highway and new or reactivated hot springs around the edge of the Resurgent Dome.

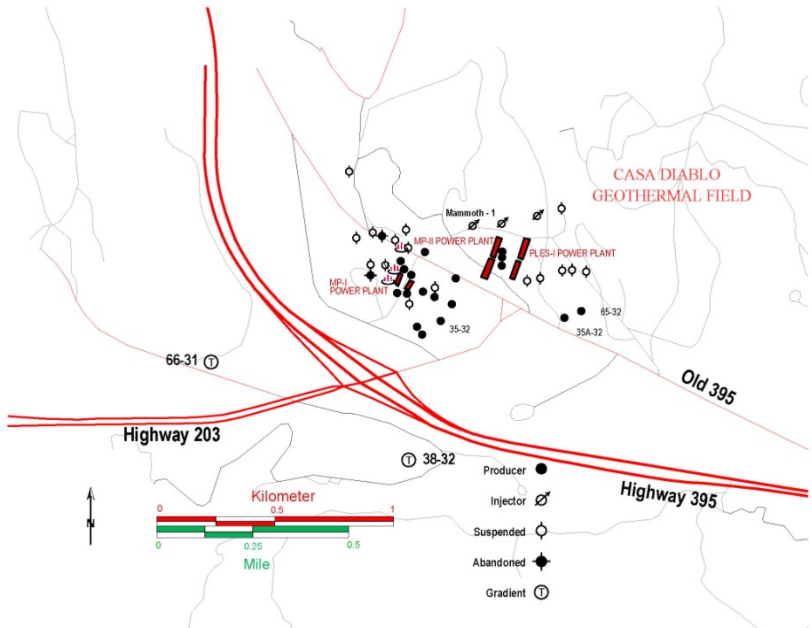

Figure 5. *Wells and temperature gradient holes in and around the Casa Diablo development area (modified from Calif. Div. of Oil, Gas and Geothermal Resources).*

The first geothermal exploration wells in Long Valley were drilled at Casa Diablo between 1959 and 1962 by Magma Power Co. A series of nine wells were drilled to total depths ranging from 125m to 324m (410-1062ft) adjacent to active fumaroles west of Old Highway 395. The wells encountered reservoir temperatures of ~170^{o}C (338°F) and Magma planned a 15 Mw generation facility but binary production technologies were still in the early stages of development in 1962 and the project was shelved. Initial development in 1984 included four production wells and 2 injection wells supplying a 10 Mw (gross) pilot binary production facility within the original Magma well field (Figure 5). Successful generation led to additional drilling, and in 1990, the installation of two 15 Mw binary MP-II and PLES-1 generating plants that currently use 6 production wells and 5 injection wells to produce ~750 L/sec (~12,000 gal/min) to generate a combined 40 Mw (gross) of electricity. The project is managed and operated by Mammoth Pacific LP for Ormat Nevada Inc. supplying base load electricity under contract to Southern California Edison (SCE). The project has won numerous awards for safe operations, innovation and environmental stewardship from The California State Assembly, The Governor's Environmental and Economic Leadership Council, the US Forest Service and the California Department of Conservation.

Mammoth-1, drilled by Unocal east of Old Highway 395 in 1979, was the first well drilled at Casa Diablo to evaluate potential deep production from the intracaldera Bishop Tuff and the caldera basement. Mammoth-1 drilled through 390m (1280ft). of Early Rhyolite, 863m (2831ft) of Bishop Tuff and 230m (755ft) of metasedimentary rocks that correlate with the Convict Lake roof pendant to the south, bottoming at 1605m (5265 ft) Mammoth-1 was also the first well within the caldera to encounter a landslide block of chaotically mixed metapelite and granite at 466m in the upper section of Bishop Tuff (Suemnicht, 1987). The well is currently used as a backup injector.

The results from Mammoth-1 and other deep tests indicate that production at Casa Diablo is limited to shallow (<200m; 650 ft) permeable Early Rhyolites and that the source of the current system is not directly beneath the Resurgent Dome (Suemnicht, 1987). Mineralization ages (Sorey and others, 1991) indicate that the Bishop Tuff magma chamber supported a vigorous geothermal system from 300, 00 to 130,000 years ago producing widespread hydrothermal alteration in and around the Resurgent Dome. Drilling results establish that magmatic activity beneath the central part of the caldera has waned over the past 100,000 years while activity in the western caldera has increased. Shallow wells at Casa Diablo produce 170^{o}C (338°F) outflow that is supplied by upflow from the currently active geothermal system in the west. Injection wells return the produced fluid to deeper (750m; 2460 ft) permeable zones in the underlying Bishop Tuff. The shallow Early Rhyolite reservoir is stratigraphically separated from the underlying Bishop Tuff by an impermeable landslide block that controls the vertical distribution of shallow hydrothermal circulation in the southern caldera allowing sustained production and injection at Casa Diablo by isolating warm shallow outflow from deeper cold natural recharge and injection fluids that might quench the system.

