APPENDIX D

Geologic and Geothermal Resources Technical Report

This page intentionally left blank

Technical Geologic Overview of Long Valley Caldera for the Casa Diablo IV Geothermal Development Project

Prepared for:

Geologica Inc.
5 Third Street, Suite 224
San Francisco, CA 94103

ESA
550 Kearny Street, Suite 800
San Francisco, CA 94108

October 29, 2012

By
EGS Inc.
3883 Airway Drive, Ste 210

EGS INC

This page intentionally left blank

Table of Contents

1 Introduction 5

2 Regulatory Framework 6

3 Geology, soils and minerals 6

3.1 Geologic Background 6

3.2 Structure 8

3.3 Seismic Setting 8

3.3.1 Seismic Hazards 9

3.3.2 Faulting and Surface rupture 9

3.3.3 Ground shaking 10

3.3.4 Liquefaction 10

3.3.5 Induced Seismicity 11

3.4 Slope stability 11

3.5 Subsidence 12

3.6 Volcanic Hazards 13

3.6.1 Eruptive Potential 14

3.6.2 Eruption effects 15

3.6.3 Magmatic Gases 16

3.7 Soil Resources 17

3.8 Mineral Resources 18

4 Surface Water and Shallow Cold Groundwater 18

4.1 Surface water 19

4.1.1 Mammoth Creek/Hot Creek 19

4.1.2 Basalt Canyon drainage 20

4.1.3 Murphy Gulch drainage 20

4.2 Shallow cold groundwater 21

4.2.1 Shallow groundwater quality 22

5 Geothermal resources 24

5.1 Long Valley geothermal resource 25

5.1.1 Hot Springs and Fumaroles 25

5.1.2 Geochemistry 27

5.1.3 Geothermal exploration 32

5.1.4 Geothermics 33
5.2 Long Valley conceptual model 34
5.2.1 Long Valley geothermal development 35
5.3 Project plans 36
5.4 Long Valley hydrologic monitoring 36
5.4.1 Early development monitoring 37
5.4.2 Recent development monitoring 38
5.5 Thermal/non-thermal hydrogeology in Long Valley 39
6 Conclusions 42
7 References 45
Figures 53
Tables 91

List of Figures

Figure 1 - Location map of Long Valley Caldera and the CD-IV Project area 54
Figure 2 - Generalized geology of Long Valley Caldera (after Bailey, 1989) 55
Figure 3 - Locations ages and types of eruptive events in the Mono-Inyo volcanic zone (from USGS) 56
Figure 4 - 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) and predominant regional tectonic features. 57
Figure 5 - Quaternary and Recent faults in the Long Valley region from USGS (http://earthquake.usgs.gov/hazards/qfaults/) 58
Figure 6 - Long Valley seismicity and uplift. 59
Figure 7 - Inyo Craters, part of the Mono-Inyo Craters volcanic chain, stretch northward across the floor of long Valley Caldera approximately 7 km north of he CD-IV project area. 60
Figure 8 - Thickness of volcanic ash from eruptions <500 yrs old along he Inyo volcanic chain. 61
Figure 9 - Areas potentially affected by pyroclastic flows from vents in the LVC and vicinity: Potentially impacted area South Moat vent is pink, from Inyo crater potential vents, is orange. Map from USGS website: http://volcanoes.usgs.gov/lvo/hazards/pfzone_bot 62
Figure 10 - NRCS soil classifications for Long Valley 63
Figure 11 - Mammoth Groundwater basin from Wildermuth (2009). Water production wells are located close to the Town of Mammoth Lakes. All of the existing geothermal wells are drilled east of well RDO-8. 64
Figure 12 - USGS Hydrologic monitoring points in Long Valley 65
Figure 13 - Light stable isotope data for groundwater and thermal water in Long Valley Caldera 66
Figure 14 - Distribution of the landslide block of Paleozoic metasedimentary rocks from the southern rim of Long Valley caldera. 67
Figure 15- Monitoring well locations in Long Valey (after Sorey, 2010). 68
Figure 16 - Comparative hydrographs for shallow non-thermal groundwater monitoring wells M-14, ESN, SC-2, 1995-2010. 69
Figure 17- Comparative hydrographs for groundwater monitoring wells ESN and SC-2 and thermal monitoring wells CW-3 and RDO-8, 1995-2010. 70
Figure 18- Contours of water level elevations in MCWD wells of the Mammoth Basin. 71
Figure 19- Cl/B ratios and temperatures for various types of cold and hot waters sampled in the Long Valley caldera. 72
Figure 20- Hydrothermal manifestations in Long Valley caldera. 73
Figure 21 - Helium isotope variations in Mammoth Mountain fumaroles after earthquake swarms and potential dike injection at depth. 74
Figure 22 - Geothermal wells at Casa Diablo (after CDOGGR, 2012; ftp://ftp.consrv.ca.gov/pub/oil/maps/Geothermal/G1-1.pdf). 75
Figure 23 - Long Valley wells penetrating the Bishop Tuff (orange) or the caldera floor (red). 76
Figure 24 - Temperature distribution in Long Valley Caldera from geothermal well records (CDOGGR) or published temperature data (Farrar and others, 2010). 77

Figure 25 - Wellbore schematic for Unocal Mammoth -1 at Casa Diablo. 78
Figure 26- Total flow rate and production reservoir pressure at Casa Diablo from 1985 to 1995. 79
Figure 27 - Mass flow from Casa Diablo wells versus pressures in well 65-32 from 1995 to 2010. 80
Figure 28 - Comparisons of seasonal variations in pressure and water level in thermal monitor wells 65-32 at Casa Diablo, non-thermal wells SC-2 in the Mammoth Groundwater Basin and monthly precipitation, 1995-2010. 81
Figure 29 – Total mass flow to the Casa Diablo power plants versus pressures in well 65-32 from 1995 until 2010. 82
Figure 30 - Long-term plots of pressures in wells ESN (Elementary School New) and 28-34 and CW-3 and Hot Bubbling Pool from 1995-2010 relative to the onset of production from Basalt Canyon (2006) 83
Figure 31 - Pressure histories of ESN, 28-34 and CH 10B 10 km east of Casa Diablo 1995-2010. 84
Figure 32- - Long-term pressure histories in geothermal monitoring wells 66-31 and 65-32, 1995-2010 (unreliable data noted). 85
Figure 33 - long-term pressure histories of geothermal monitoring wells RDO-8 and 48-29 completed in the deeper Bishop Tuff injection reservoir in Long Valley, 1995-2010. 86
Figure 34 - Pressure monitoring data 2005-2010 for geothermal monitoring wells12-31 completed in western Bishop Tuff production reservoir in the Basalt Canyon area and 48-29 completed in the eastern Bishop Tuff injection reservoir north of Casa Diablo. 87
Figure 35 - Lithologic columns of western caldera wells showing a landslide block of impermeable Paleozoic rocks in wells 12-31 and Mammoth-1 but absent in corehole RDO-8 father west. 88
Figure 36 - Composite pressure monitoring records for eastern caldera monitoring wells. 89

List of Tables

Table 1 –Summary of Long Valley hydrologic monitoring data for Mammoth Creek/Hot Creek 92

Geologic Overview of Long Valley Caldera
Potential Environmental Impacts

1 Introduction

Long Valley Caldera in eastern California has been explored for geothermal resources since the 1960s. Early exploration wells less than 1000ft (<300m) were drilled around Casa Diablo near the most prominent hot springs and fumaroles on the southwest flank of the Resurgent Dome (Figure 1). Deeper exploration wells were drilled to evaluate early federal lease offerings in the central caldera and later a portion of the caldera west of the Resurgent Dome. Well data established 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 current hydrothermal system is more complex with shallow production at Casa Diablo supplied by upflow and outflow from a geothermal source beneath the western caldera moat.

EGS has been retained by Geologica, Inc., to provide background data for ESA in preparing the environmental documentation required to assess the potential geologic and hydrogeologic impacts of the planned expansion of geothermal production. This report addresses geologic and hydrogeologic considerations in preparing an EIS/EIR including:

- Geology, soils and minerals
- Geologic hazards
- Seismic hazards
- Faulting/surface rupture
- Ground shaking
- Slope stability
- Liquifaction
- Volcanic hazards
- Surface water and shallow groundwater
- Hot springs and fumaroles
- Geothermal resources
- Geothermal system evolution
- Geothermal development
- Conceptual basis for numerical modeling

This review is based on relevant background geologic reports and geothermal exploration experience in Long Valley Caldera. Additional drilling and exploration inherently yields new knowledge or unanticipated results. All of the geologic issues that could result in significant impacts related to expanded geothermal production may not have been identified or may require additional analysis in the future.

2 Regulatory Framework

Agencies involved in project permitting in Long Valley include:

U.S. Forest Service

The Pacific Southwest Region (Region 5) of the U.S. Forest Service adopted a set of best management practices for the protection of water quality and the prevention of soil erosion (USDA, Forest Service 2000). Included is the requirement for the preparation of an erosion control plan to limit and mitigate erosion and sedimentation.

State of California

The Alquist-Priolo Earthquake Fault Zoning Act (CGS, 2012) prohibits the location of most structures for human occupancy across the traces of active faults. The State Geologist (Chief of the California Division of Mine and Geology) is required to identify "earthquake fault zones" along known active faults in California. Counties and cities must withhold development permits for human occupancy projects within these zones unless geologic studies demonstrate that there would be no problems.

Mono County

County administration has adopted the 2001 California Building Code (replacing the "Uniform Building Code"). Among other elements, this code dictates the design and construction standards applicable to resist seismic shaking.

3 Geology, soils and minerals

The Project Site is located in the Long Valley Caldera, a 17 X 32 kilometer (km) topographic depression created approximately (~) 760,000 years ago by the eruption of an estimated 600 km^3 of rock (Bishop Tuff) (Figure 2 after Bailey, 1976). The topographic floor of the caldera slopes from ~8,500 feet above sea level (asl) in the west across uplands and hills in the west and central part of the caldera to a relatively flat alluvial plain at approximately 6,700 feet at Lake Crowley on the east. The caldera's topographic walls reach elevations of 9,800 at Glass Mountains on the northeast to 11,500 feet in the Sierra Nevada on the south and west.

3.1 Geologic Background

Long Valley 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. Complex volcanic, tectonic and glacial processes have controlled the caldera's formation and shaped the surface features of the caldera. Volcanism associated with Long Valley began ~ 4 million years ago with widespread eruptions of intermediate and basaltic lavas accompanying the onset of large-scale normal faulting that formed the eastern front of the Sierra Nevada and the Owens Valley graben (Figure 2). Discontinuous erosional remnants of these precaldera extrusive rocks are scattered over a 4000 km2 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 2). The caldera-forming Bishop Tuff eruption partially evacuated the underlying magma chamber and the floor of the caldera subsided along semicircular systems of ring fractures that define the structural margin of the caldera. Approximately 350-400 km^3 of the Bishop Tuff filled the caldera depression and is the deeper potential geothermal reservoir within the caldera.

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 2). 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; Bailey and others, 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 part of the 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 south of the caldera. A series of rhyodacitic eruptions also occurred in the western caldera moat 110,000 – 50,000 years ago; the most prominent of these is Mammoth Mountain on the southwestern topographic rim of the caldera (Bailey 2004). The main bulk of the mountain was formed in less than 2,000 years (Mahood and others, 2010) and 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 3). 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 km^3) within the chain over the past 5000 years. The most recent dome-forming eruptive events occurred at the north end of the Mono Craters about 600 years ago (Bursik & Sieh 1989) and along the south end of the Inyo Domes about 700 years ago (Sorey and others, 1998). The magma source for these eruptions is an 8–10-km-long dike that trends north out of the caldera. 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 mixed composition eruptions from the active Mammoth Mountain–Inyo Domes magmatic system (Hildreth, 2004).

The Project site is located in western caldera moat and within the ring fracture system that defines the southern and western boundary of the caldera. The Project site is located in the northern part of the Mammoth Creek drainage that flows through the southwestern caldera moat and includes the seasonal drainage of Basalt Canyon and Rhyolite Plateau upland north of the Town of Mammoth Lakes (Figure 5).

3.2 Structure

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 4) (Hill, 2006). Transtensional deformation and active magmatism within the Eastern California Shear Zone are attributed to distributed right-lateral slip that accounts for 15 - 25% of the relative motion between the Pacific and the North American plates (Dixon and others. 2000). The region remains tectonically active. The USGS Quaternary Fault Database and the California Geologic Survey mapping identifies numerous faults that have been active in recent times based on offset glacial till or alluvial units within and outside the caldera (Figure 5).

The structural floor of the caldera is composed of Paleozoic metasedimentary rocks and Mesozoic crystalline intrusive rocks segmented into a number of discrete blocks with varying offsets. Extensional strain is complexly resolved within the caldera because of the inherited older crustal faulting and fracturing that defined the pre-existing Sierran range front embayment and accommodated 1-2 km of subsidence as the caldera's floor foundered. 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 (Suemnicht and Varga, 1988).

3.3 Seismic Setting

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). The Project site is located in a broad region of active and potentially active fault zones identified in the USGS Quaternary Fault Database (USGS, 2006) and in seismic hazard maps compiled by the California Division of Mines and Geology (CDMG, 2005) (now California Geologic Survey).

Beginning in the late 1970s, Long Valley Caldera began a period of unrest that included earthquake swarms, approximately 80 cm of inflation over approximately 4 km^2 within the resurgent dome, changes in the outflow from hot springs and fumaroles and increased carbon dioxide (CO_2) emissions around the flanks of Mammoth Mountain (Figure 6). 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 included four M>6 earthquakes within and around the caldera on May 25, 1980.

3.3.1 Seismic Hazards

Long Valley caldera remains a tectonically active area. The Hilton Creek fault that deforms the southeastern caldera margin and splays across the Resurgent Dome is a significant range-bounding normal fault along the eastern side of the Sierra Nevada and is one of the most studied faults within the Sierra Nevada-Basin and Range boundary zone (USGS, 2006). Exploratory indicates the fault is characterized by down-to-the-east normal displacement and it offsets late Tioga lateral moraines and outwash deposits that are ~10,000 years old. Surface-fault rupture along the Hilton Creek Fault was associated with four M 6+ earthquakes that occurred in May 1980 (Taylor and Bryant, 1980). Latest Pleistocene vertical slip rates range from 0.9 mm/yr to 4.2 mm/yr (USGS, 2006).

3.3.2 Faulting and Surface rupture

The Geologic Map of Long Valley (Bailey, 1989), Mt. Morrison Earthquake Fault Zoning Map (CDMG, 1982) and the USGS Quaternary Fault database identify several Quaternary-Recent-Historic north-northwest trending fault zones within the Project area (Figure 5). The CDMG evaluated the effects of the 1980 period of seismic unrest and identified ground cracks and minor fault offsets within the Resurgent Dome northeast of the project area and the north-northwest striking Taylor-Bryant fault zone crossing the junction of Route 203 and Highway 395 just west of the existing MP-I power plant (Sherburne, 1980). Additional north striking faults deform the Rhyolite Plateau north of the Project area in the vicinity of proposed well 55-31 (CDMG, 1982; EMA, 2005).

The principal damage risk of surface fault rupture (exclusive of induced slip or settling) is deformation or offset along the actual location of a fault break. To avoid those potential risks, California's Alquist-Priolo act was passed in 1972 and both State and Federal geologic surveys have worked to identify faults the represent the greatest risk of near-term movement and surface rupture. The fundamental design criteria for earthquake stability and seismic hazard avoidance were in place when the current G-1 plant was built in 1985. The existing G-1 plant at Casa Diablo has not had a significant seismicity related problem despite nearly three decades of continued seismic unrest and multiple locally felt earthquakes in and around Casa Diablo. Engineering studies completed in advance of a proposed M-1 replacement plant identified a <u>suspected</u> fault and "has no evidence of 1980 or even Holocene (*within the last 10,000 years*) movement," The trenching revealed "no direct evidence of faulting," based on the lack of deformation in Pleistocene (1.8 million to 10,000 year old) sediments (Black Eagle Consulting, 2011). While engineering work for the planned CD-IV facility has not been completed, the planned plant site is less than 0.5 mi (0.8km) northwest of the trenching locations for the M-1 replacement plant along the same fault trend that should have a similar movement history.

3.3.3 Ground shaking

Proximity and composition of subsurface materials affect the potential for ground shaking during an earthquake. California permitting agencies set suitable levels of protection for the peak ground acceleration anticipated at individual project sites. The closer the site is to an epicenter location, the more severe the impacts of ground shaking. Wells within and adjacent to the Project area penetrate a thin section of poorly consolidated poorly sorted coarse alluvial, colluvial or till units that have the potential for substantial seismic ground shaking related to soft soil/rock conditions. Quantitative analysis of in-situ liquefaction or earthquake induced slide potential requires site-specific assessment of ground shaking levels. There is a ten percent probability that the peak ground acceleration from an earthquake will be between 40 to 50 percent of gravity in the next 50 years (EMA, 2005).

Project Impacts

The planned Project will fully comply with all applicable building codes including planning and construction for seismic hazards. The completed engineering studies comply with the requirements of the Alquist-Priolo Act and document that no definitive active faults could be identified within the area of the planned facility. Trenching for foundation engineering is now a standard method for determining as conclusively as possible the presence of an active fault. Under the Alquist Priolo Act, "an active fault is one that has ruptured in the last 11,000 years" (CGS, http://www.conservation.ca.gov/cgs/rghm/ap/Pages/main.aspx). In accord with the general US Geological Survey definition: "Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years" (USGS, http://earthquake.usgs.gov/learn/glossary/?term=active%20fault).

As noted (Section 3.3.2 *Faulting and Surface Rupture*), the project site is within a region of Quaternary-Recent faulting that the California Geologic Survey with the greatest risk of ground shaking resulting from a major earthquake (CDMG, 2005). The existing Casa Diablo plants have operated since 1985 through a peak period of earthquake swarms and three decades of sustained seismic unrest within the caldera without any significant ground shaking effects.

3.3.4 Liquefaction

Liquefaction, or the conversion of soils from a solid state to a more liquefied state, can occur in areas of a shallow groundwater table where unconsolidated sediments or poorly consolidated rock units are saturated at shallow (<10ft; <3m) levels. Neither condition occurs in the project area. Lithologic logs from groundwater wells within and adjacent to the Project area indicate the area is underlain by a thin section of poorly consolidated poorly sorted coarse alluvial, colluvial or till units that are unsaturated because water table depths are 50 -150 ft. (15-45 m) below the ground surface.

Project Impacts

Liquefaction from ground shaking during a seismic event is highly unlikely based on soil conditions within the project area. The existing Casa Diablo plants have operated since 1985 through a 20-year

period of peak earthquake activity within the caldera and at Casa Diablo without any liquefaction events. Project plans specifically avoid potential areas of saturated soils such as wetlands or minor topographic lows that might accumulate seasonal runoff.

3.3.5 Induced Seismicity

Increased levels of seismic activity can occur around developed geothermal fields and is one form of induced seismicity (Majer and others, 2007). The induced events are typically small (M<3.0) and are not generally felt (Majer, 2011). Long Valley is a seismically active area and swarms of earthquakes have occurred within and outside of the caldera during the period of seismic unrest following a series of M6± earthquakes in 1980. Brief flurries of small (M<2.3) earthquakes beneath the north flank of Mammoth Mountain were triggered by the M=7.2 Hector Mine earthquake of 16 October 1999 (epicentral distance ~ 420 km). Surface wave propagation from the M=7.9 Denali Fault earthquake of November 3, 2002 (epicentral distance ~ 3 460 km) also triggered microearthquakes beneath the south flank of the mountain (Prejean and others, 2004). Remotely triggered earthquake swarms could be related to a variety of physical processes. Similarly timed remotely triggered events occurred in Yellowstone, The Geysers and Coso implying some relationship with changes in the existing hydrothermal systems and active transport of hydrous fluids in the crust (Hill & Prejean 2005).

Project Impacts

Given the high level of background seismicity in the region, induced seismicity directly related to geothermal activity has not been observed in the extensive records compiled from the regional and local seismic network established to monitor caldera unrest. Known induced seismicity within the caldera has been limited to remotely triggered swarms common to other hydrothermal systems. Seismic unrest within the caldera has declined since the 1990's. Few if any microearthquakes are currently detected on regional or local USGS monitoring networks (http://earthquake.usgs.gov/earthquakes/recenteqsus/Maps/special/Long_Valley.php) and none can be directly linked to geothermal development at Casa Diablo despite continued production and injection through and beyond the period of seismic unrest.

3.4 Slope stability

Slope instability could be related to shallow soil development, the presence of excess water, or a lack of shear strength at the soil/rock interface or in the soil itself. Seismicity, combined with these pre-existing instabilities, could trigger landslides, earthslip or mudflows.

Project Impacts

There are no known unstable slopes in the immediate vicinity of the project site.

3.5 Subsidence

Land subsidence is the loss of surface elevation as a result of the removal of subsurface support caused by a variety of natural mechanisms or human activity. One common cause of land subsidence is the removal subsurface fluids from underground reservoirs without replacing the extracted volume. Since geothermal production removes fluid from an underlying reservoir and can result in minor amounts of subsidence or inflation depending on the type of geothermal resource and the reservoir management strategy for a specific resource. One of the major factors in declaring a volcanic hazard alert for Long Valley was the ~80cm of measured uplift across the caldera's Resurgent Dome potentially related to magma intrusion. Subsidence of ~25 cm was also noted in the vicinity of Casa Diablo from the same monitoring surveys (Farrar and others, 1995; Howle and others, 2003). The subsidence was superimposed on the general pattern of uplift that began in 1980 so that actual land surface elevations at Casa Diablo remained relatively constant with subsidence nearly balanced by uplift. The U.S. Geological Survey related the subsidence to geothermal production from the comparatively shallow outflow reservoir at Casa Diablo (Howle and others, 2003). Increased production withdrawal for expanded production has the potential for inducing additional subsidence.

Project Impacts

Subsidence is not been considered an important environmental consequence for geothermal development in Long Valley because of the minimal amount of documented movement at Casa Diablo, the small affected area compared to the overall deformation across Long Valley and the known variability of deformation events during unrest in volcanic areas (Hill, 2006). Measured subsidence rates for Casa Diablo averaged 25 mm/year that is less than other developed geothermal systems (Mossop and Segall, 1997; Allis and others, 2009) and considerably less than subsidence rates in regions of extensive groundwater extraction (Poland and Lofgren, 1984). Notably, as with repeated inflation/deflation events of much greater magnitude in other well-studied active caldera complexes such as Yellowstone and Campi Flegri in Italy, calderas do experience complex inflation and subsidence during periods of unrest (Hill, 2006). Neither Yellowstone nor Campi Flegri or any one of many other volcanic centers experiencing complex deformation events are linked to geothermal production. The well-documented unrest in Long Valley caldera has been episodic and not necessarily uniform. Recent deformation within the resurgent dome in the west central part of Long Valley caldera has been punctuated by periods of abrupt rapid uplift, relative quiescence and even minor subsidence (Hill, 2006). The leveling data are not necessarily a uniform record and although early USGS short baseline leveling studies around Casa Diablo document the amount of subsidence in a noisy record was less that 25% of the total uplift noted across the resurgent dome.