Exit the geothermal facility and turn left on Casa Diablo Cutoff Road. Turn right (west) on Highway 203 and cross under the Highway 395 freeway bridge. Turn immediately left (southeast) onto the south-bound onramp of Highway 395. Drive southeast on Highway 395 toward the Mammoth-Yosemite Airport. Turn left (northeast) across Highway 395 onto Hot Creek Hatchery Road. BEWARE OF TRAFFIC! Continue north past Airport Road and turn right (northeast) on Hot Creek Hatchery Road. Follow the road northeast past the Hot Bubbling Pool on the north side of Hot Creek and the Hot Creek Fish Hatchery on the south side of the creek (at approximately 0.5 miles (0.8 km) from the intersection of Hot Creek Road and School Road).

Hydrothermal Outflow Monitoring, Hot Bubbling Pool

Hot Bubbling Pool is not a scheduled stop but is discussed here because it is part of a network of monitoring points (Figure 6) that includes hot springs, fumaroles, cold springs, and stream flow and precipitation measurements in and around the geothermal development at Casa Diablo. Federal agencies and Mono County require hydrologic monitoring of geothermal operations in the caldera. Monitoring is carried out by the U.S. Geological Survey and MPLP and is overseen by the Long Valley Hydrologic Advisory Committee (HAC), a cooperative effort of both public and private sector stakeholders.

Hydrologic data have been collected and interpreted by the USGS since the program's inception in 1985. The monitoring data establish that the Long Valley hydrologic system is affected by variations in precipitation, recharge, geothermal production, non-thermal groundwater withdrawals, earthquakes and crustal deformation.

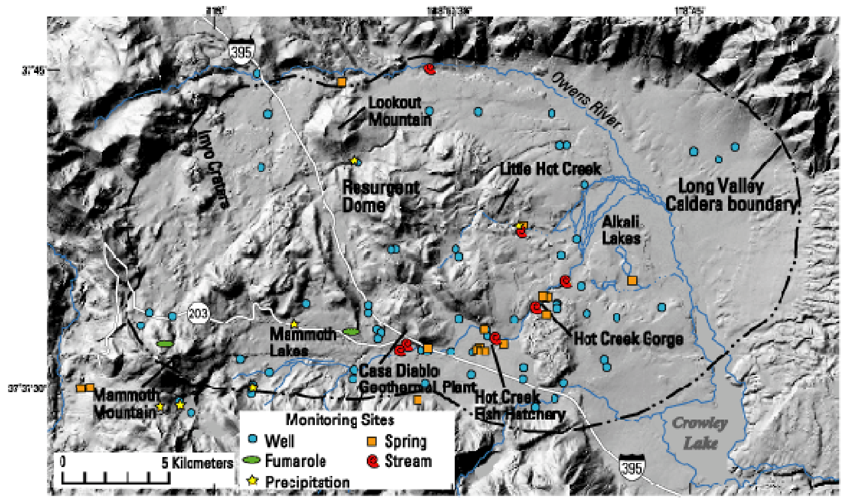

Figure 6. *Hydrologic monitoring sites in Long Valley* (*USGS)*

Recharge, dominated by precipitation at high elevations around the caldera's topographic rim, is the primary influence on the caldera's hydrologic system (http://lvo.wr.usgs.gov/HydroStudies.html). Thermal springs occur along faults in the southern and eastern parts of the caldera in and around the Resurgent Dome. Approximately 75% of the thermal water discharge in the caldera occurs at Hot Creek (Stop 5) while minor springs contribute comparatively smaller but important thermal outflow. For example, warm springs at the Hot Creek Fish Hatchery operated by the California Department of Fish and Game immediately to the east of Hot Bubbling Pool account for only 2-5% of the caldera's total thermal outflow but their thermal input raises water temperatures an average of 5°C (41°F) above background. Hatchery fish are planted in many surrounding Sierra lakes and streams and are an important part of regional recreation and the local tourist industry. An example of the influence of geothermal development comes from production changes in 1991 that resulted in reservoir pressure declines of approximately 30 psi (~70 ft) at Casa Diablo (Sorey, 2005). Water levels in Hot Bubbling Pool, a 90°C (194°F) hot spring ~ 5 km (3mi) from the production facilities at Casa Diablo declined about 5 feet in 1991 when injection wells were deepened and production rates were increased at Casa Diablo. In contrast, springs in Hot Creek Gorge (Stop 5) some 10 km (6mi) east of Casa Diablo were unaffected by the 1991 pressure declines at Casa Diablo and have remained unaffected by the a decade of production.

Recent studies of spring flow, temperature and water chemistry at the Fish Hatchery have shown that no significant temperature changes have occurred in the mixed thermal and non-thermal warm springs in response to geothermal development at Casa Diablo. This appears to reflect the fact that hatchery spring temperatures are buffered by heat transfer between reservoir rock and fluid in the flow zone carrying mixed water from the Casa Diablo area to the Hatchery (Sorey and Sullivan, 2006).

Continue east on Hot Creek Road. Turn left (northwest) into the parking lot and public access area at the top of Hot Creek gorge.

***Incremental Distance** – 7.6 mi / 12.2 km* ***Cumulative distance** – 17.5 mi. /28.2 km*

Stop 5 – Surface Manifestations, Hot Creek

Figure 7. *Hot Creek Gorge view west (USGS photo).*

The most prominent hot springs and fumaroles in Long Valley are located at Hot Creek, Little Hot Creek, and the Alkali Lakes around the southern and eastern edge of the Resurgent Dome. The hot springs and fumaroles in Hot Creek Gorge (Figure 7) discharge ~250 L/sec of near-boiling water representing nearly 75% of the geothermal system's outflow. The creek cuts through a 288,000 year-old rhyolite flow that originated from a Moat Rhyolite dome 4 km to the south (Bailey, 1976; Bailey and others, 1989). The lower portion of the flow erupted into Pleistocene Long Valley Lake burying existing lake sediments and pervasively hydrating the rhyolite. Brecciated and perlitically altered flow units are exposed along the paved trail that leads down to the Hot Creek. Bailey (1976) described the Hot Creek flow as sparsely porphyritic, sanidine-augite bearing rhyolite; a composition slightly different from other hornblende-biotite rhyolites of the moat eruptive sequences. He interpreted the mineralogic difference as evidence that new mafic magma injections rejuvenated the Long Valley magma chamber, inflating the Resurgent Dome and initiating basaltic eruptions in the western caldera moat. Age dates on the hot spring mineralization indicate that part of the hydrothermal alteration common in Hot Creek Gorge resulted from a vigorous geothermal outflow from 300,000 – 100,000 years ago (Sorey and others, 1991).

Intense hydrothermal alteration and boiling (93^{o}C;199°F) springs at Hot Creek are localized along two north-striking faults that cut the rhyolite flow and form a small graben that contains the Hot Creek swimming hole. Smaller or cooler springs are localized along the contact between the flow and underlying lake sediments. Numerous earthquakes that occurred during caldera unrest in the 1980's commonly affected the flow of the springs. Additional boiling springs developed or were reinvigorated in May 2006 expanding beyond the protective fencing on the north side of the gorge. Changes in spring discharge were accompanied by temperature increases in nearby monitoring wells and pressure increases in adjacent cold-water aquifers in response to above normal precipitation in the preceding winter (Farrar and others, 2007). The swimming area remains closed as a precautionary measure.

Return to Hot Creek Road and retrace the route to Highway 395. Turn right (north) onto Highway 395. Continue north toward June Lake and pull off at the widened side of the highway east of Obsidian Dome.

***Incremental Distance** – 16.2 mi / 26.1 km* ***Cumulative distance** – 33.7 mi. / 54.3 km*

Stop 6 - Bishop Tuff, Northern Lobe

The Bishop Tuff eruption produced approximately 600 km^3 of rhyolite air fall and ash flow tuff evacuating the upper part of the Long Valley magma chamber causing the chamber roof to subside approximately 1-2 km creating Long Valley Caldera (Figure 8). Approximately ⅔ of the ash ponded within the caldera depression. Air fall ash from the eruption is recognized as far east as Kansas and Nebraska (Izett, 1982) and in deep sea cores from the eastern Pacific (Sarna-Wojcicki and others, 1987). Collapse of the eruption column produced as many as seven ash flow lobes that blanketed 1500 km^2 surrounding the caldera (Hildreth, 1979). The ash flow completely covered precaldera topography and is thickest near the margin of the caldera thinning at the northern and southern distal edges.

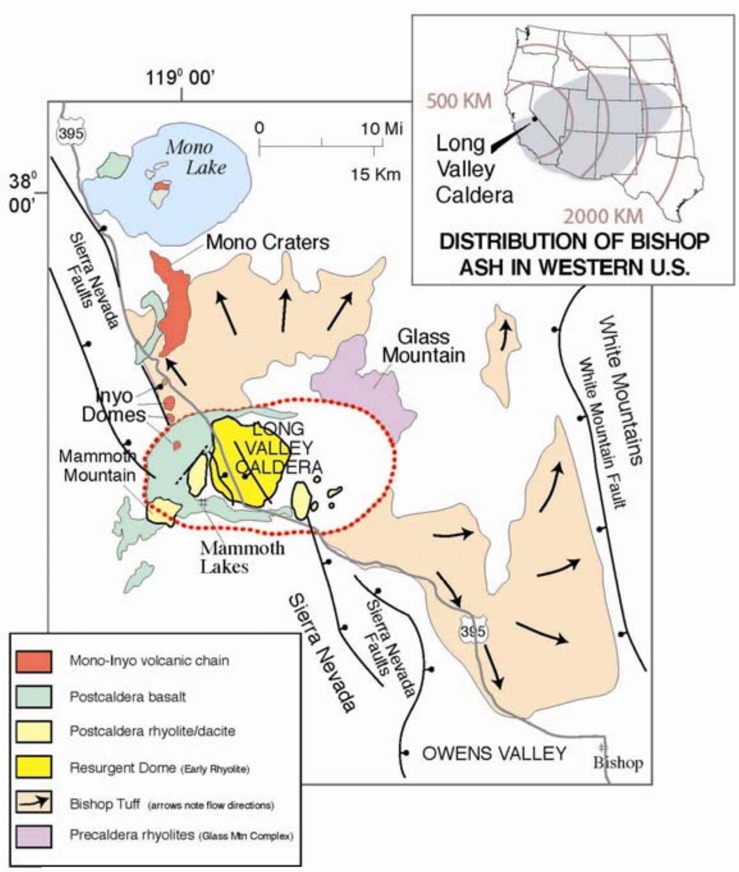

Figure 8. *Generalized geologic map of Long Valley Caldera and the extent of Bishop Tuff (USGS)*