The potential for subsidence is reduced by the differing reservoir conditions across the caldera and modern geothermal field management practices of developing the reservoirs in stages and complete return of all the produced fluid to the subsurface to avoid large-scale and irreversible effects on surface features and resource sustainability. Caldera deformation, particularly subsidence at Casa Diablo, has been discontinuous since 1988 and the record of deformation across the entire caldera including Casa

Diablo has not necessarily been constant or uniform (Langbein, 2003). The USGS observed that the apparent amount of subsidence was limited and spatially related to the producing area around Casa Diablo. Interpretations related the minor amount of subsidence to a combination of thermal contraction in the deeper 700m deep injection zone and slow pressure declines in the shallow 200m deep production zone (Farrar and others, 1995; Langbein, 2003). Later USGS publications on the Casa Diablo field also suggest alternative mechanisms for the subsidence such as comparatively shallow effects like changes in shallow unconfined aquifers and the slow dewatering of relatively compressible, porous sediments and hydrothermally altered volcanic tuffs or tuffaceous sediments that underlie the topographic low of the structural graben that contains most of the Casa Diablo development (Howle and others, 2003). The shallow effects are part of the changes limited to the early production history of the field and are not necessarily continuous or continuing. The USGS continues to monitor deformation with fixed global positioning system (GPS) stations and 2-color geodimeter instruments (http://earthquake.usgs.gov/monitoring/edm/longvalley/continuous.php). Records for the monitoring station nearest Casa Diablo indicate vertical displacement in the area has been relatively stable and within the last year has begun to rise in response to a more recent minor inflation event within the Resurgent Dome.

The planned development into Basalt Canyon will produce from a much deeper reservoir in indurated Early Rhyolite and Bishop Tuff which should reduce the effect of changes in shallow aquifer conditions and relatively compressible poorly consolidated altered alluvium/colluvium noted at Casa Diablo. Reservoir modeling (Section 5.5) of potential pressure declines related to the Basalt Canyon development are forecast to be in the range of 1.45 psi to 10 psi or approximately 20% of measured pressure declines from existing Casa Diablo facilities. Howle and others (2003) note that the Casa Diablo subsidence could be due to shallow effects like changes in shallow unconfined aquifers and the slow dewatering of relatively compressible, porous sediments and hydrothermally altered volcanic tuffs or tuffaceous sediments in the topographic low of the structural graben that contains most of the Casa Diablo development. Those shallow effects will be minimized because Basalt Canyon wells will be completed in and produce from zones two to three times deeper than the existing Casa Diablo production reservoir in competent welded Bishop Tuff separated from less competent overlying sediments.

3.6 Volcanic Hazards

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). The intense earthquake sequence on May 25, 1980 included four M>6 earthquakes within and around the Long Valley that 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. 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.

3.6.1 Eruptive Potential

The USGS volcanic hazards response plan for Long Valley (Hill and other, 2002) reasoned that potential future eruptions in the region would be similar to the types and scales of eruptive events that have occurred within in the recent past. Eruptive events in the region within the last 50,000 years include explosive eruptions of silicic lavas like those occurred along the north striking Mono Craters and Inyo Domes 500 to 600 years ago (Miller, 1985). Volcanic unrest at single-vent volcanoes have been monitored much more closely after the 1980 eruption of Mt St. Helens and patterns of seismic activity, deformation and rapid changes in hydrothermal systems have given strong indications of the location of eruptions shortly before magma reaches the surface. Long Valley more complex than a single vent volcano and symptoms of volcanic unrest may persist for decades or even centuries at large calderas, such as Long Valley Caldera. Recent studies indicate that only about one in six such episodes of unrest at large calderas worldwide actually culminate in an eruption (Newhall & Dzurisin 1988; Newhall, 2003).

The USGS California Volcanic Observatory (CalVO) monitors volcanic activity through seismicity, emissions of volcanic gas and ground swelling. 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 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.

Project Impacts

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 (http://volcanoes.usgs.gov/observatories/calvo/). The USGS reasoned that "….the probability of such an eruption occurring in any given year is less than 1%. This is comparable to the annual chance of a magnitude 8 earthquake (like the Great 1906 San Francisco Earthquake) along the San Andreas Fault in coastal California or of an eruption from one of the more active Cascade Range volcanoes in the Pacific Northwest, such as Mount Rainier" (USGS Fact Sheet 073-07).

3.6.2 Eruption effects

If, as the USGS suggests, potential future eruptions are similar to the most recent eruptive events in the last 5000 years along the Mono-Inyo volcanic chain the eruptions are likely to be small and the overall impact will depend on the location, size and type of eruption and the wind direction. The well-documented eruptive progression along the Mono-Inyo chain is apparently controlled by magma type, the depth of penetration into the shallow crust, variations in country rock and groundwater. Dike intrusions, similar to the Mono-Inyo dike, would fragment and produce phreatic eruptions that discharge a mix of rocks, ash and steam around an explosion craters like the Inyo Craters (Figure 7) and phreatic craters on the north face of Mammoth Mountain but without surface extrusions. The initial phreatic explosions clear a path for later magma to make it to the surface and, if an eruption progressed, magma extrusion to the surface would eventually build a rhyolite dome in the center of a tephra ring that could be overridden by upwelling lava to produce lava domes like the Inyo Domes 550 years ago (Miller 1985). The recent domes along the Mono-Inyo chain are relatively small volcanic cones, less than 1,000 feet (300 m) in diameter, that produced hot, viscous lava flows that extended only a few miles.

The pumice and ash from an anticipated small eruption may be blown by the wind tens to hundreds of kilometers from the vent before falling to the ground. At the surface, the ash becomes finer grained and smaller in volume with distance from the vent (Figure 8). Based on other recent eruptive events, the USGS projects that a thin dusting of fine ash could disrupt social and economic activities for weeks or months and that modest ash accumulations would pose no immediate threat to life or property in part because most structures in the Mammoth Lakes region are built to withstand substantial snow loads. Larger volume explosive eruptions can produce turbulent hot pyroclastic flows that can be more devastating (Figure 9). Several sites over the past 5,000 years, along the Mono-Inyo chain have produced narrow, pyroclastic flows that extended more than 5 miles. The potential of snow melt and volcanic mud flows (lahars) persist if an eruption were larger scale occurred during the winter and was located at higher elevations such as Mammoth Mountain (Miller and others, 1982).

Project Impacts

The project area is more than 3 km from the potential future eruption sites like the phreatic explosion craters on Mammoth Mountain and more than 5 km from potential eruptive areas around the Inyo Craters. Early volcanic hazard evaluations (Miller and others, 1982) considered areas of earthquake swarms around the southern caldera moat (Figure 9) as a potential eruptive site. The area remains a potential vent area but seismicity has since declined and, as the USGS notes in its volcanic hazard

assessment, “pinpointing the precise time and location of the next eruption in the Long valley area is not feasible,” and “Future eruptions in the region are most likely to consist of one or more of the types of volcanic activity that have occurred in the past few thousand years along the Mono-Inyo Craters volcanic chain”(http://volcanoes.usgs.gov/volcanoes/long_valley/long_valley_hazard_9.html). Project buildings and facilities would conform to accepted construction requirements to withstand heavy snow loads and should be able to accommodate light ash fall. Larger scale events and larger volumes of erupted materials are not projected for probable future eruptions.

3.6.3 Magmatic Gases

Increased gas emissions have been noted at the ground surface within the caldera since the 1990’s and have been interpreted as another manifestation of the pattern of volcanic and seismic unrest in the area (Hill and others, 2002). The increased gas emissions attributed to magmatic activity are distinguished from the natural releases of gas dissolved in geothermal fluids by the distinct helium and carbon isotope contents related to increased magma input at depth beneath at least the Mammoth Mountain section of the caldera (Sorey and others, 1998; Gerlach and others, 1998). The potential magma-related gas emissions vary from diffuse gas flow over broad areas and prominent surface steam vents such as a fumarole on the north slope of Mammoth Mountain 4 km from the project area and at less prominent surface manifestations in the western caldera moat. A broad zone of diffuse gas flow at Horseshoe Lake resulted in trees dying off in the early 1990's during a period of increased earthquake activity beneath Mammoth Mountain generally interpreted as new dike intrusions and magmatic gas input deep beneath Mammoth Mountain (Hill, 2005). The CO_2 gas flow at Horseshoe Lake was measured at 5800 g/d/m^2 of ground surface, a level usually associated with hot gases at the summit of active volcanoes. The high CO_2 gas flow was sufficient to interrupt root zone respiration killing trees in a 0.2 km^2 area (Sorey and others, 1998). Localized areas of potential gas flow within the project area occur at fumaroles north and east of Shady Rest Park and Basalt Canyon within the project area. The RDO-8 DOE exploration hole ~0.5 km north Shady Rest in the project area had elevated levels of CO_2 and H_2S in and around a containment structure over the wellhead and the hole was plugged and abandoned in 2007.

Gas dissolved in geothermal fluids at reservoir depths can be released when geothermal fluids are released to the atmosphere. Although such releases are not part of normal operations of the planned project, they will occur occasionally during flow testing, start-up or power plant outages. These geothermal gases represent a small (<1%) component of the geothermal fluids. The gases are primarily carbon dioxide with minor amounts of other gases such as hydrogen sulfide, methane, ammonia, nitrogen, and hydrogen.

Project Impacts

Gas emission hazards are not anticipated to be a problem within the project area. Gas emissions are currently monitored as part of the USGS volcanic hazards program to permit avoiding any areas of elevated gas concentrations or to note where confined spaces might create a hazard. Increased gas emissions from further magmatic or seismic unrest would most likely take place over an extended

period of time. Project construction and drilling operations regularly monitor gases as part of geothermal workplace safety. Gas emissions from wells is a common air quality issue but should not be a problem with standard completion practices to maintain wellbore integrity.

3.7 Soil Resources

The Project area is situated in a variety of soil types in the southwestern caldera. Based on NRCS mapping (Figure 10), project soil distribution includes:

Vitrandic Haploxerolls soils in the vicinity of Shady Rest Park. These soils are composed of 0 to 60 inches of gravelly coarse sand derived from pumice and/or residuum weathered from obsidian and support Jeffrey Pine habitats (NRCS-1).

Haypress family soils around proposed wells to the northeast and southwest of Sawmill Road. These soils are gravelly loamy and coarse sand derived from till and granitic rocks (NRCS-1) on steep slopes in mountain foothills where water table depths are usually over 80 inches (NRCS-1). Haypress soils primarily support open Jeffrey Pine, Ponderosa Pine, Manzanita, black oak, and some grass and sagebrush (Great Basin scrub) habitats. Haypress family soils typically support livestock grazing and timber production (NRCS-2).

Both the Haypress family and Vitrandic Haploxerolls have low erosion hazard, low runoff potential, rapid permeability and low to moderate soil productivity (EMA, 2005).

Calpine family soils around proposed wells in the flatter lowland areas to the east and west of Highway 395 in the southeastern portion of the Project area. Calpine family soils are composed of gravelly sandy loam derived from alluvium in alluvial fans and stream terraces (NRCS-1; NRCS-2) primarily supporting Great Basin scrub, livestock grazing with some areas used for irrigated agriculture (NRCS-2). Calpine soils are well drained, have low surface runoff potential, moderately rapid permeability, and low to moderate erosion hazard (NRCS-2; EMA, 2005).

Biglake-Chesaw family soils in the hills immediately to the northeast of several proposed well locations. Biglake-Chesaw soils are composed of very gravelly, coarse sand with occasional rock outcrops and typically occur on moderately sloping terrain. These soils are well drained and have rapid permeability (NRCS-2).

Project Impacts

All of the soils in the Project area have a low to moderate erosion hazard and very low to moderate soil productivity. No substantial soil erosion or the topsoil loss is anticipated related to the Project.

3.8 Mineral Resources

Known mineral resources in the region include the current geothermal system (see Section 4), potential precious metal deposits and industrial minerals such as clay, aggregate, pumice and cinders). The Blue Chert mine or prospect is a drilled and identified epithermal gold deposit on the southeastern side of the Resurgent Dome with inferred gold reserves of 68 M tons @ 0.018 oz/ton (Jessey, 2009, Prenn and Dyer, 2008). Sources of pumice or cinders generally occur 2-3 km north of the Project area. Claims for kaolinite clay sources include the Hundley Clay Pit in the northern part of the Resurgent Dome and numerous small hydrothermally altered areas distributed within the central caldera. Magma Power Company completed annual claim work on these minor prospects during the 1970's to maintain grandfather mineral/geothermal rights prior to federal geothermal lease sales in the 1980's. The claims include alteration areas adjacent to the Project area but the potential deposits were never fully evaluated or developed. The Hundley Clay Pit has operated intermittently since 1952. Standard Industrial Minerals, the current owner, trucks kaolinite from the Hundley pit to the company mill north of Bishop. Uses include paint filler, plastic, rubber, paper processing, Portland cement, ceramics, insecticides, pharmaceuticals, and stucco (Wilkerson and others, 2007; Lipshie, 2001).

Project Impacts

Geothermal development is not anticipated to interfere with any future gold mining activity because the Blue Chert prospect is approximately 10 km northeast of the Project area and central part o the geothermal system is located in the western caldera. Geothermal development has not and is not anticipated to interfere with kaolinite mining activity because the Clay Pit is approximately 8 km northeast of the Project area and central part o the geothermal system is located in the western caldera.

4 Surface Water and Shallow Cold Groundwater

Surface water in the vicinity of the Project area consists of perennial streams, ephemeral streams, small lakes and dams. Snow melt from the surrounding Sierra Nevada is the principal source of surface water runoff that recharges both the shallow cold groundwater system and deep geothermal system in Long Valley Caldera. Surface and groundwater generally follow topography flowing from very high elevation Sierra peaks to the west and south toward the topographic low of Lake Crowley to the southeast or northeast through the Dry Creek Basin to Big Spring along the Owens River headwaters in the northeast. Sources of cold groundwater and geothermal recharge include a portion of the same snow melt infiltration from surface water features and underflow or subsurface flow in shallow poorly consolidated glacial till or alluvium or in penetrative faults and fractures (Sorey, 2005; Wildermuth, 2009). Some additional recharge comes from higher elevations of the Glass Mountains complex in the eastern part of the caldera but the influx is less than recharge from the western and southern topographic margins of the caldera because precipitation is limited east of the Sierran Range front.

4.1 Surface water

Surface water flow follows topography within the Project Area originating at higher elevations on the topographic margins of the caldera to the south and west flowing downgradient to the north and east towards Mammoth Creek and eventually towards the Owens River below Lake Crowley reservoir. The Town of Mammoth Lakes is the principal water demand within the caldera. The Mammoth Community Water District (MCWD) supplies the Town of Mammoth Lakes through a mix of surface water and groundwater from the Mammoth Groundwater Basin (Figure 11) and recycling or conservation. The Project Area is located in the central- western portion of the Mammoth Groundwater Basin. The current maximum surface water right for MCWD in a wet year totals 2760 acre-feet (ac-ft) (Wildermuth, 2009) but surface water supplies are often limited because the caldera is subject to climatic extremes and prolonged periods of drought. A five-year average of recent diversions within the Mammoth Groundwater Basin totals 1,440 ac-ft (MCWD, 2012). Groundwater pumping makes up the greatest portion of the difference between water demand and surface water supply. Groundwater use averages 1595 ac-ft for normal years but varies between a low of 1331 ac-ft during a wet year but increases to 1942 ac-ft during a dry year (Wildermuth, 2009).

4.1.1 Mammoth Creek/Hot Creek

The perennial stream of Mammoth Creek is the principal surface water feature in the Mammoth Groundwater Basin flowing from the Lake Mary Basin in the Sierra highlands eastward through the Town of Mammoth Lakes and immediately south of the Project area. Near Hot Creek Fish Hatchery, Mammoth Creek becomes Hot Creek because natural thermal discharge from springs in and near the creek contribute to the flow (EMA, 2005). The Federal Emergency Management Association (FEMA) designated a 0.1 mile buffer zone around Hot Creek west and east of Highway 395 and south of the Project Area as a Zone A Flood Hazard or High Risk Area with a 1% annual chance of flooding and a 26% chance of flooding over 30 years (FEMA, 2011). Additional areas along Mammoth Creek in the Town of Mammoth Lakes are also designated as Zone A by FEMA; however these zones lie well outside the Project area.

The USGS maintains six Mammoth Creek/Hot Creek gauging and/or sampling stations in the vicinity of the Project Area (Figure 12):

- Western edge of the Town of Mammoth Lakes (Mammoth C AB)
- Mammoth Creek Park (Mammoth C Sherwin Rd and Mammoth Creek Flume within 100 meters of each other) in the Town of Mammoth Lakes
- Mammoth Creek - Highway 395 crossing upgradient of Hot Creek
- Hot Creek approximately 100 m and 600 m downstream

Periodic monitoring results (Table 1) for the western (upstream) reaches of Mammoth Creek document low water temperatures (6.5 – 11.5^{o}C), variable discharge rates (17 – 34.8 cfs). Comparatively elevated levels of silica (20.9 mg/L) boron (14 µg/L) and arsenic (4 µg/L) were analyzed in samples collected

periodically between 1983 and 2008 at the Mammoth Creek/Hwy 395 monitoring point (Table 1). East of Highway 395, monitoring established a baseline stream flow rate of approximately 40 cfs for the Hot Creek drainage between 1996 and 2010 (http://lvo.wr.usgs.gov/HydroStudies.html). Increased discharge above background conditions occurred in 1996 (280 cfs), 2006 (190 cfs) and 2007 (240 cfs) during periods of high precipitation and runoff (Wildermuth, 2009; Farrar and others, 2010). Temperatures and surface water chemistry from periodic surface water samples collected from 1982 to 1986 downstream of Casa Diablo near where Mammoth Creek joins Hot Creek were distinctly different from those collected upstream. Analytical results from the site also show a comparatively higher average temperature of, and elevated levels of sulfate (115 mg/L), silica (188 mg/L), chloride of 193 mg/L and total dissolved solids (866 mg/L) (USGS National Well Information System http://waterdata.usgs.gov/nwis).

4.1.2 Basalt Canyon drainage

The U.S. Forest Service designates the Basalt Canyon drainage as an ephemeral/intermittent riparian conservation area (RCA) under the Sierra Nevada Forest Plan Amended Record of Decision (SNFPA ROD), (USDA, Forest Service, 2004). The Basalt Canyon drainage originates in the hills to the north and west of the Project area and includes a small upper tributary drainage near Shady Rest Park (Figure 12). The Basalt Canyon drainage parallels Sawmill Cutoff Road from northwest to southeast through the project area. The drainage turns east parallel to Pole Line Road until it crosses Highway 395, joins another ephemeral drainage that extends through the existing spill containment basin at the previously developed Casa Diablo portion of the project area before entering Mammoth Creek (Figure 12) (EMA, 2005). The Basalt Canyon drainage is not considered in FEMA's flood hazard mapping.

4.1.3 Murphy Gulch drainage

Murphy Gulch drains from west to east parallel to the north side of State Route 203 and is another ephemeral riparian conservation area south of the Project area and north of Mammoth Creek (Figure 12)(USDA Forest Service, 2004; EMA, 2005). Two small dams and siltation basins less than one-quarter mile south of proposed well 55-31 collects and stores sediment from storm water and snow melt runoff from the Town of Mammoth Lakes. Approximately one-third of a mile downstream from the siltation basin, Murphy Gulch flows under State Route 203 and into Mammoth Creek (EMA, 2005). The Murphy Gulch drainage does not appear in FEMA's flood hazard mapping program (2011); however, an earlier

Environmental Assessment for the Basalt Canyon Geothermal Pipeline mentions that the Murphy Gulch RCA is within a 100-year flood hazard zone (EMA, 2005).

Project Impacts

One potential surface water effect of the Project could be changes to the thermal spring input in the Mammoth Creek/ Hot Creek drainage. The proposed project shifts production farther west decreasing the potential for detrimental effects on thermal discharge of springs. Reservoir pressure changes are forecast to be relatively small for the planned production increase and small reservoir changes are less

likely to have a significant impact on the thermal discharge that contributes to the surface waters such as Hot Creek. Additional injection wells proposed for the southern part of the Casa Diablo field will follow the current injection scheme returning produced fluids to permeable zones at ~2000 feet (~600m) within the deeper underlying Bishop Tuff. Over the 27 year production and injection history of the field, deeper injection has had no affect on thermal springs.

Project plans include mitigation measures designed to reduce the potential for adverse impacts to surface water quality in compliance with CSWRCB Construction General Storm Water Permit. Ditches would channel off-site storm water around construction and well sites to minimize erosion. Site storm water would be collected and contained and a Project Spill or Discharge Contingency Plan would be followed to clean up any incidental material or geothermal fluid spills. USFS or State of California best management practices for storm water would be followed and the Project would also comply with best erosion management practices during flood periods.

Geothermal fluids would not be discharged under normal operating conditions. Accidental releases could occur; however, large discharges of geothermal fluids are extremely unlikely because of well planned management practices, frequent inspections, testing, flow and pressure monitoring and automatic well shutdown features. A large release of geothermal fluid might pose a threat to surface water quality because of higher dissolved solids content but the Project Spill or Discharge Contingency Plan or Well Blowout Contingency Plan would be followed to prevent, control, contain, clean up and mitigate the impacts of any large spills.

4.2 Shallow cold groundwater

Light stable isotopes of deuterium (D) and oxygen 18 (^{18}O) have been used to determine the origins and interactions of groundwater and surface water in many hydrologic settings and in Long Valley. These data indicate that the recharge source for cold groundwater is snowmelt around Mammoth Mountain or the upper part of Mammoth Creek and from and the southern caldera margin predominantly Sherwin Creek (Figure 13) (Sorey and others, 1991; Sorey, 2011; Evans, pers. comm.). The cold groundwater system is differentiated from the deeper hotter geothermal system by geologic units, depth, temperature, and fluid chemistry (see Section 5.1.2 *Geochemistry*). Shallow non-thermal groundwater in the Mammoth Groundwater Basin is generally are colder (7 – 9 °C), shallower (25-265m), lower in total dissolved solids (TDS) and constrained to shallow glacial till, moat basalt and/or alluvium/colluvium aquifers of the Mammoth Groundwater Basin. These cold groundwater aquifers are separated from the deeper hotter geothermal system by either intense alteration of thick ash-rich Early Rhyolite units in the western caldera or low permeability rocks of a landslide that slid into the south central part of the caldera at the end of the catastrophic collapse of the caldera 760,000 years ago (Figure 14). Impermeable Early Rhyolite units have been penetrated by temperature gradient holes MLGRAP-1 and 2 and Oh Well-1 in the western part of the Mammoth Groundwater Basin (Figure 11) and the MCWD generally considers these units as impermeable unproductive consolidated bedrock (Wildermuth, 2009). Mammoth Basin groundwater supply wells produce cold groundwater from the hydrologic region drained by the upper reaches of Mammoth Creek

(Figure 11). Total production averaged 1.3 cfs (37 L/s; 590 gpm) over the 1983-2001 period (Sorey, 2005). The MCWD uses 1460 ac ft of groundwater on average but groundwater use can increase to as much as 3360 ac ft in extremely dry years (Norby, 2012).

4.2.1 Shallow groundwater quality

Monitored shallow non-thermal groundwater wells in the Mammoth Groundwater Basin include well M-14 by the Mammoth Community Water District), Sherwin Creek 2 (SC-2) by the USGS, and Elementary School New well (ESN) by Mammoth Pacific (Figure 15). Hydrographs for these wells are compared in Figure 16. Well ESN is a relatively shallow, non-thermal domestic water supply source for the local Elementary School located near geothermal monitoring wells 28-34 and CW-3. Because topography within the caldera varies considerably, depth to water or pressure readings are commonly converted to values of pounds per square inch – absolute (less atmospheric pressure) (PSIA) at a common elevation of 2072m (6800 ft) asl for the caldera-wide hydrologic monitoring program (Sorey 2005, 2010). Shallow cold water monitoring points are close to pressures plotted for the thermal wells in Long Valley At the 6800 ft datum. Average computed pressures of ~132 PSIA in the ESN supply well are close to those in nearby thermal monitoring point CW-3 (Figure 15). Average computed pressures of ~ 240 PSIA in SC-2 are close to ~ 230 PSIA measured in thermal well RDO-8 in the western caldera (Figure 17). Computed pressures of 340 PSIA in cold supply well M14 (Figure 16) are the result of closer proximity to recharge sources from the southern topographic margin of the caldera and illustrate that non-thermal groundwater monitoring points in different parts of the caldera have pressure histories that reflect proximity to recharge sources and the hydrologic characteristics of varying geologic units. The range of multiyear pressure variations computed for well SC-2 (Figure 16) is ~ 12 psi (28 ft of cold water head), but computed pressures in ESN are only 3 psi (7 ft of cold-water head). Seasonal variations have less of an effect at groundwater well SC-2 because the well is completed below a shallow confining bed. Cold supply well ESN is completed in the shallow unconfined aquifer in Chance Meadow resulting in relatively large annual variations in pressure related to variations in recharge but more subdued record of longer (multiyear) pressure variations.

Production temperatures and chemistry are slightly different for MCWD wells along the northwestern side of the basin compared to wells located to the east and south of the western edge of the Mammoth Groundwater Basin (Figure 18). MCWD production wells 16, 17 and 20 drilled in the northern part of the basin (Figure 11) range in temperature from 15 – 21 °C, approximately 10°C warmer than production wells in other parts of the basin. Well No.18 produces water at temperatures of 19-20°C and is the only warm shallow groundwater well located to the south. Slightly elevated temperatures 42°C were also noted at ~200m during the drilling and completion of well No. 26 in the central part of the Basin (Figure 11) but no stable static surveys were run to confirm the temperatures. The slightly warm MCWD wells in the northwest basin border the Rhyolite Plateau and the central part of the deeper geothermal source reservoir in the western caldera (Figure 5). The MLGRAP 1 and 2 and Oh Well-1 temperature gradient holes in the western caldera (Figure 15) were drilled to 460-665 m, considerably deeper than the 216 m total depth for the MCWD wells, and encountered maximum temperatures of 75-85°C. No fluid analyses

are available for the temperature gradient wells but MCWD water quality analyses detect a very low concentration of 2-5 mg/L Cl and gradually declining pH in well No. 17 from 1992-2001.

Analyses for soluble conservative constituents like Cl and trace elements like As, B, Fl and Li have been used to identify and track the geothermal source of fluids in several geothermal systems including Long Valley (Sorey and others, 1978). Elevated Cl concentration and ratios of conservative elements such as CL/B are often used to estimate the geothermal contribution to hot springs, identify sources and to track changes in hydrothermal systems over time (Sorey, 2000). Within Long Valley, Cl/B ratios generally fall in the range of 23 although absolute Cl concentrations vary (Figure 19). Analytical data for cold MCWD groundwater supply wells was not available until the USGS collected samples in 2011)(Sorey, 2011; Evans, pers. Comm.). The Cl/B ratios of 22.4 in samples from well No. 17 in the far northwestern part of the Mammoth Groundwater Basin (Figure 18) are within the range of Long Valley geothermal waters; however, very low Cl concentrations of 5.17 are considerably less than ~250 mg/L typical of high temperature deep geothermal water.

Project Impacts

Monitoring records document no changes the chemistry of groundwater wells in the Mammoth Groundwater Basin from 1996 to 2009 during continual production of the geothermal system at Casa Diablo. There is no apparent relationship between current-day groundwater and geothermal chemistry. Based on Cl concentrations of only 5 mg/L in well No. 17 analyses, the geochemistry suggests a tiny 1-2% thermal component in this one groundwater well. Based on geochemistry, slightly warmer temperatures in groundwater wells in the northwestern corner of the Mammoth Groundwater Basin are not likely the result of a strong upward flow of hot water into the basin.

Because the shallow cold groundwater system and the deeper geothermal system are physically separated from the principal supply aquifers of the western Mammoth Groundwater Basin, geothermal production from the project is not expected to adversely affect the water quality in MCWD wells through either depleting the aquifer or by drawing in lower quality waters because of pressure declines. Reservoir pressures monitored in well 65-32 declined 60 psi during the prior 27 years of production from the field with no detrimental effects on shallow cold groundwater quality in the Mammoth Groundwater Basin supply wells (Sorey, 2011). Numerical simulations of the planned Basalt Canyon development forecast reservoir pressure declines in the range of 1.45 psi to 10 psi, which would be at the maximum less than 20% of the maximum monitored pressure declines to date. Regular monitoring data reviews by the BLM and the LVHAC should assure there are no adverse affects on the quality of shallow cold groundwater and would give permitting agencies the ability to order corrective actions should any adverse effects be determined.

5 Geothermal resources

Geothermal energy is the natural heat of the earth that, depending on temperature, permeability and fluid circulation, can be used in a range of applications from space heating to generating electricity. Geothermal electrical generation from conventional hydrothermal systems requires a relatively shallow young active heat source (<1 my old), highly permeable rocks and convectively circulating water at temperatures above ~ 130°C at economically accessible depths (currently ≤ 3,000 m or 10,000 ft). These unique conditions occur primarily around current volcanic areas or tectonic regions at the active margins of the earth's crustal plates. In a conventional geothermal resource, cold water recharge penetrates through faults and fractures in the crust where relatively high heat flow in areas of active tectonism and/or recent volcanism heats the water at depth. Hot water is less dense and rises in permeable zones in the overlying rock units eventually cooling and descending to be heated again. Mineral deposition or overlying impermeable rocks can form a barrier or cap limiting the vertical circulation of hot water and maintaining convective fluid flow in a permeable geothermal reservoir at depth. Most permeability barriers are imperfect or can be broken by the active tectonic processes responsible for the development of a geothermal system. Comparatively small amounts of water and/or gas leak to the surface along fractures and faults and show up as hot springs or steam vents (fumaroles) at the surface.

A conventional geothermal resource is generally defined as a hydrothermal system capable of supporting electrical generation. Geothermal resources vary in size, temperature, permeability and chemistry depending primarily on the geologic setting and the rocks that make up a geothermal reservoir. Based on reservoir fluids, geothermal systems occur as either water-dominated or steam-dominated resources. Steam-dominated systems like The Geysers, north of San Francisco, are comparatively rare but have the advantage of using the steam to directly power a turbine generator. Water dominated systems like Long Valley are more common and require that a portion of the geothermal fluid be flashed to steam or that the geothermal fluid can be used to vaporize a low vapor pressure secondary working fluid. Either the flashed steam or the vaporized working fluid powers a turbine. The generation system at Casa Diablo uses isobutene as a secondary working fluid that is vaporized by heat exchanged with the produced geothermal fluid.

About 10,715 megawatts (MW) of geothermal power is generated in 24 countries (GEA, 2010). Geothermal resources in the US account for 3,817 MW of installed capacity from 77 power plants generally in active tectonic or volcanic areas in the western US (US EIA, 2012). There are 25 known geothermal resource areas and 46 operating geothermal plants in California and 14 of the geothermal resources have temperatures over 148°C (300°F) with a combined total installed electrical capacity of 2,516 MW (California Energy Commission, 2012). The largest producing system is the steam-dominated Geysers with 1,517 MW of active installed capacity. Water-dominated geothermal systems in the eastern Sierra include 270 MWe at Coso, 90 MWe from Steamboat Springs and 40 MWe from Casa Diablo within the planned project area. More efficient generating plants and gathering systems and improved resource management strategies, primarily through injecting the produced fluids or

augmenting injection, have increased the life-span and electrical generating capacity of many geothermal resources.

5.1 Long Valley geothermal resource

The USGS designated the Mono-Long Valley region as a Known Geothermal Resource Area (KGRA) in the 1970's because the young voluminous 760,000 year old silicic volcanism that formed a 17 X 35km collapsed caldera depression provided ample evidence of a shallow active magmatic heat source and the welded Bishop Tuff ignimbrite ponded in the caldera depression forms an ideal fractured geothermal reservoir over a wide area and depth range. Later volumes of Early (post collapse) Rhyolite, moat eruptives and a bimodal assemblage of <200,000 years old intracaldera volcanics were evidences of continued magmatic input into a viable magmatic heat source required to sustain a hydrothermal system. Widespread hot springs and fumaroles over more than 120 km^2 (45 mi^2) inside and outside the caldera are direct evidences of a viable circulating geothermal system.

5.1.1 Hot Springs and Fumaroles

Surface hydrothermal manifestations in Long Valley vary from weak fumaroles or steam heated ground at higher elevations west of the Resurgent Dome to hot springs flowing at varying rates and temperatures at lower elevations in the central and western part of the caldera (Bailey, 1989; Sorey and others, 1978, 1991). Most of the prominent higher flow rate springs within the caldera occur in the southern caldera moat localized along faults within or around the southern edge or within the Resurgent Dome primarily at Casa Diablo, Hot Creek Gorge and Little Hot Creek (Figure 20).

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 areas of high-temperature minerals and hydrothermal alteration that are the result of hot geothermal fluids interacting with rocks. Age dating of the minerals indicates that vigorous hydrothermal outflow occurred along deeply penetrating faults in the western caldera <100,000 years ago.

Hydrothermal circulation in Long Valley has varied through time (Bailey and others, 1976, Sorey and others, 1978; 1991). Different alteration mineral assemblages in and around the Resurgent Dome and differing age dates indicate that hydrothermal activity 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 (Sorey and others, 1991), 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 (Suemnicht and others 2007). Alteration mineralogy for several relict outflow zones shows that significant surface manifestations

occurred at higher elevations in the western caldera in the early phases of the current hydrothermal system. 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 (Suemnicht and others, 2007).

The project area includes the active thermal zone at Casa Diablo Hot Springs on the southwestern side of the caldera's Resurgent Dome, fumaroles in the Basalt Canyon drainage west of Casa Diablo and weak fumaroles or thermal ground in and around Shady Rest on the east side of the Rhyolite Plateau in the western caldera moat (Figures 5, 20). Active and relict fumaroles, mudpots and hot springs at Casa Diablo are localized along a major northwest trending normal fault system that forms a graben within the Resurgent Dome. The discharge characteristics of some of the Casa Diablo features changed and some previously dormant fumaroles were reactivated during the initial phases of caldera unrest and Resurgent Dome uplift from 1980 to 1983.

Key geothermal features of concern within the caldera include:

Hot Creek Springs is localized along two north-striking faults that form a small graben that contains the Hot Creek Geologic Site. Numerous earthquakes that have occurred during caldera unrest that began in 1980 commonly affect 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 and forcing the USFS to close the area for swimming. 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).

Hot Bubbling Pool, located approximately 5 km east of Casa Diablo, experienced a 1.2 m in water level decline with the onset of expanded production and deeper injection in 1991.

Hot Creek Fish Hatchery, operated by the California Department of Fish and Game, is located immediately to the east of Hot Bubbling pool (Figure 20) and accounts for 2-5% of the caldera's total thermal outflow. The thermal water contribution raises water temperatures of an average of 5°C (41°F) above background, which is ideal for spawning. Hatchery fish are planted in many surrounding Sierra lakes and streams and are an important part of regional recreation and the local tourist industry. The dominant influences on Fish Hatchery spring flow and thermal discharge are seasonal and annual fluctuations in snow melt and recharge (Sorey and Sullivan, 2006). The total discharge of the Fish Hatchery springs declined ~2.5 cubic feet per second (cfs) between 1984 and 1995 with the onset of geothermal production or as the production scheme was changed in 1991; however, the region also experienced a long-term drought that affected the entire hydrologic system during that same time period. Through 2012 the combined Fish Hatchery spring discharge rate matched or exceeded pre-drought levels of 12-24 cfs while geothermal production has continued (Howle and Bazar, 2012). Based on chloride flux estimates, the thermal water contribution to the total spring flow has declined ~0.15 cfs since 1988 but the average spring temperatures have only changed ~2 ^{o}C through 2012 because of the buffering effect of conductive heat loss within the flow system.

Thermal ground occurs in several locations in the southern caldera moat related to active or reactivated fumarolic areas or older broad altered zones of nutrient-poor clay-rich soils. Surface manifestations and areas of thermal ground have varied considerably during the period of caldera unrest and geothermal development. Several relict mudpots and fumaroles at Casa Diablo became active after the earthquake swarms of the 1980's and have since decline. In part, the increased in fumarolic activity is related to shallow reservoir pressure declines as production increased in 1990. Pressure declines resulted in two-phase conditions at very shallow levels. Two-phase steam heating effectively increased heat flow to the shallow heated groundwater system that, in turn, increased the steam fraction in local fumaroles (Sorey, 2000). Several liquid hot springs at Casa Diablo converted to steam vents accompanied by increases in ground temperature within the field during 1991-1993 (Sorey et al, 1995, Sorey, 2010); however, many reactivated springs or fumaroles also occur at considerable distances from Casa Diablo, or at higher elevations and further west in the caldera moat. Changes in fumaroles, high CO_2 gas flow and tree deaths at Horseshoe Lake and the flanks of Mammoth Mountain were not related to geothermal production from Casa Diablo but were an apparent response to potential magmatic input around Mammoth Mountain after 1990 (Sorey and others, 1999). The rapid onset of dying trees was apparently related to CO_2 interfering with nutrient uptake through the tree roots (Sorey and others, 1999; Bergfeld and Evans, 2011).

Little Hot Creek

A group of hot springs near the head of Little Hot Creek approximately 2 miles (3 km) north of Hot Creek have maximum temperatures are near 175 ^{o}F (80 ^{o}C). Spring flow has systematically been measured and chemical samples have been collected at Little Hot Creek as part of the LVHAC monitoring system. The average total spring flow from this area was about 0.35 cfs (10 L/s). During the 1980s, total spring discharge varied with earthquakes of M>4-5 in the Long Valley region, similar to other springs in the eastern caldera. Little Hot Creek and other thermal springs and observation wells located between Hot Creek and Lake Crowley indicate a continuation of the zone of thermal outflow originating at Casa Diablo, with ultimate discharge occurring as seepage into the lake. Because the thermal and non-thermal ground water aquifers tend to merge near the surface in this high-water table area, the thermal water is cooler and more dilute than that discharging in Hot Creek gorge.

5.1.2 Geochemistry

The chemistry of a hydrothermal system reflects the source of the thermal water and the path it takes through permeable rocks as the water is heated, cooled and eventually reheated in a viable convecting geothermal system. Water-rock interaction changes the chemistry of both depending temperature, water-rock ratio and the original chemistry in each part of the system. Hydrothermal circulation alters the rocks that water circulates through, resulting in a chemical signature for the water that allows an evaluation of thermal water source and the processes affecting it on its permeable pathway to the surface. Complete evaluation of fluid chemistry and reservoir interaction typically requires sampling the deep geothermal fluids, surface manifestations and local cold water recharge to determine all of the interactions that affect the system.

The chemistry of Long Valley surface manifestations has been studied for more than four decades, initially for geothermal exploration (Waring, 1965; Mariner and Wiley, 1976; Sorey and others, 1978) and later as part of volcanic hazards monitoring (Farrar and others, 1987, Sorey and others, 1999) or for cooperative hydrologic monitoring of geothermal development through the Long Valley Hydrologic Advisory Committee (LVHAC). More recent geochemical data includes analytical results from producing geothermal wells, isotopic studies to determine potential hydrologic interactions within the caldera and gas analyses to evaluate changes related to potential magma intrusion and caldera unrest.

Active and relict fumaroles, mudpots and hot springs are generally localized along faults that deform the caldera (Bailey, 1976, 1989; Mariner and Wiley, 1976; Sorey and others, 1978). For example, fumaroles at Casa Diablo are distributed along a major northwest trending normal fault system that forms 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. 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 younger (129,000-62,000 year-old) postcaldera moat basalts. Hot spring temperatures across the caldera generally range from 79-93°C with ≤ 1330 milligrams per liter (mg/L) total dissolved solids and chloride concentrations of 200-300 mg/L. More dilute warm springs occur between Hot Creek and Lake Crowley (Figure 20).

Long-term flow measurements and mass-flux estimates based on conservative element concentrations like B and Cl indicate that the total thermal throughput of the hydrothermal system remains relatively constant. Prior to the 1985 onset of geothermal production, the total estimated flow of the entire hydrothermal system was at 13 cfs (370 L/s, or 5,900 gpm) (Sorey and others, 1991; Sorey, 2005). Of this total flow, as much as 8.8 cfs (248 L/sec ; 3900 gpm) or roughly 70% of the hydrothermal outflow occurs at Hot Creek on the southeastern edge of the Resurgent Dome (Figure 20). The median flow of thermal springs in Hot Creek Gorge has remained at 8.75cfs (245 L/sec; 3930 gpm) during the entire period of geothermal production through 2012 (Howle and Bazar, 2012); https://137.227.239.76/lvo/activity/monitoring/hydrology/hotcreekgorge.php). Geochemical estimates of source reservoir temperatures range from 200°C – 280°C (Sorey and others, 1978; 1991; Mariner and Wiley, 1976) whereas initial published geochemical estimates of potential geothermal source reservoir temperatures range from 200°C – 240°C (Sorey and others, 1978; 1991; Mariner and Wiley, 1976).

Light stable isotopes and trace elements have been important in determining the general west-east flow of source waters across the caldera for both the thermal and non-thermal water (Figure 13). Analyses and comparisons of light stable isotopes deuterium (D) and oxygen 18 (^{18}O) from Long Valley show that cold groundwater recharge for the shallow glacial till, moat basalt and alluvium/colluvium aquifers of the Mammoth Groundwater Basin originates from snowmelt around Mammoth Mountain or the upper part of Mammoth Creek and from and the southern caldera margin predominantly Sherwin Creek (Sorey and others, 1991; Farrar and others, 2003). Based on deuterium values, deeper recharge for the hot geothermal water beneath the western caldera is recharged from snowmelt along the northern base of Mammoth Mountain and the upper reaches of Dry Creek. Changes in isotopic values trace geothermal

flow from the west moat to the south and east to Casa Diablo and beyond (Figure 13). Some conservative trace elements like boron are unique in geothermal systems and trace element concentration ratios with chloride have been used in Long Valley (Sorey and others 1978, 1991; Sorey, 2011; Evans, pers. comm.) and other geothermal systems for decades (White, 1957). Nearly constant Cl/B ratio of 23 for geothermal waters east and west of Casa Diablo indicate a common hot water source reservoir at depth beneath the caldera's west moat.

Carbon dioxide (CO_2) is the principal non-condensible gas in geothermal systems including Long Valley. Trace amounts of other gases like helium and isotopic analyses of gas constituents can be important in evaluating the nature and extent of geothermal systems or monitoring volcanic hazards (Farar and others, 1987; Sorey and others, 1999; USGS, 1996). In a liquid-saturated system like Long Valley, non-condensible gases are dissolved in the geothermal fluid and are released (for example by fluid rising to the surface) as pressure declines forming a gas ± vapor phase. Non-condensible gas output in Long Valley is primarily CO_2 and occurs through diffuse soil discharge, dissolved in groundwater or from steam vents or fumaroles. Past changes in the outflow from hot springs and fumaroles and increased CO_2 emissions around the flanks of Mammoth Mountain have been interpreted as potential indicators of magma moving to shallower crustal levels fracturing and releasing gases during dike emplacement in 1989 (Sorey and others, 1999).The gas emissions on Mammoth Mountain have been accompanied by rising $^3He/^4He$ ratios (Figure 21) and ^{13}C carbon isotope ratios have been interpreted as potential indicators of magma moving to shallower crustal levels (Sorey and others, 1998) rather than changes in the produced geothermal system. Magma-related gas emissions include increased CO_2 output that has resulted in several areas of tree death around the flanks of Mammoth Mountain (Sorey and others, 1999; USGS, 1996) and around the Resurgent Dome (Bergfeld and Evans, 2011). Higher than normal CO_2 concentrations in the soil kills the trees by denying their roots oxygen (O_2) and by interfering with nutrient uptake.

Geochemical changes in geothermal production fluids, particularly declines in chloride concentrations from 1990 to 2003, suggest that the cooling trend in produced fluids from approximately 338 ^oF (170^oC) to between 302 to 329 ^oF (150 ^oC and 165 ^oC) over a similar time period is predominantly related to the intrusion of small amounts of cold meteoric water or cold groundwater into the shallow geothermal reservoir (Geologica, 2003). Declining chloride typically indicates mixing with cold meteoric water (or groundwater) because cold recharge water has virtually no chloride (less than 5 mg/L) while chloride levels in the Casa Diablo geothermal resource vary between 265 and 300 mg/L. Based on geothermometer calculations, temperatures of the Casa Diablo reservoir fluid declined between 8 to 32ºF (5 to 20ºC) shortly after production expanded to 40 MW but then stabilized and have remained relatively constant.

Fluid leaks are rare in binary generation systems like Casa Diablo because of the cost of the secondary working fluid and the efficiency of the system requires total integrity of the heat exchanger. Some short-term isobutane leaks have provided an inadvertent tracer test for the Long Valley geothermal system (Evans et al., 2004). Isobutane is a non-toxic low-solubility gas that strongly fractionates to the vapor phase (Wilhelm et al, 1977). Small leaks have introduced trace amounts of immiscible and unreactive isobutane to the spent geothermal brine that is injected deep into the Bishop Tuff injection zone.

Isobutane has been detected in Basalt Fumarole in Basalt Canyon, 2 km west of Casa Diablo, but not in steam vents in the Shady Rest thermal area closer to well RDO-8 (Figure 20). Data collected from 1993 through 2004 (Evans and others, 2004) identified trace isobutane concentrations in dissolved gas samples from wells, thermal springs, and steam vents. To date, trace amounts have been detected in:

Well 66-25 (5 km west)
Basalt Fumarole (2 km west)
Hot Bubbling Pool (5 km east)
Well 28-34 (3 km east)
Well CW-3 (5 km east)
Fumarole Valley (4 km east)
Hot Creek gorge springs (10 km east)
Well CH10B (10 km east)

Transport of dissolved isobutane away from Casa Diablo, both within the production and injection reservoirs is poorly understood, even though the initial timing and appearance can be detected in surface manifestations and wells. The combination of isobutane migration and reservoir pressure transmission in the production zone and injection zones signifies a high degree of lateral continuity within the relatively shallow geothermal source reservoir beneath the south moat.