The ash flow sheet at this stop is the moderately welded upper part of the northern Mono Basin lobe of the eruption (Hildreth, 1979). At least 75% of the original expanse of northern Bishop Tuff is covered by post caldera glacial outwash, Lake Russell/Mono Lake sediments and Mono Craters tephra. The Bishop Tuff outcrops in the Mono Basin are referred to as the Aeolian Buttes. The mineral assembly of quartz+sanidine+ biotite is typical of the Bishop Tuff. Hildreth (1979) noted that the mineral compositions within the tuff changed as the eruption progressively tapped deeper and hotter levels of the magma chamber. Calculated Fe-Ti oxide eruption temperatures of 756-790°C establish the Mono Basin lobe of the Bishop Tuff as the highest temperature phase of the eruption. Pumice fragments within the tuff are still relatively coherent here with little evidence of collapse or welding in this upper part of the ash flow sheet. Some lithic inclusions can be found in northern and eastern lobes of the tuff but are much more prevalent in southern ash flow lobes. Hildreth and Mahood (1986) interpreted rock types and lithic fragment amounts to indicate that the caldera forming eruption progressed from the south central margin near Lake Crowley counterclockwise to the north and west culminating on the northern caldera margin. Detailed stratigraphic studies and eruption modeling suggest that the Bishop Tuff eruption probably took a week or less (Wilson and Hildreth, 1997).

Most volcanic activity over the last 200,000 years has occurred in the western moat of Long Valley and over the last 50,000 years volcanism has occurred north of the caldera into the Mono Basin. Obsidian Dome across Highway 395 to the west is one of the Inyo Domes eruptive centers that poured thick pasty high-silica rhyolite lava to the surface 600 yrs ago along the Mono-Inyo volcanic chain. Pumice outfall from Mono-Inyo eruptions over the last 2,000 years mantles the Bishop Tuff outcrop at this location and extends over much of much of the area including the interior of the Mono Basin.

Continue north on Highway 395 toward the town of Lee Vining. Approximately .25 mi (400m) north of town, turn right on the access road to the US Forest Service National Scenic Area Visitors Center. Park in the parking lot.

Incremental Distance – *16.7 mi / 26.9 km* **Cumulative distance** – *50.4 mi / 81.2 km*

Stop 7 – Mono Craters Visitor Center

The Mono Craters National Scenic Area is operated by the Inyo National Forest and provides an excellent overview of Mono Lake and the Mono-Inyo volcanic chain. The Mono Craters are the result of several thousand years of volcanic activity that began ~40,000 years ago. At least 20 small volume eruptions have occurred along the chain over the past 5000 years at intervals of 250 to 700 years (Bursik & Sieh, 1989). The progression of eruptions over the past 2 Ma from Glass Mountain on the eastern margin of Long Valley Caldera to Mammoth Mountain on the west and the Mono–Inyo volcanic chain in the north suggests that the caldera's magmatic system has declined with time and has been supplanted by mixed composition eruptions from the active Mammoth Mountain–Inyo Domes magmatic system (Hildreth, 2004; Mahood and others, 2010).The progression of eruptions in the area did not end 600 years ago with Panum Crater or with the extrusion of the Inyo Domes. A shallow intrusion beneath Mono Lake ~250 years ago pushed up lake-bottom