Project Impacts

The potential effect of geothermal development on sensitive hot springs or other thermal features and the potential impacts on surface or groundwater quality were principal reasons for initiating detailed hydrologic monitoring in Long Valley. Each of the most sensitive thermal features have been closely monitored during the initial development and expansion at Casa Diablo:

Hot Creek Springs were a concern because of the site is a prime recreation area for the US Forest Service. Changes in geothermal production have not resulted in drastic variations in spring flow during the history of production from Casa Diablo. Many of the variations in spring flow have occurred during periods of caldera unrest that do not correlate with production changes at Casa Diablo. The 2006 boiling events and expansion of the hot spring area in the Hot Creek gorge that forced the closure of the swimming area are a notable example. The 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) and do not correlate with the recent history of production from Casa Diablo.

Hot Bubbling Pool is potentially sensitive because it is one of the thermal springs closest to Casa Diablo and monitoring records show that water levels in the pool are particularly sensitive to aquifer pressure changes (https://137.227.239.76/lvo/activity/monitoring/hydrology/hbp_main.php). For example, pool levels increased by about 1.5 feet (0.46m) in July 1986 because of above average groundwater recharge related to winter precipitation 150% above the long-term average in Mammoth Lakes. The water level declined approximately 3.5 feet (1 m) with the onset of expanded production and deeper injection at

Casa Diablo in 1991. Water levels in Hot Bubbling Pool recovered approximately 4 feet (1.22m) within days after production has shifted west to Basalt Canyon and continue to rise.

Hot Creek Fish Hatchery springs are sensitive because of the small (2-5%) contribution of thermal water that improves spawning conditions at the Hatchery. Recent studies of spring flow, temperature and water chemistry at the Fish Hatchery (Sorey and Sullivan, 2006) 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. Total net changes in temperature at the two main Hot Creek Fish Hatchery springs during the most significant period of geothermal development at Casa Diablo (1988-2003) were less than 2°F, and while greater annual temperature declines have occurred during this time period (~4°F in 1995). The changes were related to high winter precipitation, greater snow melt runoff and high spring flow rates during the spring and summer. Consequently, it is difficult to identify the smaller effects of geothermal development on thermal-water components at the Hatchery springs because climatic variations and geothermal reservoir pressure changes have both occurred simultaneously. Sorey and Sullivan (2006) note that projected temperature changes computed from measured chemical flux values for boron and chloride show significant overestimates of spring temperature changes. Temperatures are maintained by heat derived from the surrounding rock and fluid in the flow zone carrying mixed water from the Casa Diablo area to the Hatchery effectively moderating the influence of cold water input (Sorey and Sullivan, 2006).

Thermal ground, CO_2 outflow and stressed vegetation are a natural consequence of the shallow outflow in the Long Valley geothermal system. Widespread hydrothermally altered areas related to outflow from the earlier (300,000 to 130,000 years old) geothermal system within the caldera are more extensive than the recently noted more limited tree kill areas. Hydrothermally altered soils are clay-rich, depleted in nutrients and relatively high in trace element concentrations that inhibit vegetation growth. Consequently, the lack of vegetation cannot exclusively be related to changes in geothermal production. Prominent altered areas like the clay-altered major fault zones that define the Casa Diablo graben or the Hundley Clay Pit in Antelope valley have no vegetation at all but are unrelated to currently active thermal ground or elevated CO_2 emissions. The relict fumarolic mounds around Shady Rest are similarly bare because of alteration not specifically because of increased thermal ground. In discussing the potential mechanisms for the lack of vegetation around Shady Rest Bergfeld and Evans (2011) noted that CO_2 fluxes at Shady Rest are lower than average fluxes at Basalt Canyon fumarole area to the east and that gas collected at Shady Rest contains no detectable isobutane to link emissions chemically to geothermal fluid production.

Fewer shallow thermal effects are anticipated as production is increasingly supplied from Basalt Canyon because the production wells will be 2-3 times deeper than the Casa Diablo wells, the wells will produce from a comparatively deeper reservoir section lessening pressure declines and the Basalt Canyon reservoir is physically separated from the overlying outflow effectively buffering changes in heat flow and limiting or preventing gas loss to shallower levels. Project plans also include additional injection wells in the southern part of the Casa Diablo field. Like the existing injectors, the planned wells will return produced fluids to permeable zones at ~2000 feet (~600m) within the deeper underlying Bishop

Tuff to prevent reservoir cooling noted when injection was placed at the same level as the production reservoir. Two-phase steam/water conditions are not anticipated in the deeper production reservoir in Basalt Canyon and it is unlikely that any steam would reach the surface through the thick section of altered Early Rhyolite and the low permeability landslide block underlying the Basalt Canyon area.

As noted by Sorey (2000), pressure declines around the shallow Casa Diablo production reservoir (<200m) resulted in two-phase conditions (water+steam) near the top of the reservoir that increased the heating of isolated overlying shallow groundwater aquifers. This increase in heat flow resulted in more steam output from local fumaroles. Unlike Casa Diablo, shallow aquifers in the Basalt Canyon area are physically separated by thick sections of impermeable to very low permeability rocks (landslide block and altered Early Rhyolites) overlying the production reservoir. Potential reservoir pressure declines are also more limited based on reservoir modeling forecasts (GSI, 2012, Garg, 2012). The Long Valley geothermal reservoir model (Section 5.4) was developed from detailed geologic and reservoir data and validated by matching pressure and temperature data from 27 years of production history at Casa Diablo. Model results indicate that shifting production to Basalt Canyon will result in smaller reservoir temperature and pressure declines than the earlier development at Casa Diablo (GSI, 2012, Garg, 2012). Reservoir simulations show that maximum reservoir pressure declines should range from 1.45 psi to 10 psi, at the maximum and that is only 20% of the pressure declines observed during the prior 27 years of production from Casa Diablo. Consequently, the physical separation, the depth of the production reservoir and the limited potential of marked changes in heat flow related to shallow two-phase conditions limit the potential for increasing areas of thermal ground.

5.1.3 Geothermal exploration

Early exploration drilling in Long Valley focused on the southern and central part of the caldera. Magma Power Co drilled the first geothermal exploration wells in Long Valley at Casa Diablo between 1959 and 1962. A series of nine wells were drilled to total depths ranging from 125 m to 324 m (410-1062 ft) adjacent to active fumaroles west of Old Highway 395 (Figure22). The first deep well (66-29) was drilled in 1976 to evaluate the resource potential in the southeast moat (Figure 23). 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 caldera's Resurgent Dome and the first deep wells to penetrate the entire section of the caldera fill (Figure 23). Mammoth-1 drilled through 390m of Early Rhyolite, 863 m of Bishop Tuff and 230m of metasedimentary rocks that correlate with the Mt. Morrison roof pendant to the south, bottoming at 1,605m. 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 23). The well encountered temperatures of 218°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 23) 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 the RDO-8 core hole at Shady Rest (Wollenberg and others, 1989), and an ultra-deep (3 km) Long Valley Exploratory Well (LVEW) intended to test the presence of magma near the center of the Resurgent Dome (Finger and Jacobsen, 1999) (Figure 23).

5.1.4 Geothermics

Because accessible viable geothermal systems represent a major thermal disturbance in the shallow crust, mapping temperature gradients, heat flow and temperature distribution at depth are critical in understanding the nature and extent of a potential geothermal resource. All other phases of exploration are based on evaluating the effects of heat but heat flow and deeper temperatures can only be determined by drilling. Nearly all of the formerly proprietary temperature data from shallow and deep Long Valley wells are publically available through California Division of Oil, Gas and Geothermal Resources (CDOGGR) well records (http://geosteam.conservation.ca.gov/Well/WellListPage.aspx) or have been compiled by the USGS (http://lvo.wr.usgs.gov/HydroStudies.html). The available data provide a relatively detailed picture of the established upflow from a deeper hotter source reservoir in the western caldera and outflow that sustains a moderate to low temperature shallower hydrothermal system to the east (Figure 24). 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 margins of the caldera where high temperature upflow is affected by cold recharge penetrating into the deeper fractured section of Bishop Tuff or underlying deep Paleozoic basement rocks (Suemnicht, 1987). 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.

The drilling results from early deep exploration wells 66-29, Clay Pit and Mammoth-1 forced a reevaluation of the Long Valley conceptual model of a geothermal system centered on the Resurgent dome. Low temperatures and sharp temperature reversals in deeper exploration wells proved that the central caldera is not the ultimate deep source of current Long Valley geothermal system and the source of the caldera's prominent hot springs is not directly beneath the Resurgent Dome. The 3 km deep LVEW well on the Resurgent Dome (Figure 23) indicate that heat flow within the Resurgent Dome is currently low relative to the southern and western parts of the caldera. The present-day thermal conditions in the

central caldera 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; Farrar and others, 2003). There is little drilling 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.

Geothermal systems and hydrothermal outflow at the surface are neither constant nor continuous. Few last 100,000 yrs. without heat replenishment (Lachenbruch and others, 1976; Cathles and others, 1997). A central Bishop Tuff magma chamber provided heat for an intense hydrothermal system 300,000-130,000 years ago that produced widespread hydrothermal alteration in the central caldera around the Resurgent Dome. The principal magmatic input in the caldera within the last 200,000 yrs. has been in the western caldera. The current hydrothermal system has probably been active for only the last 40,000 years (Sorey and others, 1991; Suemnicht and others 2007), 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.

5.2 Long Valley conceptual model

The currently active high temperature geothermal system in Long Valley is the result of upflow in an actively convecting fractured geothermal reservoir in the western caldera and outflow along faults and fractures to shallower levels in the east. Geochemistry and hydrologic data (Sections 5.1.2 and 5.5) indicate that a significant portion of the snow-melt recharge from the western rim of the caldera penetrates deeply into the fractured rocks within the caldera and, at depths of ~2 km, is heated to >220°C by young (Quaternary-Recent) shallow magma in the western caldera moat. Data on pre-development hot spring flow rates, Cl/B chemistry of natural thermal features and progressively higher (>200°C) temperatures encountered in western caldera exploration wells establish that hot upflow from a deeper source reservoir feeds lateral thermal water outflow zone that extends from Shady Rest in the western caldera to production wells at Casa Diablo and farther to the east (Figure 19). The thick section of intracaldera Bishop Tuff and the underlying fractured caldera floor have long been considered the potential deep geothermal reservoir within the caldera. Based on temperature data from exploration wells and geochemistry, the source reservoir for the present geothermal system lies within the Bishop Tuff or older (Paleozoic-Mesozoic) deeper fractured metamorphic basement rocks beneath the Bishop Tuff in the western caldera moat. The caldera inherited and modified many faults and fractures from the pre-existing tectonic framework that controlled the collapse and configuration of the caldera floor. Many of these faults and fault intersections control the high fracture density and deep permeability for convective upflow within the present geothermal system.

The moderate temperature (170°C) fluids produced at Casa Diablo and prominent hot springs and fumaroles in the central and eastern part of the caldera are directly related to hydrothermal outflow from the western geothermal system (Sorey and others, 1991; Farrar and others, 2003; Suemnicht and others, 2007). Fluid temperatures and dissolved solids content decrease progressively farther to the east

because of dilution by cold recharge and heat loss. The Bishop Tuff magma chamber supported a vigorous geothermal system from 300,000 to 130,000 years ago that circulated in a similar system of faults and 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 20). The estimated 75% of the current hydrothermal output at Hot Creek further west is outflow from the principal source of the geothermal system in the western caldera.

Existing Geothermal wells at Casa Diablo produce moderate temperature fluids from a shallower (<200m; 650 ft.) fractured Early Rhyolite reservoir. Basalt Canyon wells approximately 2 km west produce outflow from the deeper system into a mixed fractured reservoir of Bishop Tuff and deeper fractured sections of Early Rhyolite. Injection is currently limited to deeper wells (>600m) completed within the welded fractured permeable Bishop Tuff underlying the Early Rhyolite reservoir at Casa Diablo. 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 (Figure 5).

The shallow Early Rhyolite reservoir at Casa Diablo and west up to Shady Rest is stratigraphically separated from the underlying Bishop Tuff reservoir 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 (Suemnicht and others, 2007). 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 viability of 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).

5.2.1 Long Valley geothermal development

Based on the productive wells drilled around Casa Diablo Hot Springs in the 1960's, Magma Power considered a 15 Mw generation facility but binary production technologies were still in early experimental stages in 1962 and the project was shelved. Several geothermal development companies completed detailed geological, geophysical and geochemical investigations in the 1970's and drilled deep (>1500m) full-scale exploration wells to evaluate the geothermal potential of the geothermal source reservoir in the deeper Bishop Tuff ponded within the caldera depression (Section 5.1.3).

The development of Casa Diablo began in the 1980's. Initial production wells (MBP-1, 2, 3 and 5) and injection wells (IW-2, IW-1) were drilled to total depths ranging from 125 m (410 ft) to 324m (410-1062ft) in the area around Casa Diablo for the MP-1 power plant (Figure 22). Initial production rates

averaged 3200 gpm (~1600kph) from 1985 to 1990 (Sorey, 2005, 2010). Successful generation led to additional development drilling for expanded power generation from the MPII and PLES plants commissioned in 1990, including eight new production wells (24-32, 24A-32, 24C-32, 24D, 32, 24-32, 25A-32, 35-32 and 35A-32) and four injection wells (43-32, 43A-32, 44-32 and 44A-32). The average production rate ranged from 12,700 to 14,000 gpm (~6000) kph of geothermal fluid to generate 40MWe (gross)(Sorey 2005, 2010). Several research and exploration wells including RDO-8 at Shady Rest, Inyo Domes (44-16) and the Resurgent Dome (LVF 51-20 later LVEW) were also drilled in the 1980's to further define the geothermal and potential magmatic system within Long Valley Caldera (Figure 23).

The results from Mammoth-1 (Figure 25) illustrate the general production and injection reservoir sections at Casa Diablo. Shallow wells (<200m; 650 ft.) at produce 170°C (338°F) outflow shown by the shallow temperature-peak in Mammoth-1 (Figure 25) that is supplied by upflow from an active geothermal system to the west. Injection wells return the produced fluid to deeper (750m; 2460 ft.) permeable zones in the underlying Bishop Tuff shown by the second deeper temperature peak in the Mammoth-1 well (Figure 25). Casa Diablo Injection was initially placed at the same level as the producing reservoir in wells IW-1 and IW-2 causing progressive degradation in production temperatures. As a result, injection was deepened and shallow injection wells were sealed off in 1990. The impermeable landslide block in the southern caldera moat separates the Early Rhyolite reservoir from the underlying Bishop Tuff and limits the vertical distribution of shallow hydrothermal circulation in the southern caldera. The isolation of the shallow Early Rhyolite and deeper Bishop Tuff allows sustained production at Casa Diablo by isolating the shallow hotter outflow production from deeper cold injection fluids. From early 1993 to mid-1995, overall field production declined from 7,000 kph to 6,160 kph. To offset declines in flow rate and temperature, production was augmented in 2006 by completing production wells 57-25 and 66-25 to total depths of ~500m to the west of Casa Diablo in the area immediately east of Mammoth Lakes designated as Basalt Canyon by MPLP. The two wells produce higher temperature 180°C fluids that are sent to the existing Casa Diablo plants through a 3 mile pipeline bringing approximately 2000 kph (4,000 gpm) to commingle and sustain a current average of flow rate of 6,000 kph (12,000 gpm) to the Casa Diablo power plants.

5.3 Project plans

ORNI 50, LLC, plans to expand electric production by approximately 50% (3,000 kph or 6,000 gpm) by drilling additional wells in the Basalt Canyon area to produce a total of approximately 18,000 gpm (9,000 kph) to sustain generation of approximately 60 MWe (gross).

5.4 Long Valley hydrologic monitoring

The shallow hydrologic system in Mammoth Groundwater Basin has been monitored periodically by the Mammoth Community Water District and the hydrological system of the whole caldera has been investigated by the U.S. Geological Survey since the early 1980's as part of volcanic hazard studies, and

by Mammoth Pacific Limited Partnership (MPLP), as part of the cooperative monitoring of geothermal development on behalf Long Valley Hydrological Advisory Committee (LVHAC). The shallow cold groundwater monitoring network includes a limited number of supply and idle wells in the groundwater basin in the southwestern caldera moat. The caldera-wide monitoring network includes geothermal monitoring wells, shallow groundwater monitoring wells and surface hydrological features such as cold and hot springs and streams. The USGS monitors reservoir pressure and depths to water at thermal well CH10B in the southeast moat and cold-water wells SC-2 and M14 in the southwest moat (Figure 15). From 2001-2007, the USGS also monitored water levels in cold-water well CD-2 on the northern side of the production well field (Figure 15) for the MPLP monitoring well database. MPLP currently monitors producing wells for flow rate, wellhead temperature, wellhead flowing pressure and downhole reservoir pressure and also collects pressure data from six idle geothermal test wells or exploration temperature gradient holes drilled in the southern caldera moat (Figure 15).

The detailed caldera-wide LVHAC monitoring program in Long Valley has collected high quality reliable data on shallow and deep geothermal reservoir variations for more than 20 years. The collective record shows that the monitoring network is sensitive enough to detect long-term changes in relatively stable production periods (1985-1990), the onset of additional production for expanded generation (1991) and the augmented production from higher temperature wells in the Basalt Canyon/Shady Rest area (2005). The monitoring system also detected the inadvertent diversion of Casa Diablo injection into a well open to the shallower Early Rhyolite reservoir in late 2000 resulting in a very short-term production pressure increase that serves as an excellent marker obvious in all of the MPLP thermal monitor wells operating at that time. Monitoring equipment problems have also been readily detected through extreme or unusual data quality variations in the monitoring records. Data quality is sufficient that detailed short-term hourly records correlate very well between two individual monitoring points and instrumentation is sensitive enough to record diurnal changes and earth tide variations (Sorey, 2010).

5.4.1 Early development monitoring

Shallow (150-200m) fractured permeable Early Rhyolite is the principal production reservoir at Casa Diablo. All of the produced fluid is injected into deeper (600-700m) wells completed in the underlying Bishop Tuff below the landslide block that separates the shallow moderate temperature Early Rhyolite reservoir from the lower permeable fractured Bishop reservoir at depth. Between 1985-1990 and 1992-2005 drawdown rates in production wells were proportional to the total rate of production and overall reservoir pressure variations were limited in range (Figure 26 and 27). Monitoring records document pressure variations that are proportional to seasonal change or episodic production changes at Casa Diablo (Figures 28 and 29). Total production volume was increased after 1991 to support 40 MWe (gross) generation. Injection wells were deepened to avoid detrimental temperature declines in the shallow production reservoir. The result was a short-term period of more significant reservoir drawdown and a ~25 psi total reservoir pressure decline in nearby monitoring wells. Temperatures have declined from 175°C (347°F) to 150-165°C (302-327°F) in Casa Diablo production wells from 1990-2003.

5.4.2 Recent development monitoring

The production scheme for Casa Diablo was altered again in 2005 when wells 57-25 and 66-25 in Basalt Canyon (Figure 23) began to contribute ~ 4,000 gpm of higher temperature brine to the brine flow through the power plants and several cooler producing wells at Casa Diablo were either shut in or their flow rates reduced. Consequently, reservoir pressures within the Basalt Canyon area declined ~ 13 psi while pressures increased on the order of 15-20 psi in monitoring well 65-32 near Casa Diablo nearly recovering the ~25 psi total reservoir pressure decline that occurred during 14 years of expanded production (Figure 29) (Sorey, 2010).

Recent monitoring records for wells east of Casa Diablo generally correlate with pressure changes in the production reservoir at Casa Diablo prior to the onset of production from Basalt Canyon (Figures 27 and 29). Monitoring equipment problems affected the data recorded in well CW-3 (Figure 30) but reliable downhole pressure records for wells 65-32, 28-34, ESN, CW-3, and CH10B (Figures 27-32) illustrate the hydrologic continuity of the geothermal production zone to the east of Casa Diablo and the sensitivity of the hydrologic system to short-term induced pressure changes and long-term natural seasonal variations. Subtle pressure changes occurred through 2006 in USGS monitoring point CH10B at Hot Creek gorge ~ 10 km east of Casa Diablo (Figure 31) and while these changes were not as definitive as pressure variations in wells closer to Casa Diablo, changes in the CH-10B records are consistent with short-term pressure increases in late 2006 associated with the change to production from Basalt Canyon. Pressure variations in CH-10B farther east are significantly attenuated both in magnitude and amplitude compared with measured pressures close to Casa Diablo (for example well 28-34 in Figure 30) as would be expected with increasing distance in an aquifer.

Pressure records document declines from west to east for monitoring wells west of Casa Diablo from 1995 through 2006 (Figures 32-34). Pressure changes in monitoring wells 66-31 and 12-31 are consistent with the lateral continuity of the fractured Early Rhyolite geothermal production zone west of Casa Diablo. Wellbore problems in 66-31 after 2006 caused extreme variations in the recorded pressures unrelated to reservoir conditions and the monitoring well is no longer considered a reliable monitoring point (Sorey, 2010). Pressure records for monitoring well 48-29 completed within the Bishop Tuff are consistent with the lateral continuity of the fractured Bishop Tuff west of Casa Diablo. Reservoir pressures declined ~5 psi in monitoring well RDO-8 near Shady Rest and ~ 10 psi in BC12-31 with the onset of production from Basalt Canyon in 2006 (Figures 33, 34). The RDO-8 corehole completion allows communication with both the Early Rhyolite section and the underlying Bishop Tuff. The low-permeability landslide block that separates the shallower Early Rhyolite from the deeper Bishop Tuff in the southern caldera moat is absent west of corehole BC 12-31 apparently allowing hydrologic connectivity between thermal flow zones in the Early Rhyolite and Bishop Tuff, at least in the outflow region around Shady Rest. To the west, shallow cold groundwater aquifers are separated from the deeper geothermal reservoir by thick ash-rich Early Rhyolite units (Figure 14). Temperature gradient holes MLGRAP-1 and 2 and Oh Well-1 drilled into impermeable Early Rhyolite units in the western part of the Mammoth Groundwater Basin (Figure 11) and the MCWD generally considers these units as impermeable unproductive consolidated bedrock (Wildermuth, 2009).

Like many geothermal systems, fluid circulation in the Long Valley geothermal reservoir is controlled by permeable faults and fractures. Fluid upflow occurs along penetrative faults that controlled the caldera's collapse or more recent faults that deformed the caldera after collapse. Laterally fluid flow from west to east occurs in the fractured Bishop Tuff that is the primary geothermal reservoir within the caldera. The caldera collapsed along a series of penetrative E-W ring fractures that are the structural margin of the southern caldera. Later post-collapse faulting is predominantly NW-SE. In combination, these deep controlling faults connect the laterally extensive fracture permeability within the Bishop Tuff to channel upflow and outflow in the Shady Rest area.