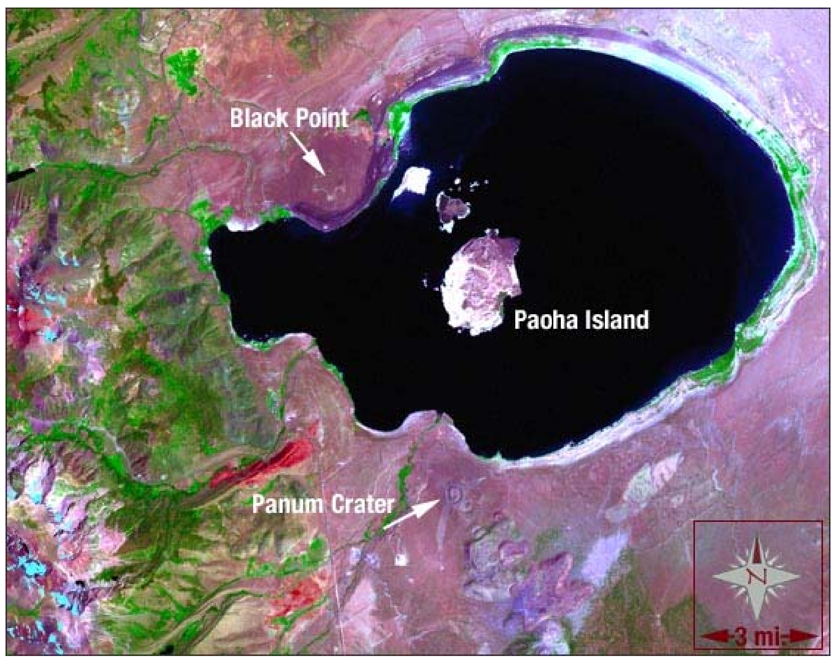

Figure 9. *False color satellite image of Mono Lake (NASA)*

sediments to form Pahoa Island (Figure 9) and produced a small volume of andesitic lavas from vents on the island's north side (Lajoie, 1968; Bursik & Sieh 1989). Mixed magma compositions are consistent with regional crustal extension in the Eastern California Shear Zone and the Mina Deflection connection to the Walker Lane to the northeast. Bursik (2003) suggested that dikes beneath the domes intrude a pull-apart structure to accommodate strain usually resolved in normal faulting.

The Eastern Sierra is also a key location for understanding regional glacial events over the last 2-3 Ma. Prominent lateral and terminal moraines along the Sierran range front west of the visitor's center are the result of the latest Tahoe (75,000 – 60,000 years) and Tioga (25,000 – 12,000 years) glacial advances and retreats during the late Pleistocene. The Casa Diablo till intercalated between ~200,000 year-old moat basalts in the southern caldera moat in Long Valley provide well-dated evidence of a Mid-Late Pleistocene 200,000 year-old glacial event that may also correlate with Mono Basin glaciation of similar age. The Sherwin till at Sherwin Creek underlies the Bishop Tuff and marks a glacial retreat approximately 800,000 years ago. Tills on McGee Mountain south of Long Valley are evidence of an earlier 2.5 Ma glaciation.

Table 1. *Correlation of glacial sequences in the Eastern Sierra (adapted from Lipshie, 2001)*

North American Continental Glacial Sequences	Sierra Glacial Sequences	Ages (years before present)
Post Wisconsin	Matthes Recess Peak Hilgard	0-700 2000-4000 9000-10,500
Late Wisconsin	Tioga	12,000-25,000
Early Wisconsin	Tenaya	~ 45,000
Illinoian	Tahoe	60,000 – 75,000
	Mono Basin Casa Diablo	~130,000 200,000(?)
Kansan	Sherwin	~800,000
Nebraskan	McGee	1.5 – 2.5 Ma

Mono Lake is the saline remnant of Lake Russell, an extensive freshwater lake that formed in the Mono Basin during Pleistocene glacial retreats. The glacial lake is named for Israel Russell who mapped and studied the region in 1881. He interpreted the moraines along the range front as evidence of at least two major glacial events in the Sierra, mapped the glacial lake shorelines and correlated the glacial advances with high water levels in Lake Russell, Lake Lahontan and Lake Bonneville elsewhere in the Great Basin (Russell, 1889). The shoreline terraces of Lake Russell extend to an elevation of 2188m (6948 ft) (Putnam, 1950) or roughly 302m (990 ft) above the present 1886m (6187ft) level of Mono Lake and are evident along the shore of the lake west of the visitor's center. The scarp along the western shoreline marks the Lee Vining Fault, one of several faults that are part of the Sierran range front fault system. Deformed uplifted shoreline terraces occur in Highway 395 road cuts along the western lakeshore exposing extensively deformed young lake beds along the fault scarp.

The predominant water source for Mono Lake is snowmelt from the creeks that flow into the Mono Basin from the Sierran range front. The Los Angeles Department of Water and Power acquired water rights throughout the basin and in 1941 began exporting water from Walker, Parker, Lee Vining and Rush creeks through an 18.5km (11.5mi) tunnel under the Mono Craters to the Owens River in Long Valley, and eventually to the Owens Valley aqueduct that extends 359 km (223mi) from Lake Crowley in Long Valley to the northern part of the Los Angeles basin. Other minor streams that drain into the closed basin contribute relatively small volumes of water. Without continued freshwater supply, evaporation eventually exceeded inflow. Lake levels declined more than 10 m and salinities began to rise. The total dissolved solid content (TDS) of Mono Lake water was 50,000 mg/ L in 1941 and at the lowest water level in 1982, salinity was 99,000 mg/L. The declining water levels eventually formed a peninsula on the north side of Negit Island exposing migratory bird nesting sites to predators. The expropriation of water was eventually restricted by court decisions and in 1994 the California State Water Resources Control Board ordered LADWP to release enough water to maintain the lake surface elevation at 1945m. The current lake level is ~2m below that elevation but Negit is once again an island and salinities are anticipated to stabilize around 70,000 mg/L.