Head data from shallow cold groundwater water wells distributed around the caldera's west and south moats and pressure data from monitoring wells correlate in time with seasonal patterns but, depending on proximity to recharge sources, differ in magnitude (Figure 28). Thermal monitoring wells show that geothermal reservoir pressures also vary seasonally. From 2007 to present, production reservoir pressures at Casa Diablo have been relatively constant with a superimposed seasonal variability similar to the magnitude and phase of seasonal variations noted prior to 2006 (Sorey, 2010). The shallow groundwater system can be affected locally by changes in heat flow from the deeper geothermal system as illustrated by the poor correlation between thermal monitoring well 65-32 and the nearby non-thermal monitor well CD-2 (Figure 28). The effects on the local shallow aquifer supplying CD-2 are related to local changes in heat flow above the production reservoir at Casa Diablo rather than regional changes in recharge or outflow. Pressure declines around the shallow Casa Diablo production reservoir (<200m) resulted in two-phase conditions (water+steam) near the top of the reservoir that increased the heating of isolated overlying shallow groundwater aquifers. This increase in heat flow resulted in more steam output from local fumaroles (Sorey, 2000).

5.5 Thermal/non-thermal hydrogeology in Long Valley

All of the monitoring results, geochemical and geologic data in Long Valley substantiate a separation between the shallow cold groundwater system and the underlying high temperature geothermal system in the western caldera moat. Drilling results establish that the shallow cold groundwater system is separated from potential geothermal influence by thick impermeable altered sections of Early Rhyolite underlying shallow groundwater aquifers in shallow moat basalt units, glacial outwash or poorly consolidated alluvium/colluvium in the western caldera. Slightly elevated temperatures occur in the northwest part of the Mammoth Groundwater Basin. MCWD wells 16, 17, 18 and 20 (Figure 11) produce water at 15.5 - 21°C slightly above production temperatures of 7.5 – 10.5°C in other parts of the basin (Sorey, 2011). Gradient holes MLGRAP-1 and Oh Well – 1 (Figure 11) also have temperature gradients slightly higher than background values in the caldera. There is no geochemical evidence that deeper geothermal fluid is leaking out into the groundwater basin (Section 4.2.1) (Sorey. 2011; Evans pers. comm.). Instead, all of these holes are located immediately south of the Rhyolite Plateau (Figure 5), the projected source reservoir for the Long Valley geothermal system. The slightly elevated temperatures are related to the increased conductive heat loss around the major thermal disturbance of the of the deeper high temperature geothermal system.

Drilling results and monitoring records also verify that a low to impermeable landslide block underlies much of the central part of the southern caldera moat separating the comparatively shallow Early Rhyolite geothermal reservoir east of Shady Rest and the deeper Bishop Tuff reservoir section where produced fluids are injected at Casa Diablo (Figure 35) (Suemnicht and others, 2007). Differences in geology, chemistry and temperature in Basalt Canyon wells 57-25 and 66-25 illustrate the complexity of interactions within the principal geothermal outflow reservoir in the western caldera. The connection between the thermal water-bearing zones in the Early Rhyolite and those in the Bishop Tuff are related to E-W and NW-SE faults in the southern caldera moat that provide discontinuous and variable vertical permeability channeling upward fluid flow between the Bishop Tuff and the Early Rhyolite. The moderate temperature thermal outflow into the shallow permeable Early Rhyolite rocks east of Shady Rest is effectively separated from the underlying Bishop Tuff and the pervasive influence of cold recharge waters around the edges of the caldera.

Highly permeable and laterally continuous hydrogeologic units over lateral distances of >10km underlie the southeastern part of the caldera. The hydrogeology is poorly defined east of Casa Diablo because fewer wells have been drilled and most do not penetrate as deep as underlying Bishop Tuff reservoir section. The available well data indicates that warm water outflow in the southern and eastern caldera is predominantly shallow (<200m; 650 ft.) occurring in permeable Early Rhyolites immediately east of Casa Diablo (monitoring well CW-3) and is entirely within shallower alluvial or lacustrine units farther east toward Lake Crowley (deep well 66-29). Pressure variations in wells 5-10 km east of Casa Diablo correlate in time and sign with those in the production reservoir (Figure 36) with only minor delays (days to weeks) in the arrivals of the pressure changes induced by changes in the production at Casa Diablo. Geochemical and thermal data from wells and springs in the southeastern caldera between Casa Diablo and Hot Creek gorge corroborate the continuity of thermal fluid flow from Casa Diablo through Hot Creek eastward to Lake Crowley (Sorey and others, 1991) and the comingling of shallow geothermal outflow and groundwater systems in the southeastern caldera. The combination of isobutane migration and reservoir pressure transmission in the production zone and injection zones signifies a high degree of lateral continuity within the relatively shallow geothermal system in the south moat.

Project Impacts

Variations in precipitation, recharge, geothermal production, non-thermal groundwater withdrawals, earthquakes, magmatic activity and crustal deformation all affect the Long Valley hydrologic system (Sorey 2000, 2010). Seasonal snowmelt is the predominant influence on the hydrology of the caldera. Deep recharge from the west supplies thermal water to the deep hot geothermal source reservoir in the western caldera moat and the eventual outflow at lower elevations to the east. Based on drilling results and pressure monitoring data, the shallow cold groundwater system appears to be isolated from the deeper geothermal system and is recharged from both the western and southern topographic margins of the caldera (Sorey, 2011; Evans pers. comm.).

Detailed hydrologic monitoring was initiated in Long Valley to address concerns that geothermal development effects would predominate resulting in detrimental changes in surface and groundwater quality and thermal features. A large part of the concern was related to short and long-term pressure

declines that would alter the established hydrologic conditions supporting sensitive thermal springs. After 27 years of geothermal production, monitoring data show that pressure changes associated with the current level of production from Casa Diablo and Basalt Canyon are within sustainable levels (Sorey, 2010). The total reservoir pressure decline from geothermal production has been about 55 psi, with 35 psi of the decline occurring in 1991, when production was increased to supply the MP II and PLES I power plants and changes in injection to return spent fluid to the deeper Bishop Tuff reservoir (Sorey, 2005, 2010).

Less pronounced pressure declines have occurred in the shallow outflow zone around Casa Diablo. Monitored pressures in well CW-3, ~5km east of Casa Diablo, declined ~2-3 psi as production increased in 1991. The limited 165 acre production area at Casa Diablo continued to sustain 40 MWe generation without drilling make-up wells and with comparatively small ~ 2 psi pressure decline from 1991-2003 (Sorey 2005, 2010). Production has since shifted west since 2006 toward the outflow source to produce deeper hotter fluid from the Basalt Canyon ~2 km west of Casa Diablo. Pressures in Basalt Canyon have declined ~ 13 psi while Casa Diablo reservoir pressures have increased 15-20 psi partially recovering the 1991-2003 reservoir pressure declines. As planned, the Project will continue to shift production toward the ultimate source of reservoir of the Long Valley hydrothermal system. Assuming continued reservoir pressure increases from the westward shift in production, the potential impact of reservoir pressure declines are expected to lessen downgradient of Casa Diablo in the shallower thermal outflow that sustains thermal springs farther east.

Drilling results and hydrologic monitoring data establish that the shallow groundwater system and comparatively shallow geothermal outflow interact in portions of the southeastern caldera moat. Extensive geochemical monitoring within the caldera has not detected detrimental changes in water quality during geothermal development based on analyses of cations, anions and trace elements in the hot spring waters derived from geothermal outflow. The concentration of conservative elements such a Cl,B, F that have been used for decades by the USGS to track the origin, evolution and circulation of geothermal fluids have remained stable and unchanged in both the exploited geothermal reservoir and the active hot springs within the caldera (Sorey, 2011; Evans pers. comm.). Rates of flow of thermal water in springs at Hot Creek Gorge and the Hot Creek Fish Hatchery have been estimated from the concentrations of chloride and boron measured in the water. The estimated rate of thermal water discharge at Hot Creek Gorge has varied little since 1988 during a time of several changes in geothermal production and increased crustal unrest. Rapid increases in the discharge rate and temperatures that led to the closing of Hot Creek swimming area in 2006 were more in response to above normal precipitation in the preceding winter (Farrar and others, 2007) and cannot be related to changes in geothermal production from Casa Diablo. Distinct pressure variations are noted close to Casa Diablo but effect attenuates with distance and the magnitude of measured pressure variations are significantly less farther east at sensitive sites like Hot Creek. Water level measurements in well CH10B, located near Hot Creek Gorge (Figure 31), do not appear to show reservoir pressure changes related to geothermal development.

Producing the deeper Basalt Canyon geothermal reservoir has less potential for adverse effects on shallow cold groundwater in the MCWD well field or the expansion of thermal ground in the western caldera. Project production will be from the deeper fractured Early Rhyolite units and the Bishop Tuff the west. Separations between the deeper geothermal reservoir and shallow cold groundwater aquifers in the central Mammoth Groundwater Basin limit the potential for impacts to groundwater quality and quantity of supply.

Updated numerical models of the Long Valley geothermal reservoir indicate that Project development should have minimal impact on surface manifestations to the east around the Resurgent Dome (GSI, 2012; Garg, 2012). As a tool to help forecast future behavior of the geothermal reservoir, the model creates a three-dimensional simulation of pressure and temperature distributions within the reservoir over time. Model validity depends on the assumptions and inputs. The numerical model for Long Valley is based on the well-constrained geologic conceptual model (Section 5.2) and is validated by calibrating and matching the calculated temperature and pressure behavior against the extensive historical temperature and pressure monitoring data from the caldera. Model forecasts indicate that reservoir temperatures should decline by ~10°C and reservoir pressure declines should range from 1.45 psi to 10 psi, at the maximum only 20% of the pressure declines monitored during the prior 27 years of production from Casa Diablo. Project wells will produce deeper hotter reservoir section than the existing shallow Casa Diablo production reservoir consequently potential effects on cold groundwater, subsidence and more distant surface manifestations related to declining reservoir pressures would be minimized. Simulation results do not forecast declines in thermal output to the most prominent hot springs from either existing production or the expanded Project (GSI, 2012; Garg, 2012). The potential impact at the Fish Hatchery Springs could be ~ 17% decline in thermal water input. The thermal water fraction of the Hatchery springs is a very small part of the total flow and spring temperatures have previously been shown to be primarily dependent on seasonal fluctuations in precipitation and not the thermal component of flow (Sorey and Sullivan, 2006).

6 Conclusions

Long Valley caldera has been an important geothermal exploration target since the 1960s. A large active young relatively shallow magmatic heat source is evident from the massive eruption of the Bishop Tuff 760,000 years ago. Still younger eruptions 600 years ago along the Mono-Inyo volcanic chain are obvious evidence of continued magmatic input supplying heat to the geothermal system in Long Valley. At least 60% of the Bishop Tuff filled the caldera depression providing a significant volume of fractured reservoir rock. Numerous hot springs and fumaroles across the caldera are ample evidence of an actively circulating hydrothermal system within the caldera. Early exploration wells (<300m) around Casa Diablo were drilled near the most prominent hot springs and fumaroles on the west flank of the Resurgent Dome. Deeper wells explored the southeastern caldera moat (Rep 66-29) and evaluated lease offerings in the northern Resurgent Dome (Clay Pit-1) and at Casa Diablo (Mammoth-1). The results 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 deeper western source reservoir.

Prior to 2006, geothermal development within Long Valley Caldera had been limited to limited to ~165 acres around Casa Diablo on the southwestern edge of the caldera's Resurgent Dome. Production has been from a shallow (<200m) moderate temperature (170 ^{o}C) outflow in a permeable Early Rhyolite reservoir. Deeper (600 m) injection wells return all of the spent fluid to the underlying permeable Bishop Tuff. Production sustained 40 MWe (gross) until 2006 without drilling any makeup wells. The proposed Project will further develop the Basalt Canyon area in the western caldera closer to the higher temperature outflow from the ultimate deep source reservoir in the west. ORNI 50, LLC, the project operator, plans to expand generation by approximately 50% (3,000 kph or 6,000 gpm) by drilling additional wells in the Basalt Canyon area to produce a total of approximately 18,000 gpm (9,000 kph) to sustain generation of approximately 73MWe (net) from four power plants.

Well monitoring data show that pressure changes associated with the current level of production from Casa Diablo and Basalt Canyon are within sustainable levels (Sorey, 2011). The pressure records and geochemical data establish that fluid injected deep into the Bishop Tuff beneath the shallower Early Rhyolite production reservoir at Casa Diablo flows both east and west within the Bishop Tuff. The shallow cold groundwater aquifers farther west in the Mammoth Groundwater Basin are separated from the underlying geothermal system by thick altered and impermeable sections of ash-rich Early Rhyolite. To the east of Shady Rest, a landside block of indurated Paleozoic rocks surrounded by intensely altered ash that slid into caldera during the last stages of Bishop Tuff eruption underlies approximately 3 km^2 of the southern moat and separates the deeper Bishop Tuff geothermal reservoir and controls the shallower outflow of hydrothermal fluids southeast around the Resurgent Dome. At some distance east of Shady Rest, the geothermal production and injection zones merge into a single zone of laterally flowing hot water sourced by a deeper upflow region in the west caldera.

Geochemistry, isobutane migration and reservoir pressure transmission in production zone and injection zones signifies a high degree of lateral continuity within the relatively shallow geothermal system beneath the southern caldera moat. The Bishop Tuff injection reservoir is laterally continuous into the western caldera moat based on detailed pressure data collected as part of hydrologic monitoring of geothermal development. Transport of dissolved isobutane away from Casa Diablo, both within the production and injection reservoirs is poorly understood, even though the initial timing and appearance can be detected in surface manifestations and wells. The geology of the Basalt Canyon area is still being evaluated but the difference in geochemistry between in wells 57-25 and 66-25 may be related to the degree of penetration and the complexity of E-W and NW-SE faults in the southern caldera moat that provide discontinuous and variable vertical permeability channeling upward fluid flow between the Bishop Tuff and the Early Rhyolite. Reservoir pressures and geochemical data are consistent with the west to east flow of thermal water across the caldera.

Factors other than pressure reductions in a geothermal reservoir that influence temperature and flow rate of surface thermal features include variations in precipitation, snow melt, groundwater recharge,

pumping of groundwater aquifers, and crustal unrest (Sorey, 2000). With increased production from Basalt Canyon wells 57-25 and 66-25 and curtailed production from Casa Diablo, monitored reservoir pressures in Basalt Canyon declined ~10 psi while pressures at Casa Diablo increased on the order of 15-20 psi. Shifting production to produce deeper geothermal outflow closer to the ultimate source reservoir in the west has had a positive effect on reservoir pressures at Casa Diablo and mitigates effects on surface manifestations to the east. Shifting production away from the comingled thermal and non-thermal hydrology around the southern Resurgent Dome should result in less stress on thermal features sourced by shallow outflow. The planned production and injection scheme for Long Valley has been evaluated with an updated numerical model of the geothermal reservoir. The Long Valley reservoir simulation is based on the well-constrained geologic conceptual model and is validated by calibrating and matching temperature and pressure behavior against the extensive historical temperature and pressure monitoring data from the caldera. Modeled development scenarios included production from Basalt Canyon and Casa Diablo with injection in part of Basalt Canyon and east of Casa Diablo. Based on modeling forecasts, reservoir pressure declines related to the Basalt Canyon development are forecast to be in the range of 1.45 psi to 10 psi, which would be equivalent to approximately 20% of measured pressure declines at Casa Diablo previously measured declines over 27 years of production from Casa Diablo. Basalt Canyon wells will be completed and produce from zones two to three times deeper than the existing Casa Diablo production reservoir, consequently potential effects on shallower cold groundwater aquifers are expected to be minimized.

7 References

Allis, R., Bromley, C. and Currie, S., 2009, Update on subsidence at the Wairakei-Tauhara geothermal system, New Zealand. Geothermics 38 (2000) pp169-180.

Bailey, R.A., Dalrymple, G.B. and Lanphere, M.A., 1976, Volcanism, structure and geochronology of the Long Valley caldera, Mono County, California. Journal of Geophysical Res., Vol. 81, No. 5, pp. 725-744.

Bailey, R.A., Dalrymple, G.B. and Lanphere, M.A., 1989, Quaternary Volcanism, of the Long Valley Caldera and Mono-Inyo Craters Eastern, Field Trip Guidebook. 28th International Geological Congress, 36 pp.

Bailey, R.A., 1989, Geologic map of Long Valley caldera, Mono-Inyo Craters Volcanic Chain, and Vicinity, Eastern California. US Geol. Survey Map I-1933.

Bailey, R.A., 2004, Eruptive History and Chemical Evolution of the Precaldera and Postcaldera Basalt-Dacite Sequences, Long Valley, California: Implications for Magma Sources, Current Seismic Unrest and Future Volcanism. US Geol. Survey Prof. Paper 1692 75pp

Bergfeld, D. and Evans, W.C.,2011, Monitoring CO2 emissions in tree-kill areas near the Resurgent Dome at Long Valley Caldera, California. USGS SI-2011-5038.

Blackwell, D.D., A transient model of the geothermal system of Long Valley caldera, California. Journal of Geophysical Res., Vol. 90, No. B13, pp. 11,229-11,242

Bursik, M. and K. Sieh, Range Front Faulting and Volcanism in the Mono Basin, Eastern California, J. Geophys. Res., 94, 15,587-15,609, 1989.

California Division of Mines and Geology (CDMG). 1982. State of California Special Studies Zones, NW ¼ Mt. Morrison, Official Map. Effective: January 1, 1982.,

California Energy Commission, 2012, California geothermal energy statistics and data. http://energyalmanac.ca.gov/renewables/geothermal/index.html

California Division of Mines and Geology (CDMG), 2005, Probabilistic Seismic Hazards, Peak Ground Acceleration Atlas; Mariposa 1 x 2 Degree Sheet. Department of Conservation, California Geological Survey. http://www.consrv.ca.gov/CGS/rghm/psha/Map_index/Pages/Mariposa.aspx

California Geologic Survey, 2012, Alquist-Priolo Earthquake Fault Zones. http://www.conservation.ca.gov/cgs/rghm/ap/Pages/Index.aspx.

Cathles, L.M., Erendi, A. H. J., and Barrie, T., 1997, How long can a hydrothermal system be sustained by a single intrusive event? Econ Geo. v. 92 no. 7-8 p. 766-771

Cramer, C. H. & Toppozada, T. R. 1980. A seismological study of the May, 1980, and earlier earthquake activity near Mammoth Lakes, California. *In*: Sherburne, R. W. (ed.) Mammoth Lakes, California earthquakes of May 1980. California Division of Mines and Geology Special Reports, 150, 91–122.

Dixon, T. H., Miller, M., Farina, F., Wang, H. & Johnson, D. 2000. Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North America. Tectonics, 19, 1–24.

Eichelberger, J.C., Vogel, T.A., Younker, L.W., Miller C.D., Heiken, G.H., and Wohletz, K.H., 1988, Structure and stratigraphy beneath a young phreatic vent: South Inyo Crater, Long Valley caldera, California. Journal of Geophysical Res., Vol. 93, No. B11, pp. 13,208-13,220.

Eichelberger, J.C., 2003, Where have all the magmas gone (long time passing)? *in*: Understanding a Large Silicic Volcanic System: An Interdisciplinary Workshop on Volcanic Processes in Long Valley Caldera-Mono Craters, NSF

Ellsworth, W. L. 1990. Earthquake history, 1769–1989. *In*: Wallace, R. E. (ed.) The San Andreas Fault System, California. US Geological Survey, Washington DC, 153–187.

EMA, 2005, Basalt Canyon Geothermal Pipeline Project EA/Draft EIR

Evans, W.C., Lorenson, T.D., Sorey, M.L., and Bergfeld, & D., 2004,Transport of injected isobutane by thermal groundwater in Long Valley caldera, California, USA. in Wanty, R.B. and Seal II, R.R. eds., Water-Rock Interaction-11, Saratoga Springs, Balkema, p. 125–129.

Farrar, C.D., Sorey, M.L., Rojstaczer, S.A. Janik, C.J., Winnett, T.L., 1987. Hydrologic and geochemical monitoring in Long Valley caldera, Mono County, California, 1985. U.S.Geological Survey Water-Resources Investigations Report87-4090, 71 pp.

Farrar, C.D., Sorey, M.L., Evans, W.C., Howle, J.F., Kerr,B.D., Kennedy, B.M., King, C.-Y., Southon, J.R., 1995.Forest-killing diffuse CO_2 emission at Mammoth Mountainas a sign of magmatic unrest. Nature 376, 675-678.

Farrar, C.D., Evans, W.C., Venesky, D.Y., Hurwitz, S. and Oliver, L.K., 2003, Inferences of the hydrothermal system beneath the resurgent dome in Long Valley Caldera, east-central California, USA, from recent pumping tests and geochemical sampling. JVGR 127 (2003).

Farrar, C.D., Evans, W.C., Venesky, D.Y., Hurwitz, S. and Oliver, L.K., 2007, Boiling Water at Hot Creek – The Dangerous and Dynamic Thermal Springs at California's Long Valley Caldera. US Geol. Survey Fact Sheet 2007-3045 (http://pubs.usgs.gov/fs/2007/3045).

Farrar, C.D., DeAngelo, J., Williams, C., Grubb, F., and Hurwitz, S., 2010, Temperature Data from Wells in Long Valley Caldera, California. USGS Data Series 523 v. 1.

Finger, J.T. and Jacobsen, R.D., 1999, Phase III drilling operations at the Long Valley Exploratory Well (LVF 51-20). Sandia National Laboratories SAND99-1279 pp 356-370.

Garg, S., 2012, Long Valley Caldera/Casa Diablo Geothermal Reservoir Simulation Model: Peer Review, Geologica internal report.

Geologica, 2003, Preliminary Results, Evaluation of Production on Fluid Chemistry at Casa Diablo Long Valley, California. Mono County internal report.

Gerlach, T.M., Doukas, M.P., McGee, K.A., and Kessler, R., 1998, Three-year decline of magmatic CO_2 emissions from soils of a Mammoth Mountain tree kill: Horseshoe Lake, CA, 1995-1997:Geophysical Research Letters, v. 25, no. 11, p. 1947-1950.

Geothermal Science Inc. (GSI), 2012, Long Valley Numerical Model - Progress Update. Interim draft by Richard Holt for Ormat Technologies.

Hildreth, W. 2004. Volcanological perspectives on Long Valley, Mammoth Mountain, and Mono Craters: several contiguous but discrete systems. Journal of Volcanology and Geothermal Research, v.136, pp. 169–198.

Hill, D.P., Dzurisin, D., Ellsworth, W.L., Endo, E.T., Galloway, D.L., Gerlach, T.M., Johnston, M.J.S., Langbein, J.O., McGee, K., Miller, C.D., Oppenheimer, D., and Sorey, M.L., 2002, Response plan for volcano hazards in the Long Valley caldera and Mono Craters region California: U.S. Geological Survey Bulletin 2185, 57 p

Hill, 2006, Unrest in Long Valley Caldera, 1978-2004; in Troise, C., De Natale, G. & Kilburn, C. R. J. (eds) 2006. Mechanisms of Activity and Unrest at Large Calderas. Geological Society, London, Special Publications, 269, 1–24.

Hill, D. P. & Prejean, S. 2005. Volcanic unrest beneath Mammoth Mountain, California. Journal of Volcanology and Geothermal Research, 146, pp257–283.

Howle, J.F., Langbein, J.O., Farrar, C.D., and Wilkinson, S.K., 2003, Deformation near the Case Diablo geothermal well field and related processes Long Valley caldera, Eastern California, 1993-2000: Journal of Volcanology and Geothermal Research, v. 127, no. 3-4, p. 365-390.