Return to Highway 395. Turn left (south) to return to Mammoth Lakes. BEWARE OF TRAFFIC! Continue south to the intersection of Highway 120. Turn left (east) onto Highway 120. Drive approximately 3 mi. /5 km. and turn left (north) on the second dirt road that is poorly marked as the access to Panum Crater. Continue north approximately .5 mi. (.8 km) to the parking lot at the southeastern edge of Panum Crater.
***Incremental Distance** – 4.3 mi / 6.8 km*   ***Cumulative distance** – 54.7 mi. / 88 km*

Stop 8 – Panum Crater

Figure 10. *Panum Crater view southwest (USGS photo)*

Panum Crater is the farthest northern vent along the Mono-Inyo dike that erupted between AD 1325-1365 (Bursik & Sieh 1989). The vent is a textbook example of a rhyolite plug-dome volcano and this stop serves as the prime illustration of eruptive progressions common to the Mono-Inyo dike event 600 years ago. The tephra ring (Figure 10) is approximately .8 km in diameter and is composed of pumice, ash, lapilli, obsidian fragments and minor amounts of granitic or metamorphic fragments derived from underlying glacial deposits. Detailed studies by Sieh & Bursik (1986) indicate that phreatic explosions cleared the throat of the Panum eruptive center and progressed to pyroclastic flow and surge deposits that constructed the outer tephra ring and eventually extruding a high-silica rhyolite dome as magma made it to the surface. Stratigraphy of the surrounding pyroclastic deposits indicates two periods of explosive activity from the same eruptive center. The northern part of an early rhyolite dome apparently exploded or collapsed producing a block avalanche deposit to the northwest into Mono Lake (Wood, 1977; Sieh & Bursik, 1986).

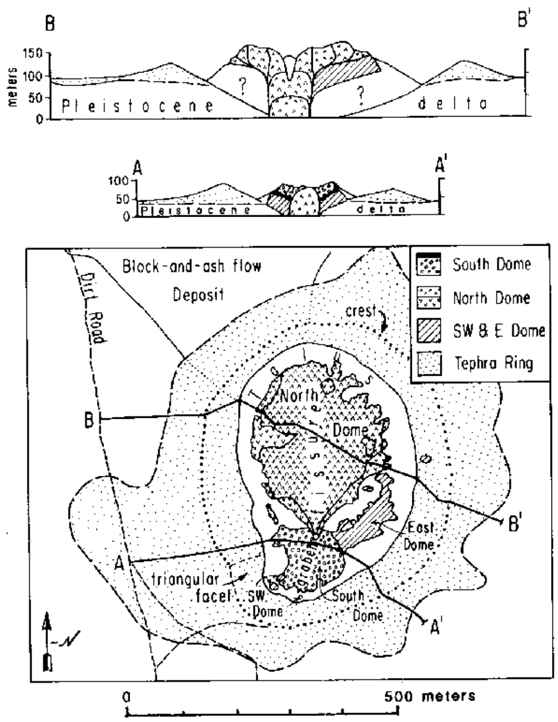

Figure 11. *Generalized map and cross-sections of Panum Dome (from Sieh and Bursik, 1986)*

Later pyroclastic airfalls healed the breach of the tephra ring and a composite dome was built by further intrusions (Figure 11). Panum rhyolite has a silica content of 75% and the rocks in the dome interior grade from highly pumiceous to dense obsidian. The flow textures within the dome illustrate the complex composite nature of dome formation. Breadcrust textures are common where viscous rhyolite surfaces cooled and degassed.

Eruptive styles along the Mono-Inyo dike are apparently controlled by magma type and depth of penetration into the shallow crust as well as variations in country rock and groundwater. Portions of the dike that intruded local groundwater may have fragmented producing phreatic explosion craters like the Inyo Craters and the phreatic craters on the north face of Mammoth Mountain without surface extrusions. Early phreatic eruptions at Panum Crater cleared the path for later magma to make it to the surface and eventually build the rhyolite dome in the center of the tephra ring. The eruptive progression continued at other places along the dike producing high-silica rhyolite flows that overrode tephra deposits producing the Inyo Domes ~ 550 years ago (Miller 1985).

Exit the parking lot and return to Highway 120. Turn right (west) on Highway 120 toward Highway 395. At the intersection with Highway 395, cross the freeway (BEWARE OF TRAFFIC!) and turn left (south) on Highway 395 heading toward June Lake Junction and Mammoth Lakes. Enter Long Valley Caldera at Deadman Summit. Continue south on Highway 395 toward Mammoth Lakes. Approximately 3.2 km (2 mi.) past the Crestview highway maintenance station, turn right (west) onto Mammoth Scenic Loop/Dry Creek Road. Continue approximately 4.8 km (3 mi.) to the intersection with Inyo Craters Road (tiny wooden sign). Turn right (north) onto Inyo Craters road and continue ~ 1.8 km (1.1 mi.) onto the dirt portion of the road north past several cross roads to the Inyo Craters parking lot. The trail to the craters is on the northwest side of the parking lot and wanders approximately 500 m (.3 mi.) northwest through the forest to the base of the craters.

***Incremental Distance** – 24.2 mi / 39 km* ***Cumulative distance** – 78.9 mi. / 127 km*

Stop 9 – Inyo Craters

The Inyo Craters were created by phreatic explosions approximately 600 years ago (Bursik & Sieh 1989) (Figure 12). The magma source for these eruptions is an 8–10km (5-6 mi)-long dike that trends north out of the caldera. Phreatic craters occurred where the dike encountered groundwater and extend from the north flank of Mammoth Mountain (across the parking lot south of the Mammoth Mountain Inn) to the Mono Basin. Dome-forming eruptive events occurred where magma made it to the surface at the north end of the Mono Craters (see Day 2, Stop 3) and south within Long Valley Caldera at the Inyo Domes immediately north of the craters.