GEA, 2010, Geothermal energy:international market update. http://www.geo-energy.org/pdf/reports/gea_international_market_report_final_may_2010.pdf

Jessey,D.R. 2009, The Blue CHERT Mine: an epithermal gold occurrenc e in the Long Valley Caldera. Desert Study Center (Cal.State Fullerton) 2009 Symposium.

Lachenbruch, A.H., Sass, J.H., Munroe, R.J., and Moses, T.H., Jr., 1976, Geothermal setting and simple heat conduction models for the Long Valley Caldera: Journal of Geophysical Research, v. 81, no. 5, p. 769-784.

Langbein, J.O., 2003, Deformation of the Long Valley Caldera, California: inferences from measurements form 1988 to 2001: Journal of Volcanology and Geothermal Research, v. 127, no. 3-4, p. 247-267.

Lipshie, S.R., 2001, Geologic Guidebook to the Long Valley-MonoCraters Region of Eastern California (2nd Ed.). South Coast Geological Society, 270p.

Mahood, G.A., Ring J.H., Manganelli, S. and McWilliams M.O., 2010, New 40Ar/39Ar ages reveal contemporaneous mafic and silicic eruptions during the past 160,000 years at Mammoth Mountain and Long Valley caldera, California. GSA Bulletin; March 2010; v. 122; no. 3-4; p. 396-407; DOI: 10.1130/B26396.1

Majer, E.L., 2011, Updated induced seismicity protocols. DOE Geothermal Technology Program, http://www1.eere.energy.gov/geothermal/news_detail.html?news_id=18045

Majer, E. L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B., and Asanuma, H., 2007, Induced seismicity associated with Enhanced Geothermal Systems. Geothermics 36 (2007).

Mariner and Wiley, 1976, Geochemistry of thermal waters in Long Valley, Mono County, California. Journal of Geophysical Res., Vol. 81, No.5, pp. 792-800.

Martini, B. A., 2002, New insights into the structural, hydrothermal and biological systems of Long Valley caldera using hyperspectral imaging. PhD. Thesis, Univ. of Calif. Santa Cruz, 291 p.

Mayo, E.B., 1934, Geology and mineral resources of Laurel and Convict basins, southeastern Mono County, California. Calif. J. Mines and Geology v.30 (1) pp79-88.

MCWD, 2012, urban water management plan. PowerPoint presentation to the LV HAC by Greg Norby.

Metz, J.M., and Mahood, G.A., 1985, Precursors to the Bishop Tuff eruption: Glass Mountain, Long Valley, California. J. Sedimentary Petrology, v. 45, pp 207-211.

Miller, C.D., Mullineaux, D.R., Crandell, D.R., and Bailey, R.A., 1982, Potential hazards from future volcanic eruptions in the Long Valley Mono Lake area, east central California and southwest Nevada; a preliminary assessment: U.S. Geological Survey Circular 877, 10 p.

Miller, C.D., 1985, Holocene eruptions at the Inyo Volcanic chain, California: implications for possible eruptions in Long Valley. Geology, v. 13, pp 14-17.

Mossop, A. and Segall, P., 1997, Subsidence af The Geysers geothermal field, N. California from a comparison of GPS and leveling surveys. Geophysical Research Letters v.24 n.14 pp 1839-1842.

Newhall, C. G. & Dzurisin, D. 1988. Historical unrest at large calderas of the world, Volumes 1 and 2. US Geological Survey Bulletin, 1855.

Newhall, 2003, A global perspective on restless calderas *in*: Understanding a Large Silicic Volcanic System: An Interdisciplinary Workshop on Volcanic Processes in Long Valley Caldera-Mono Craters.

Norby, G., 2012, mammoth Community Water District urban water management plan. Presentation to the LV HAC, February 2012.

Pitt, A. M. & Hill, D. P. 1994. Long-period earthquakes in the Long Valley Caldera region, eastern California. Geophysical Research Letters, 21, 1679–1682

Poland, J. and Lofgren, B. E. 1984, Case Histroy No. 9.13 San Joaquin Valley, California, USA in Poland, J. (ed) Guidebook to studies of land subsidence due to groundwater withdrawl. UNESCO International Hydrological Programme, Working Group 8.4.

Prejean, S. G. Hill, D. P., Brodsky, E. E., Hough, S. E. Johnston, M. J. S., Malone, S. D.,Oppenheimer, D. H., Pitt, A. M., and Richards-Dinger, K. B., 2004, Remotely Triggered Seismicity on the United States West Coast following the Mw 7.9 Denali Fault Earthquake, Bulletin of the Seismological Society of America, Vol. 94, No. 6B, pp. S348–S359.

Prenn, N., and Dyer, T., 2008, Technical Report Preliminary Assessment Long Valley Project Mono County, California USA. Vista Gold internal report

Sorey, M.L., Lewis, R.E. and Ohlmstead, F.H., 1978, The hydrothermal system of Long Valley caldera, California. US Geological Survey Prof. Paper 1044-A, 60p.

Sorey, M. L, G. A. Suemnicht, N. J. Sturchio, and G. A. Nordquist, 1991, New Evidence on the Hydrothermal System in Long Valley caldera, California, from Wells, Fluid Sampling, Electrical Geophysics, and Age Determinations of Hot Spring Deposits, Journal of Volcanology and Geothermal Research, 48 (1991), pp. 229-263.

Sorey, M.L., Evans, W.C., Kennedy, B.M., Farrar, C.D., Hainsworth, L.J., and Hausback, B., 1998, Carbon dioxide and helium emissions from a reservoir of magmatic gas beneath Mammoth Mountain, California, Journal of Geophysical Research, v. 103, no. B7, 15,303-15,323.

Sorey, M.L., Evans, W.C., Kennedy, B.M., Rogie, J., Cook, A., 1999, Magmatic gas emissions from Mammoth Mountain, Mono County, California Geology v. 52 n.5.

Sorey, M.L. and McConnell, V.S., 2000, Scientific drilling in Long Valley caldera-an update. Calif. Geology v. 53 pp 4-11.

Sorey, M. L., 2005, Hydrology of the geothermal system in Long Valley caldera, California, Unpublished report for the Long Valley Hydrologic Advisory Committee, Mammoth Lakes, California.

Sorey, M.L., and Sullivan, R., 2006, Quantitative analyses of warm spring waters at the Hot Creek Fish Hatchery, Mammoth Lakes, California, Transactions of the Geothermal Resources Council, v. 30, 947-951.

Sorey, M.L, 2010, Hydrologic Monitoring Summary Long Valley Caldera, California. ORMAT internal report.

Sorey 2011, Hydrologic and Geochemical Analyses of Reservoir Fluids in the Geothermal and Groundwater Systems in the Western Part of Long Valley Caldera. ORMAT internal report.

Suemnicht, G. A., 1987, "Results of Deep Drilling in the Western Moat of Long Valley, CA," EOS, Vol. 68, No. 40, pp. 785-998.

Suemnicht, G. A. and R. J. Varga, 1988, Basement Structure and Implications for Hydrothermal Circulation Patterns in the Western Moat of Long Valley caldera, California, Journal of Geophysical Res., Vol. 93, No. Bll, pp. 13181-13207.

Suemnicht, G. A., Sorey M.L. Moore, J. N. and Sullivan R., 2007, The Shallow Hydrothermal System of Long Valley Caldera, California. Proceedings, Stanford Geothermal Reservoir Engineering Workshop SGP-TR-183.

Taylor, G.C., and Bryant, W.A., 1980, Surface rupture associated with the Mammoth Lakes earthquakes of 25 and 27 May, 1980, *in* Sherburne, R.W., ed., Mammoth Lakes, California earthquakes of May 1980, California Division of Mines and Geology Special Report 150, 1:62,500, p. 49-67.

US Energy Information Administration (EIA), 2012, http://www.eia.gov/

U.S. Geological Survey, 1996, Invisible CO_2 gas killing trees and Mammoth Mountain, California. USGS Fact Sheet 172-96

U.S. Geological Survey and the California Geologic Survey, 2006, Quaternary fault and fold database for the United States, accessed DATE, from USGS web site: http//earthquakes.usgs.gov/regional/qfaults.

USDA, Forest Service, 2000, United States Department of Agriculture (USDA), Forest Service. 2000. Water Quality Management for Forest System Lands in California, Best Management Practices. Pacific Southwest Region, Vallejo, CA, pp. 186.

Waring,G.A.,1965, Thermal springs of the United States and other countries of the world, USGS Prof. Paper 492.

White D.E., 1957, Magmatic, connate and metamorphic waters. GSA Bulletin, v. 68 no. 12 p. 1659-1682

White, D.E. (1968). Hydrology, activity, and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada. U.S. Geological Survey Professional Paper 458-C, 109 pp.

Wildermuth, 2009, Mammoth Basin groundwater model report. MCWD internal report.

Wilhelm, E., Battino, R. & Wilcock, R.J. 1977. Low-pressure solubility of gases in liquid water. Chem. Rev. 77: 219-262.

Wilkerson, G., Milliken, M., Saint-Amand, Pierre. Saint-Amand, D., 2007, Roadside geology and mining history, Owens Valley and Mono Basin. U.S. Bureau of Land Management
Buena Vista Museum of Natural History

Wollenberg, H., Eichelberger, J., Elders, W., Goff, F., and Younker, L., 1989, DOE thermal regimes drilling program through 1988. EOS Transactions of the Amer. Geophys. Union v. 70, n. 28 pp706-707.

This page intentionally left blank

Figures

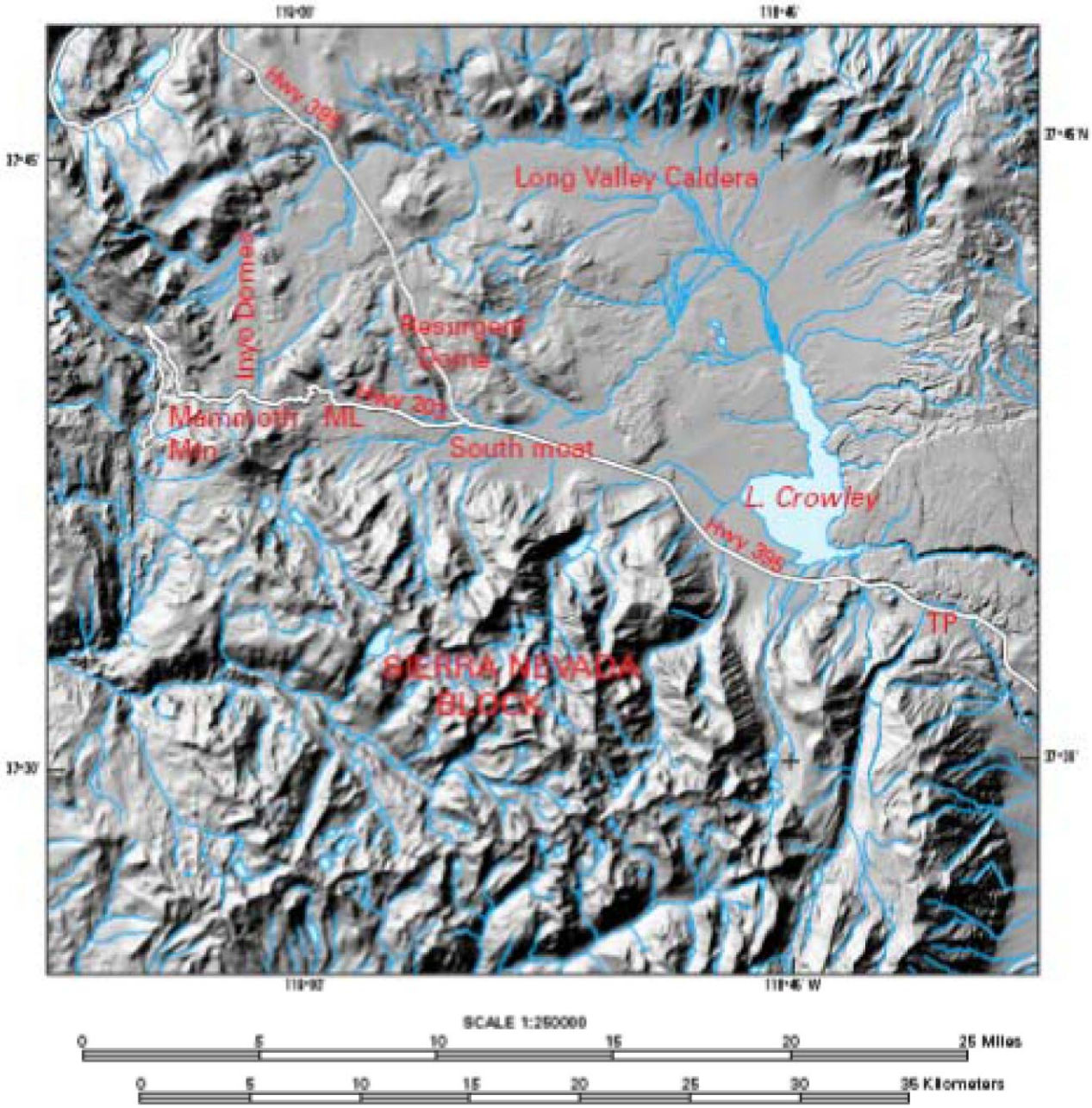


Figure 1 - Location map of Long Valley Caldera and the CD-IV Project area

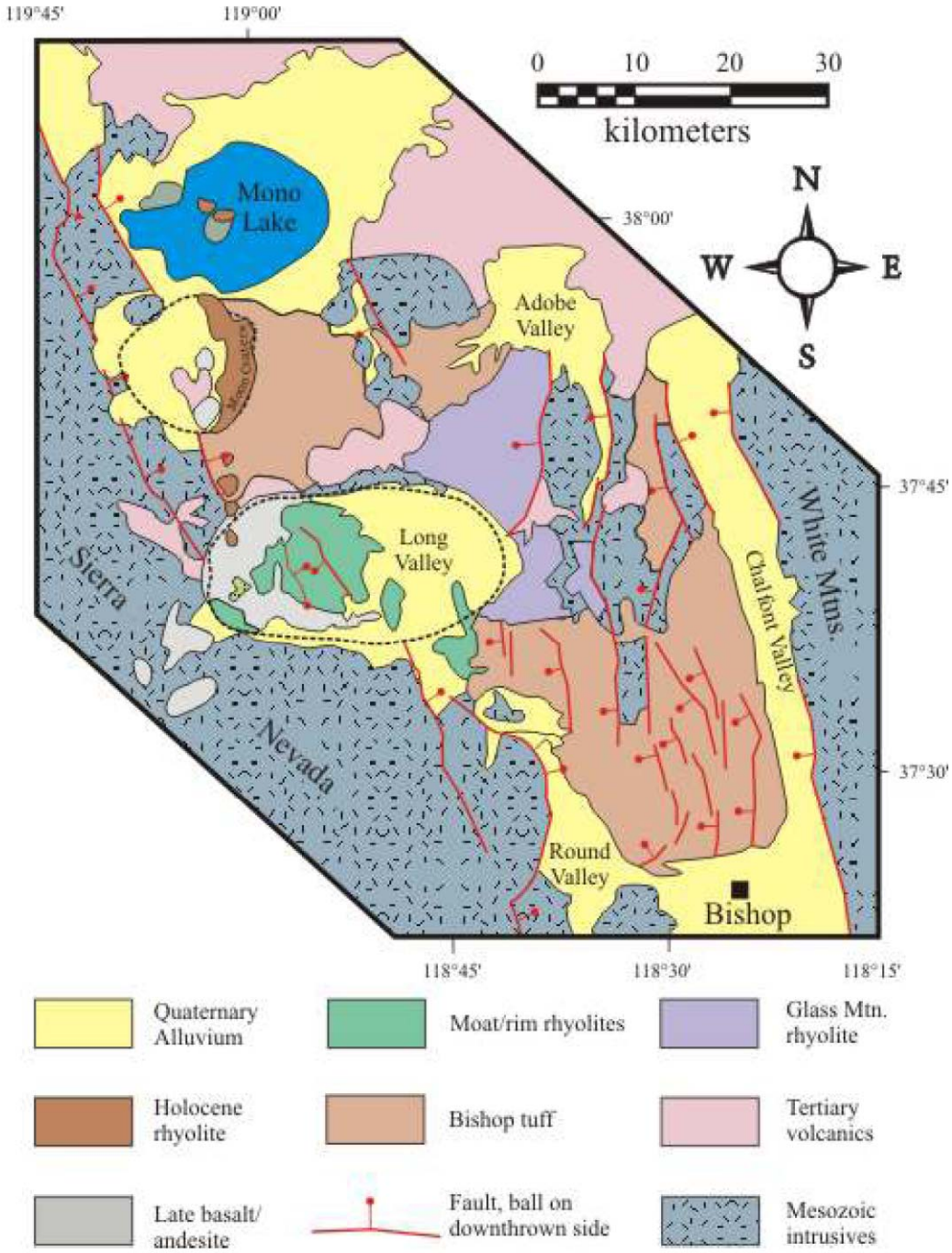


Figure 2 - Generalized geology of Long Valley Caldera (after Bailey, 1989)

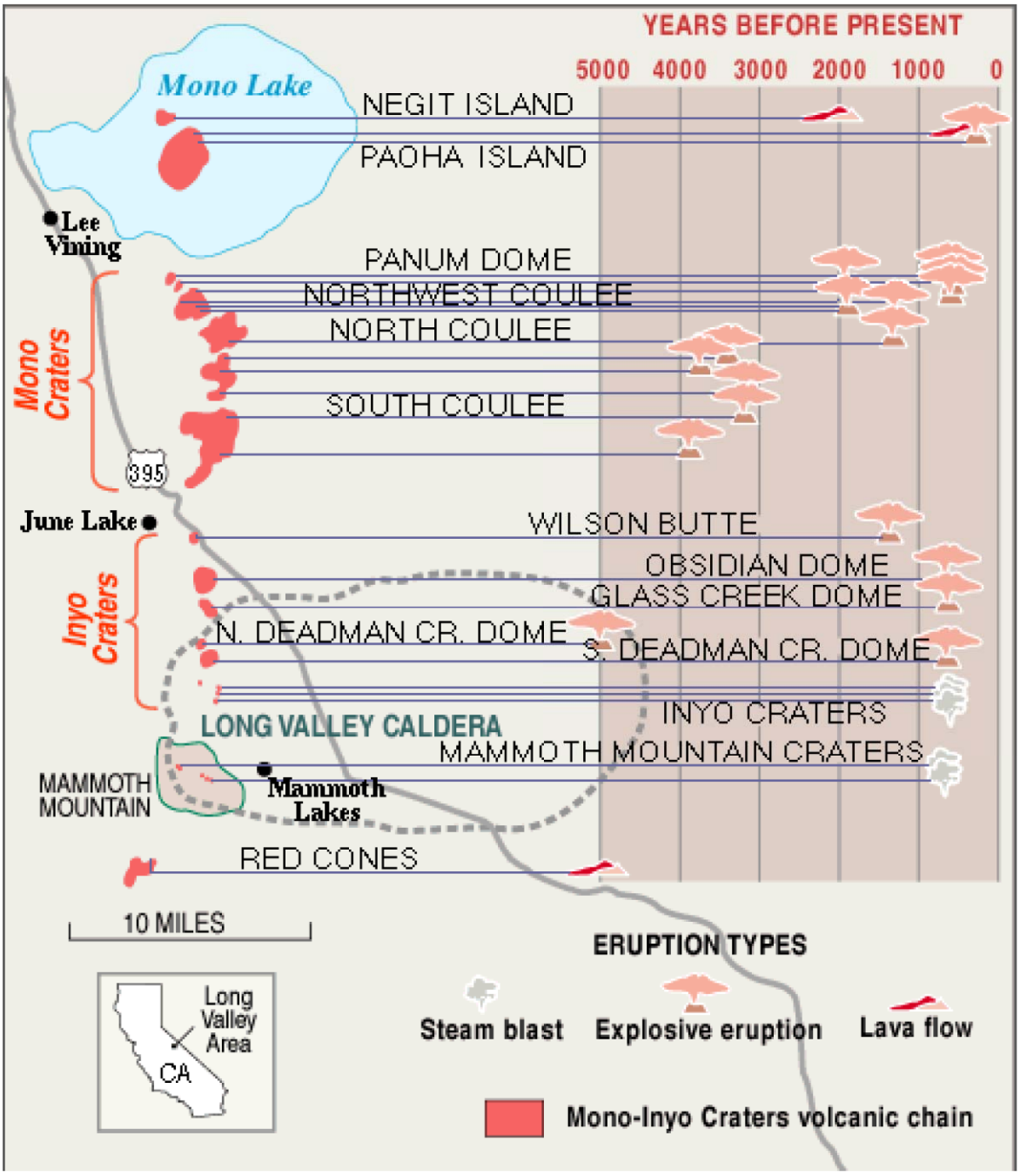


Figure 3 - Locations ages and types of eruptive events in the Mono-Inyo volcanic zone (from USGS)

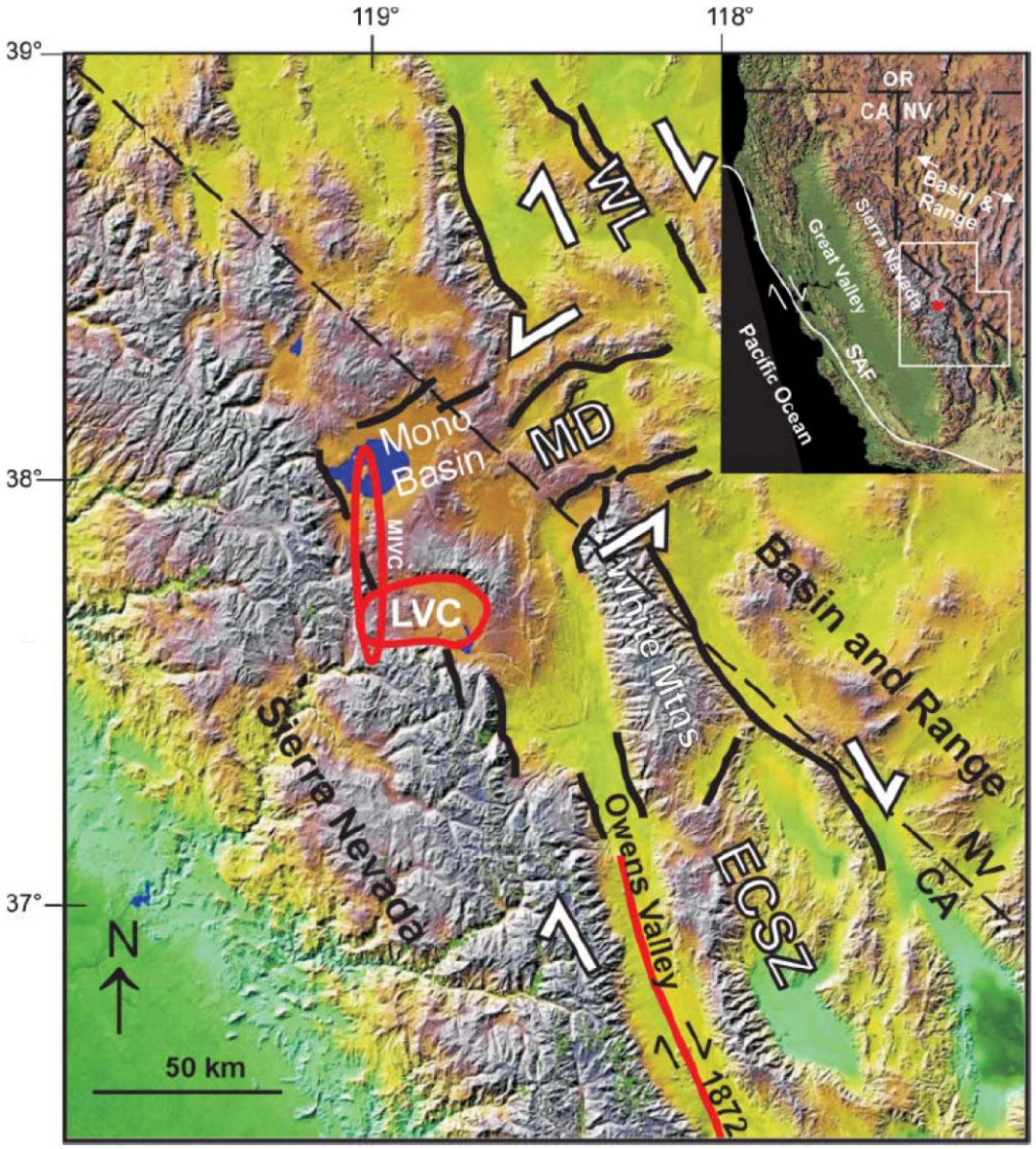


Figure 4 - Shaded relief map of east-central California and western Nevada, showing the location of Long Valley Caldera (LVC) and the Mono–Inyo volcanic chain (MIVC) and predominant regional tectonic features.