Figure 12. *Inyo Craters, view north to Deadman Dome (USGS photo)*

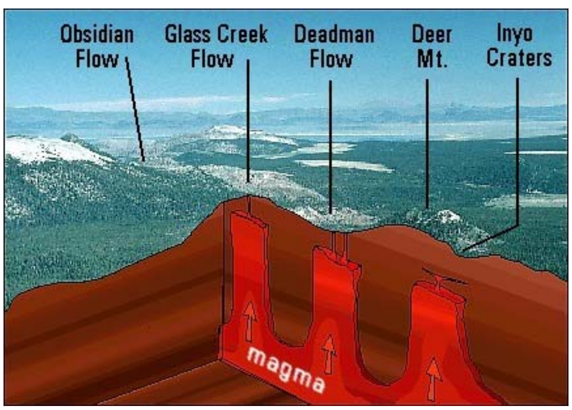

Figure 13. *Conceptual diagram of the Inyo dike (USGS adaptation after J. Fink)*

The Inyo Craters are aligned north-south along the presumed strike of the Inyo dike (Figure 13). Two southern craters are approximately 200m across and 60m deep and contain small cold (11^{o}C; 52°F) lakes that show no evidence of thermal influence. The color of the water in each lake is the result of differing types of algae or organic matter. A phreatic eruption also excavated a small northern crater at the summit of Deer Mountain, a 115,000 year-old moat rhyolite dome similar in age composition to the rhyolite plateau north of the Town of Mammoth Lakes. The light colored phreatic explosion debris at the summit (Figure 12) is fragmented hornblende rhyolite that composes the dome and the darker debris around the two lower craters is predominantly andesite derived from underlying flows exposed in the walls of the southern crater (Bailey and others, 1989). The stratigraphy exposed in the craters includes andesite flows overlain by a thin (1m) layer of Inyo Craters pumiceous rhyolite tephra overlain by a succession of poorly sorted phreatic explosion debris. Based on detailed stratigraphic studies Mastin and Pollard (1988) determined that the craters erupted from north to south with light-colored explosion deposits from Deer Mountain summit overlain by dark debris from the middle crater in turn overlain by darker debris from fragmented andesites underlying the southern crater. Phreatic debris from the southern crater extends as far as 1km (.6 mi.) to the northeast and includes granitic and metamorphic fragments probably from underlying till or basement rocks.

The Inyo Craters lie within a small .6 km wide graben defined by numerous faults and fissures with as much as 20 m of displacement extending 1.5 mi. /2.5 km north and south (Figure 14). Similar fissure and fracture zones are common in the western moat of Long Valley Caldera (see Stop #2) and control similar phreatic eruptive centers. Phreatic eruptions were widespread along the Mono-Inyo dike and numerous equally impressive but less accessible craters occur to the north and west of the Inyo Craters that do not conform to a uniform north-south orientation.

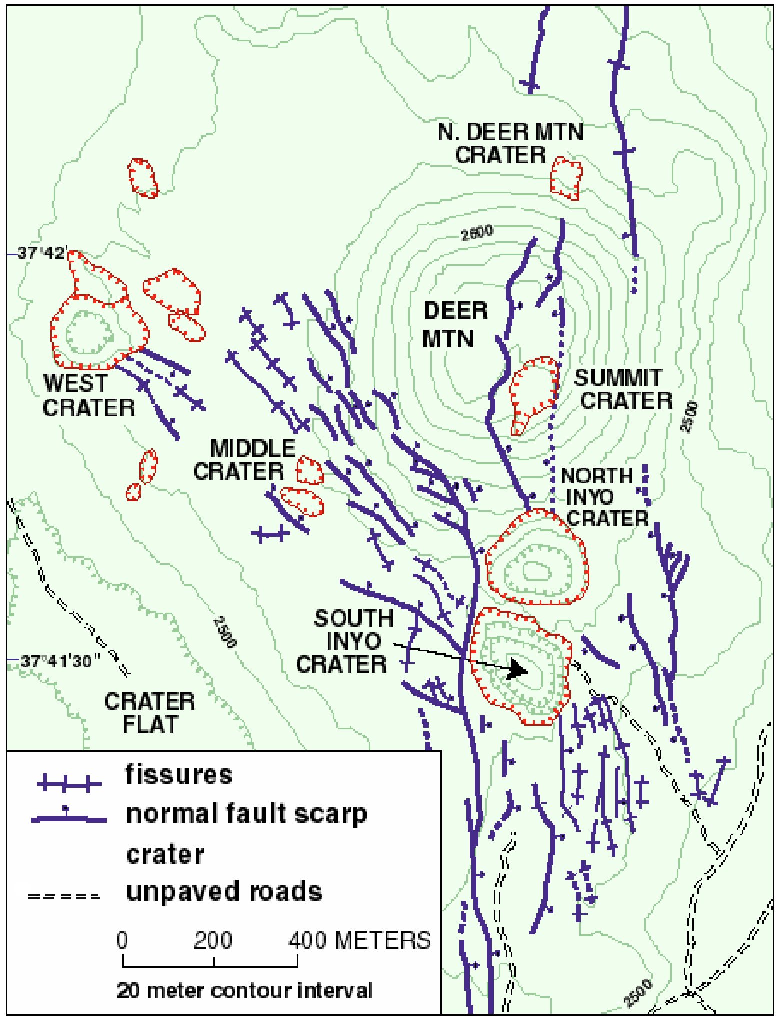

Figure 14. *Generalized map of faults and ground cracks around the Inyo Craters (After Mastin and Pollard, 1988)*