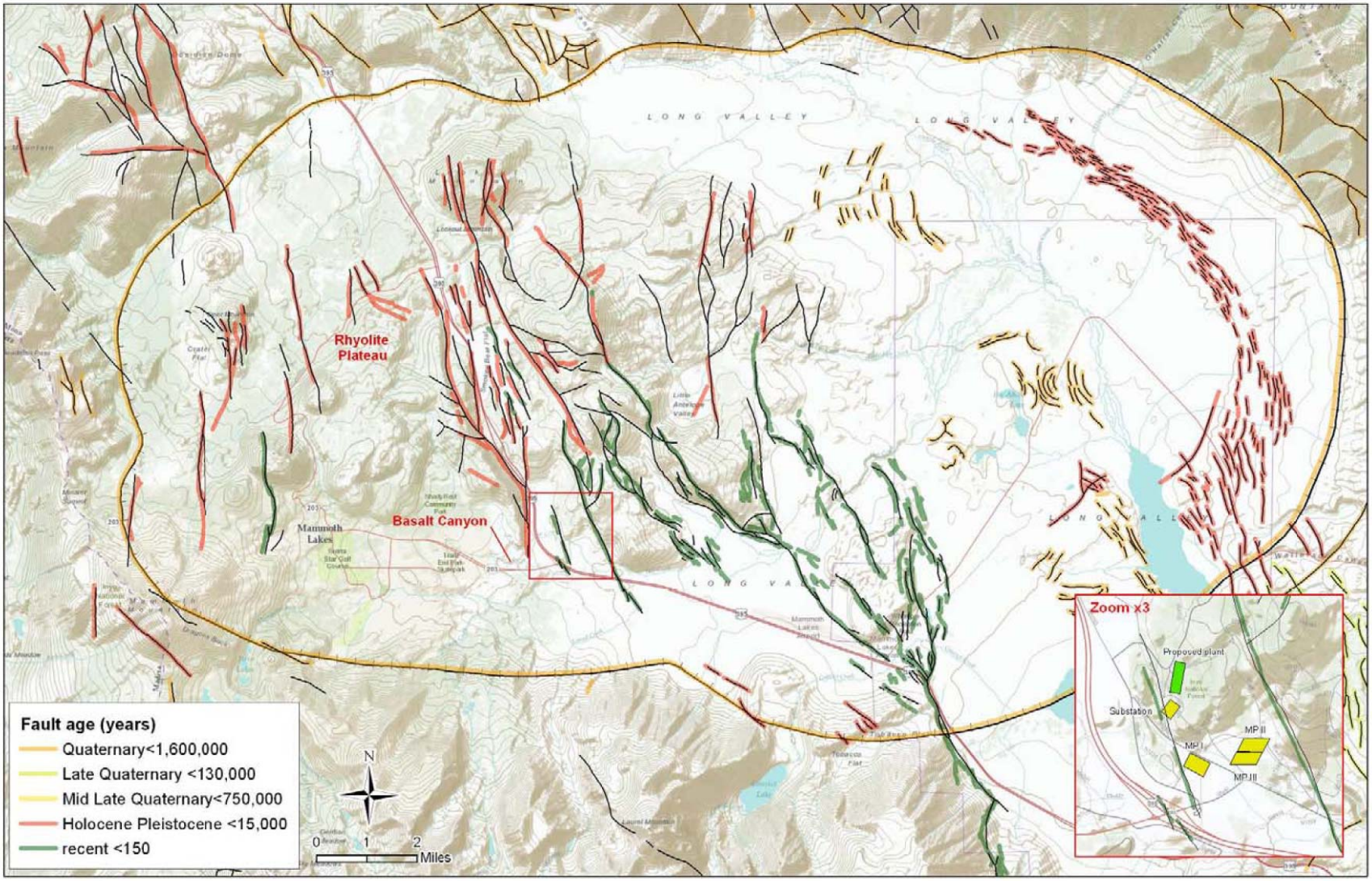


Figure 5 - Quaternary and Recent faults in the Long Valley region from USGS (http://earthquake.usgs.gov/hazards/qfaults/)

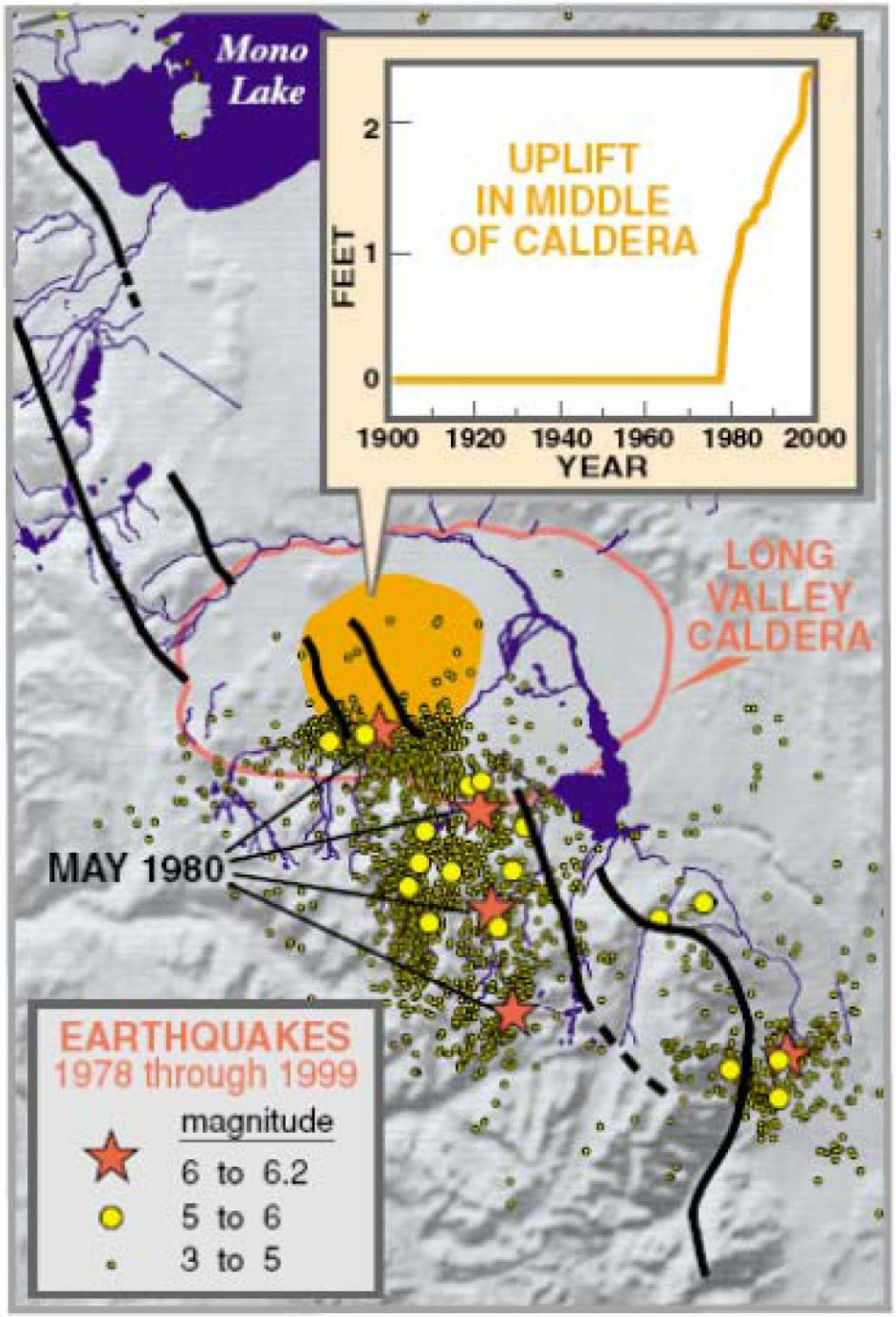


Figure 6 - Long Valley seismicity and uplift.

Figure 7 - Inyo Craters, part of the Mono-Inyo Craters volcanic chain, stretch northward across the floor of long Valley Caldera approximately 7 km north of the CD-IV project area.

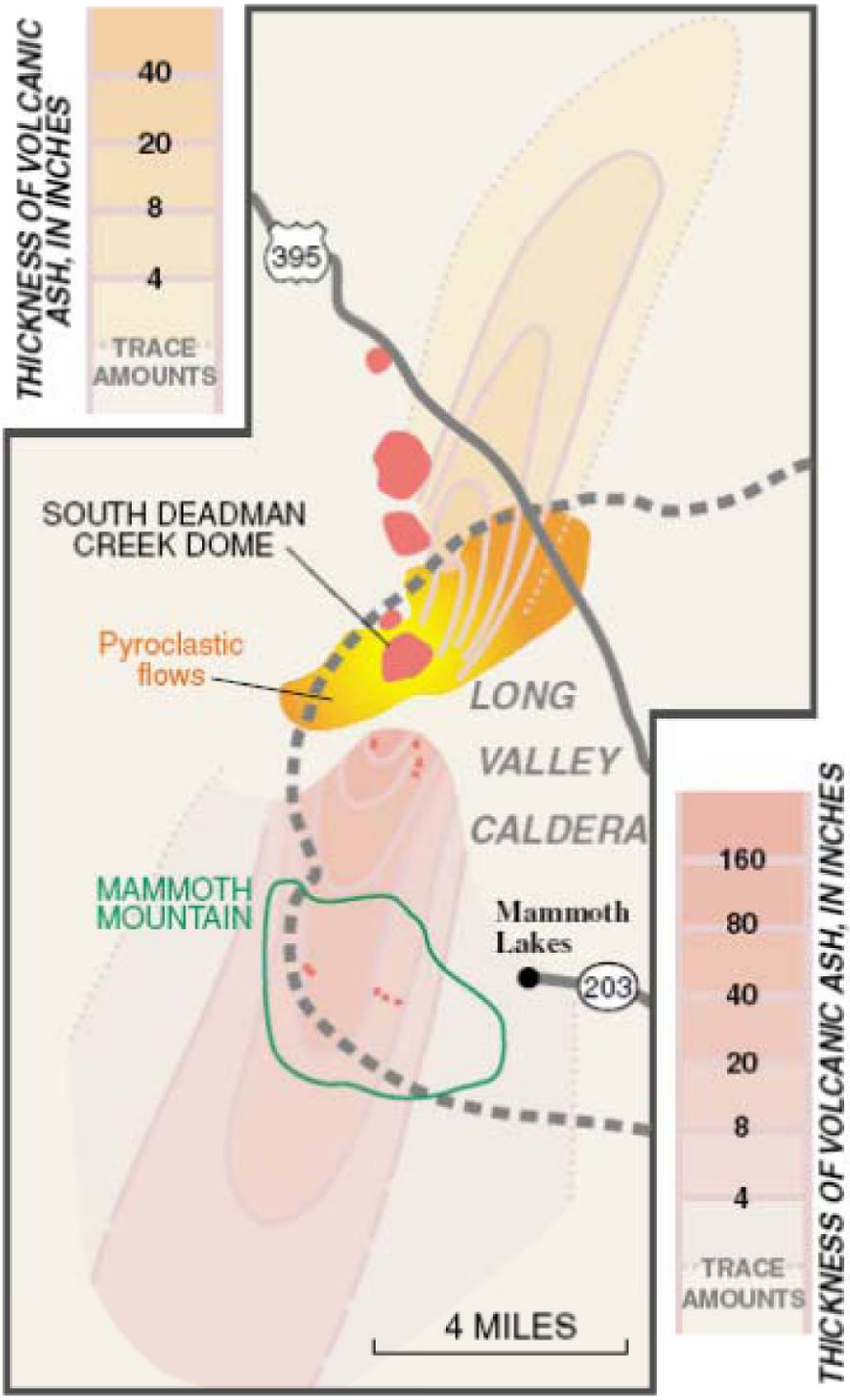


Figure 8 - Thickness of volcanic ash from eruptions <500 yrs. old along he Inyo volcanic chain.

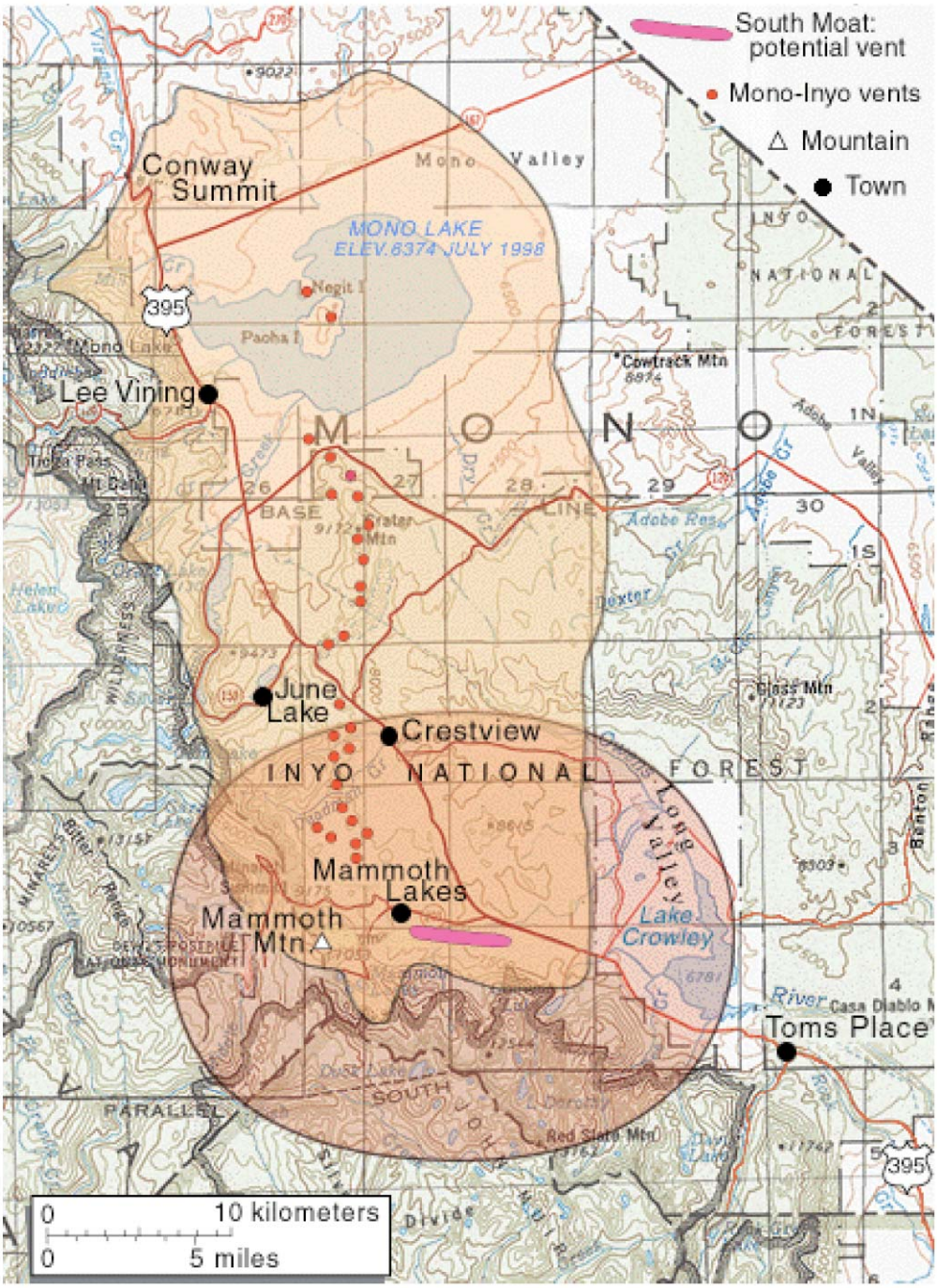


Figure 9 - Areas potentially affected by pyroclastic flows from vents in the LVC and vicinity: Potentially impacted area South Moat vent is pink, from Inyo crater potential vents, is orange. Map from USGS website: http://volcanoes.usgs.gov/lvo/hazards/pfzone_bot