A series of DOE -funded core holes penetrated and sampled the Mono-Inyo dike inside and outside the caldera. The RDO-4 corehole was drilled from the top of the fault scarp on the western side of the south Inyo Crater at an angle of 68°, penetrating 320m (1050 ft) of post caldera andesites and basalts, 50m of gravel, 360m of Early Rhyolite tuffs and flows, 63m of glacial till bottoming in 30m of Sierran metamorphic rocks (Figure 15) (Eichelberger and others, 1988). The highest temperature in the hole was 81°C (178°F) at 500m (1640 ft). The hole encountered limited amounts of juvenile high-silica rhyolite and vent breccias of Early Rhyolite and andesite directly under the southern crater. 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).

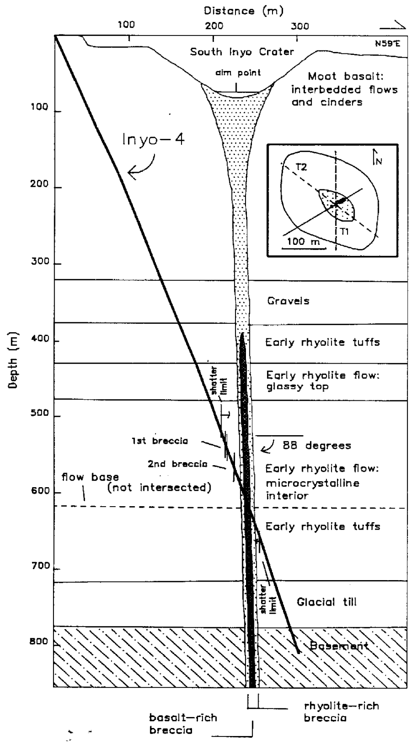

Figure 15. *Inyo-4 core hole (from Eichelberger and others, 1988)*

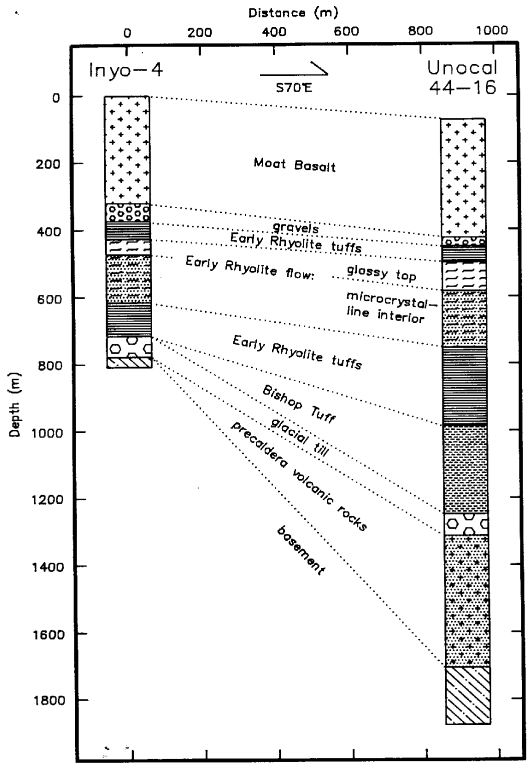

Figure 16. *Stratigraphic correlations between the Inyo-4 corehole and IDFU 44-16 adjacent to the western ring fracture system of Long Valley (From Eichelberger and others, 1988)*

The hole also helped establish the location of the structural margin of the caldera. Unocal drilled well 44-16 in 1985-86 approximately 1 km (0.6 Mi) west of the Inyo Craters to test the geothermal potential of the western caldera moat. While 44-16 is the hottest well drilled in Long Valley (218°C at 1100m)(424°F; 3608 ft) it could not sustain production because a strong incursion of cold water penetrates beneath a thin section of Bishop Tuff reservoir rocks (Suemnicht, 1987). Between the two wells, the caldera's ring fracture system offsets the metamorphic rocks of the caldera floor by approximately 1km in less than 1km lateral distance (Figure 16). As with many calderas, the structural margin of the ring fracture system can be considerably different from the topographic margin or rim of the caldera that we see today.

Retrace the route on Inyo Craters Road to Mammoth Scenic Loop. At the intersection, turn right (west) and continue southwest to the end of the Scenic Loop at Minaret Summit Road (Highway 203). At the intersection, turn right (west) on Highway 203 and drive approximately 1.5 mi. /2.4 km to the Mammoth Mountain parking lot.

Incremental Distance *– 7.3 mi / 11.8* km ***Cumulative distance*** *– 82 mi. / 138.7 km*

END OF TRIP