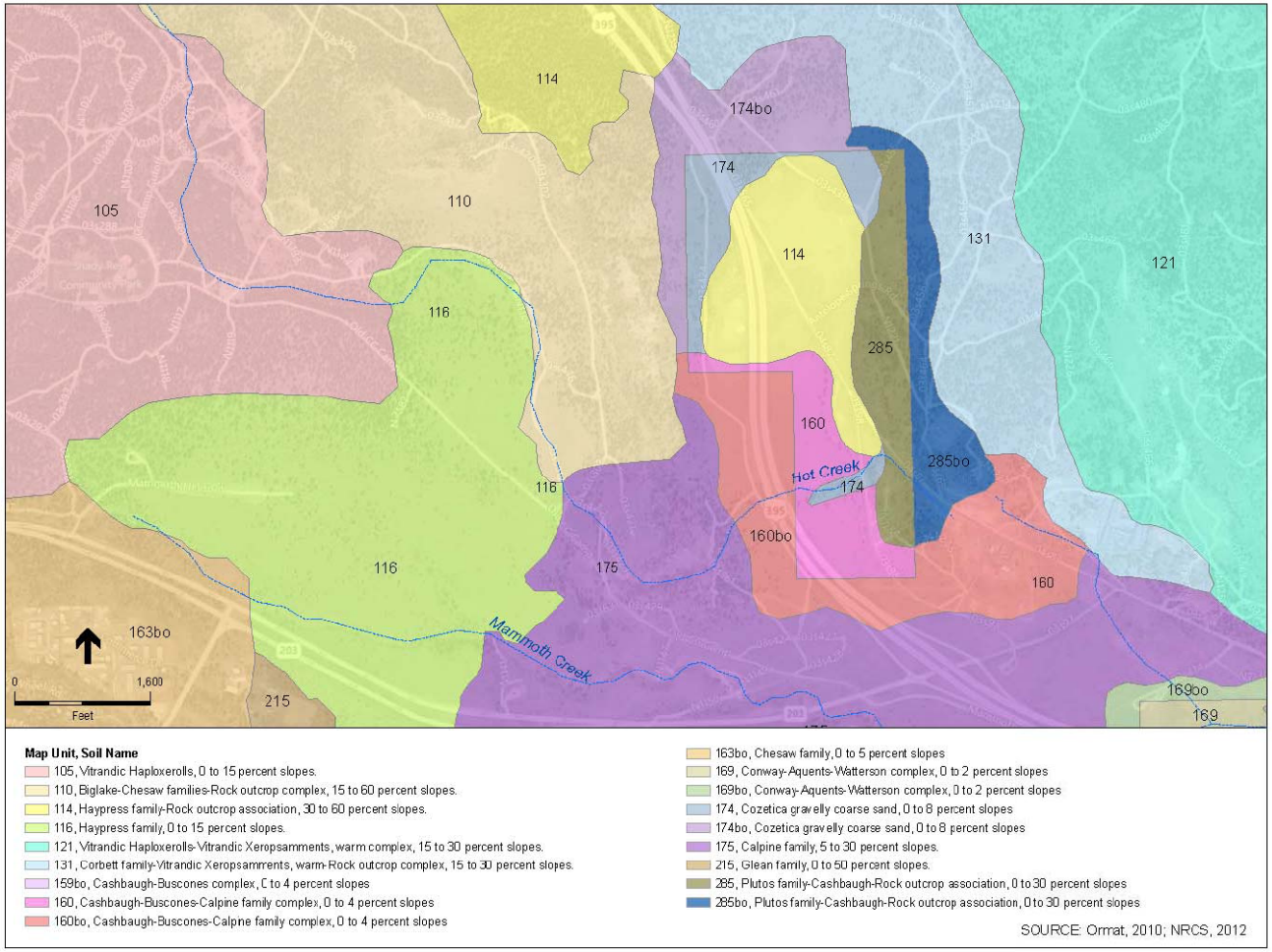


Figure 10 - NRCS soil classifications for Long Valley

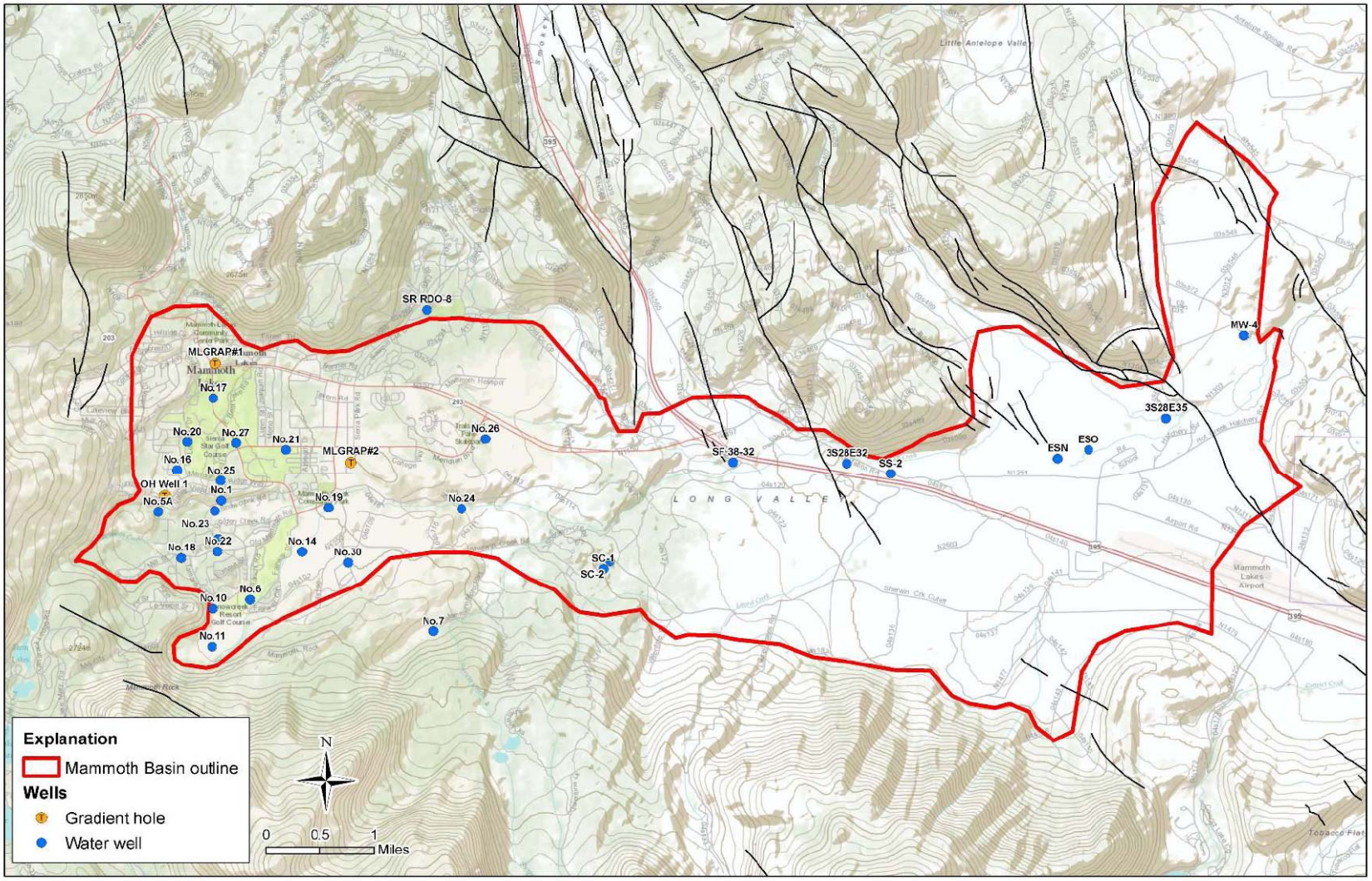
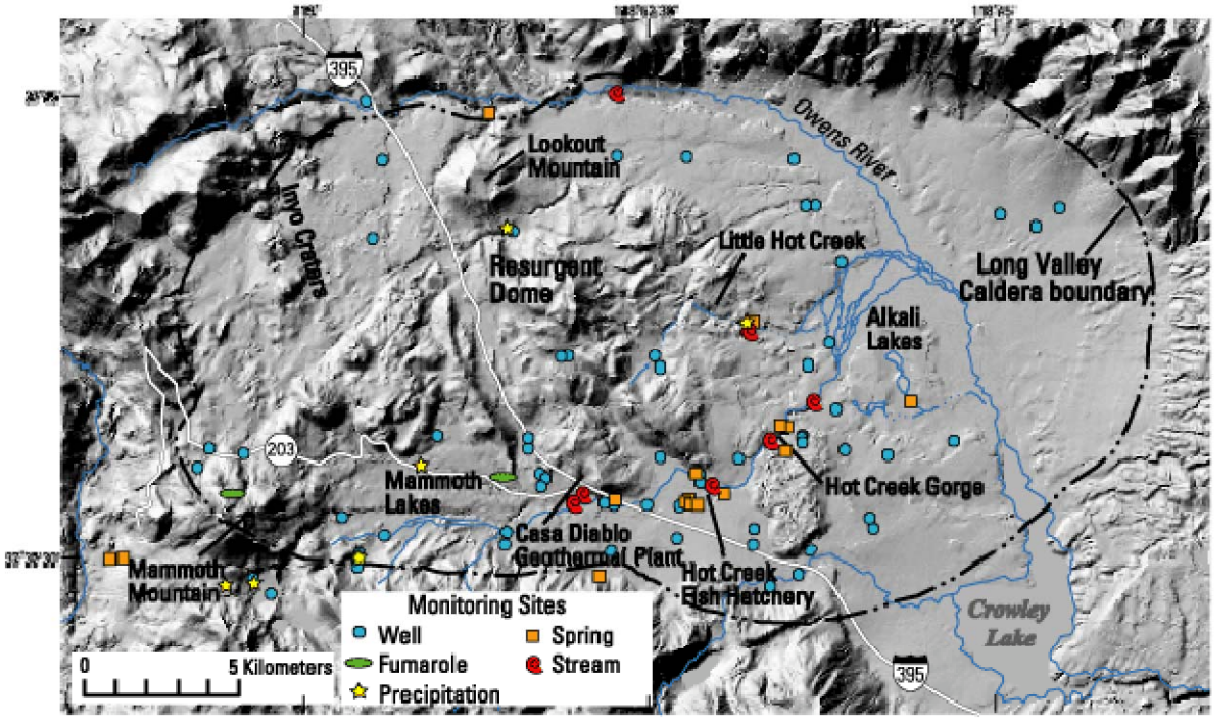


Figure 11 - Mammoth Groundwater basin from Wildermuth (2009). Water production wells are located close to the Town of Mammoth Lakes. All of the existing geothermal wells are drilled east of well RDO-8.



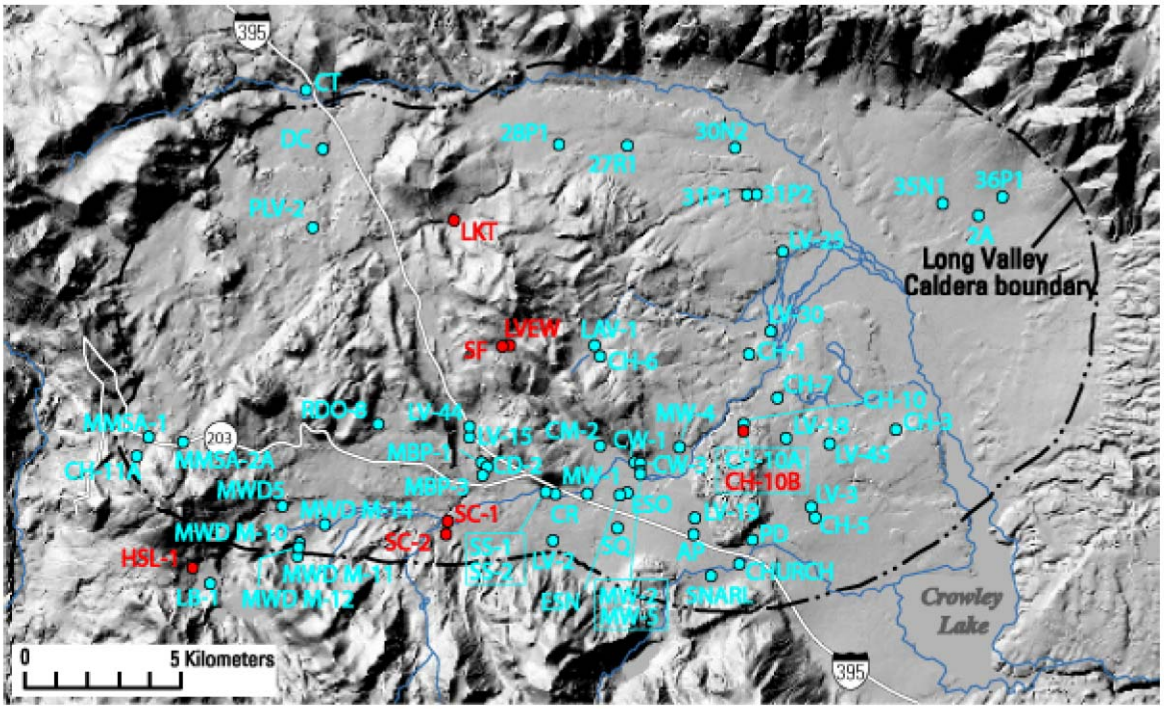


Figure 12 - USGS Hydrologic monitoring points in Long Valley

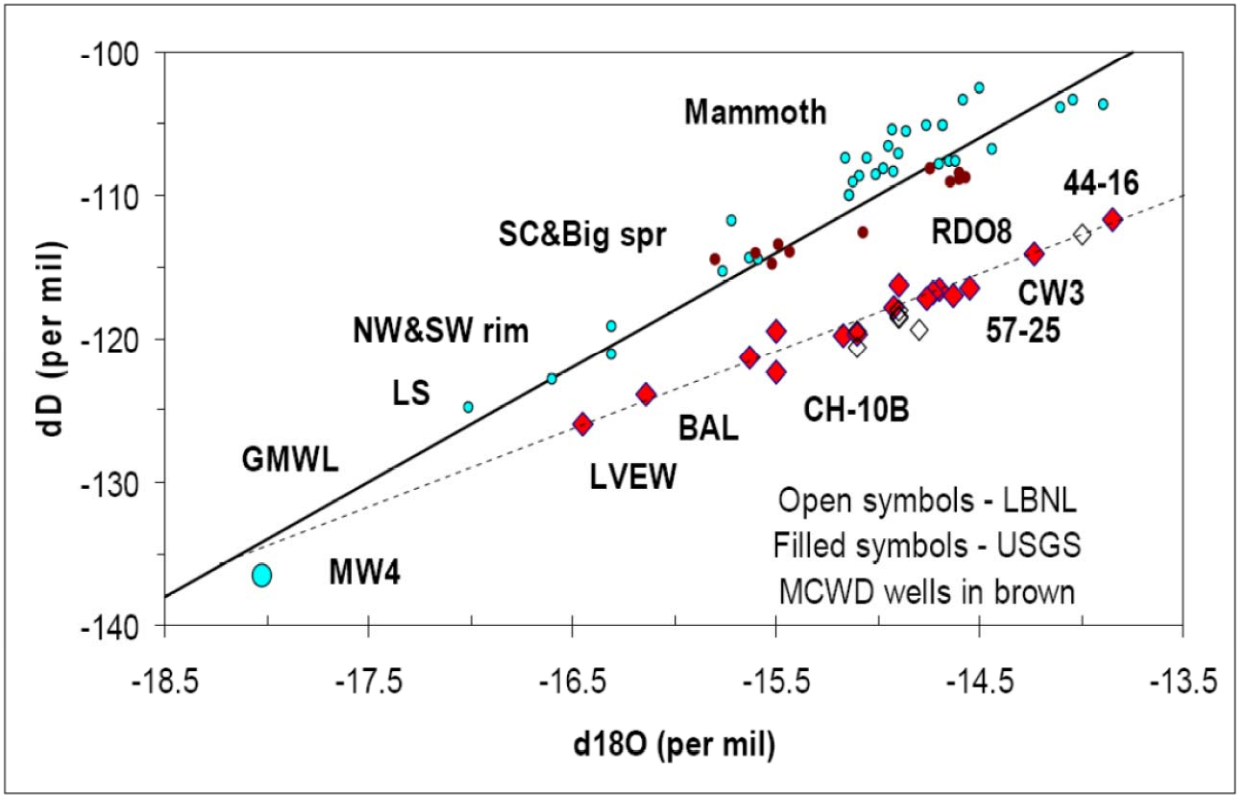


Figure 13 - Light stable isotope data for groundwater and thermal water in Long Valley Caldera

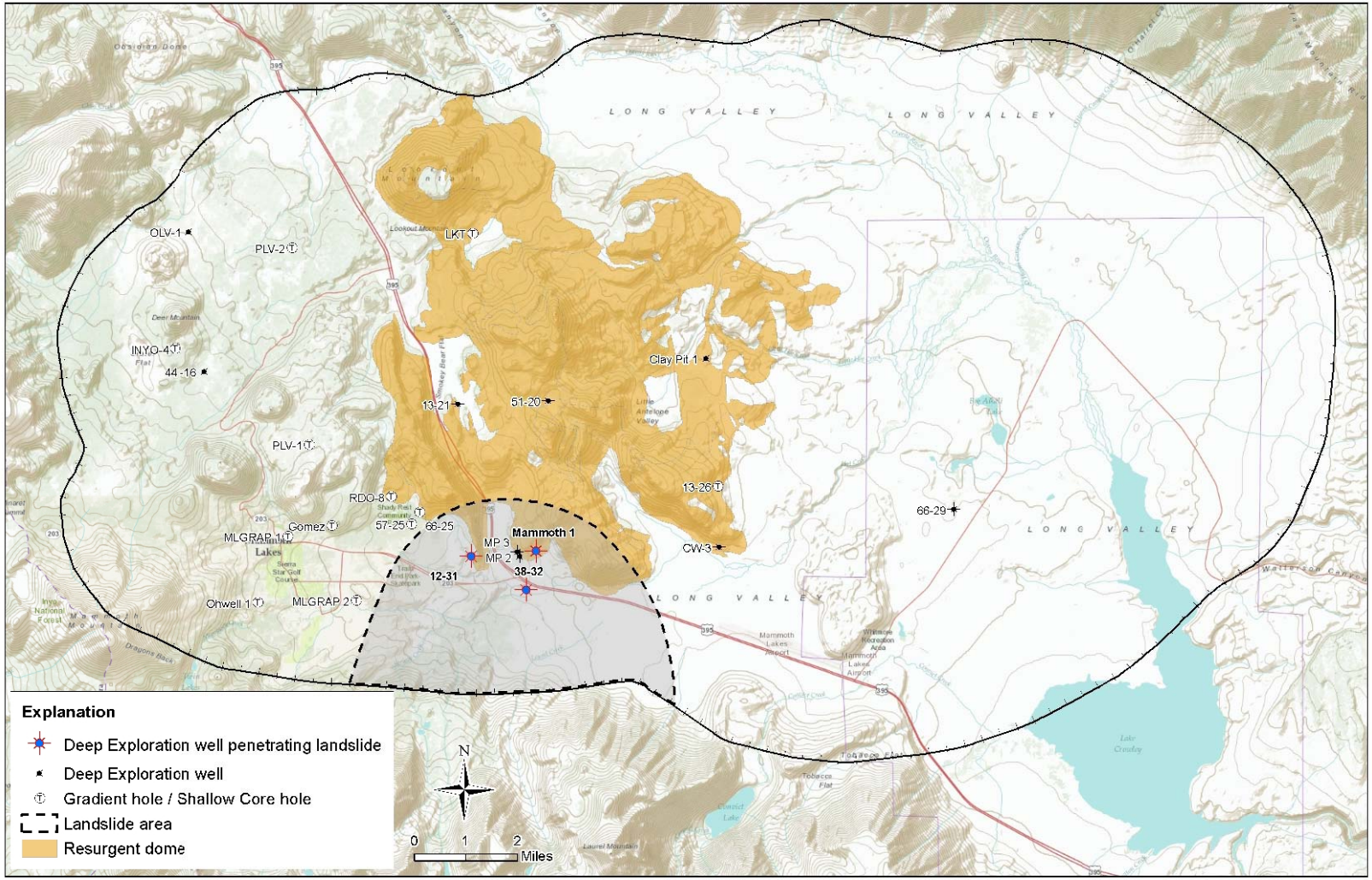


Figure 14 - Distribution of the landslide block of Paleozoic metasedimentary rocks from the southern rim of Long Valley caldera.

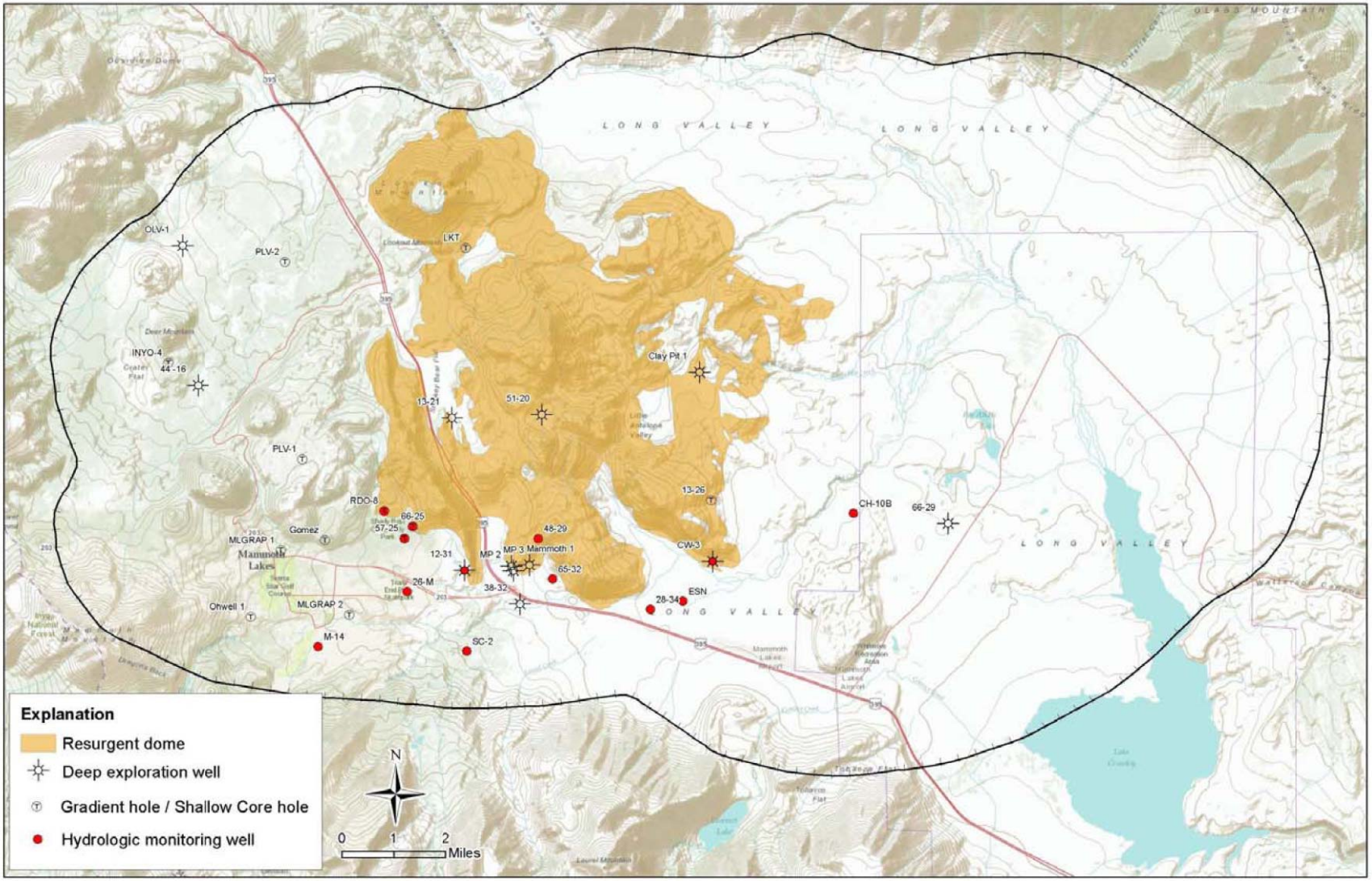
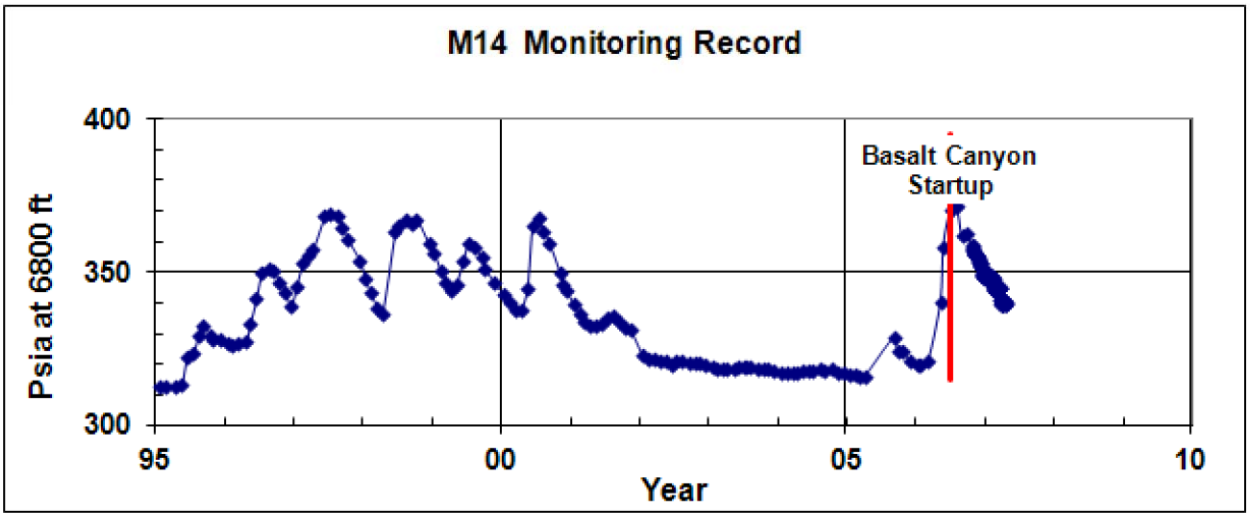
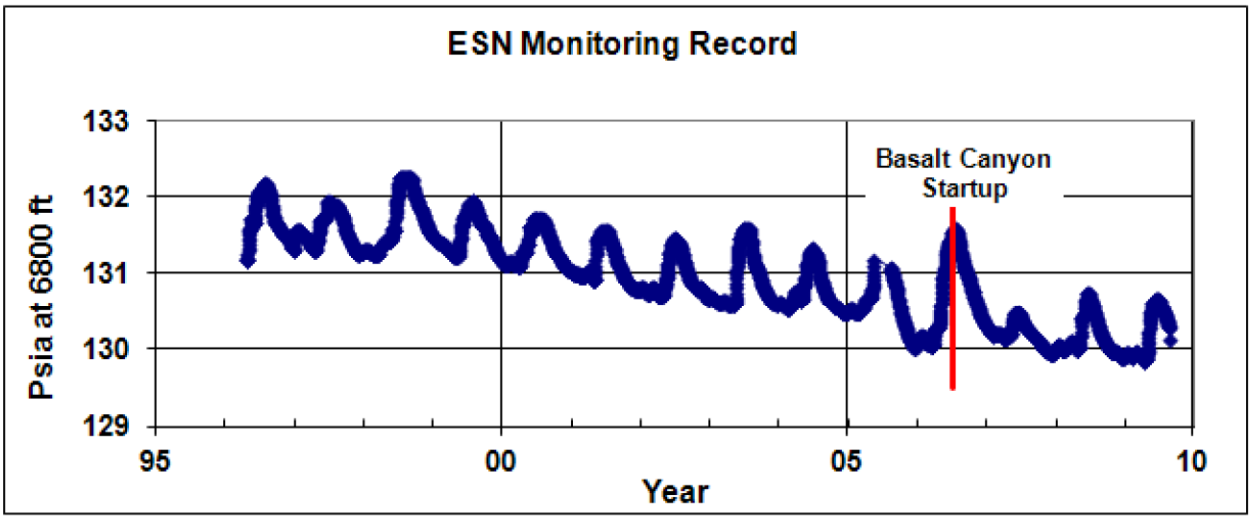


Figure 15- Monitoring well locations in Long Valley (after Sorey, 2010).





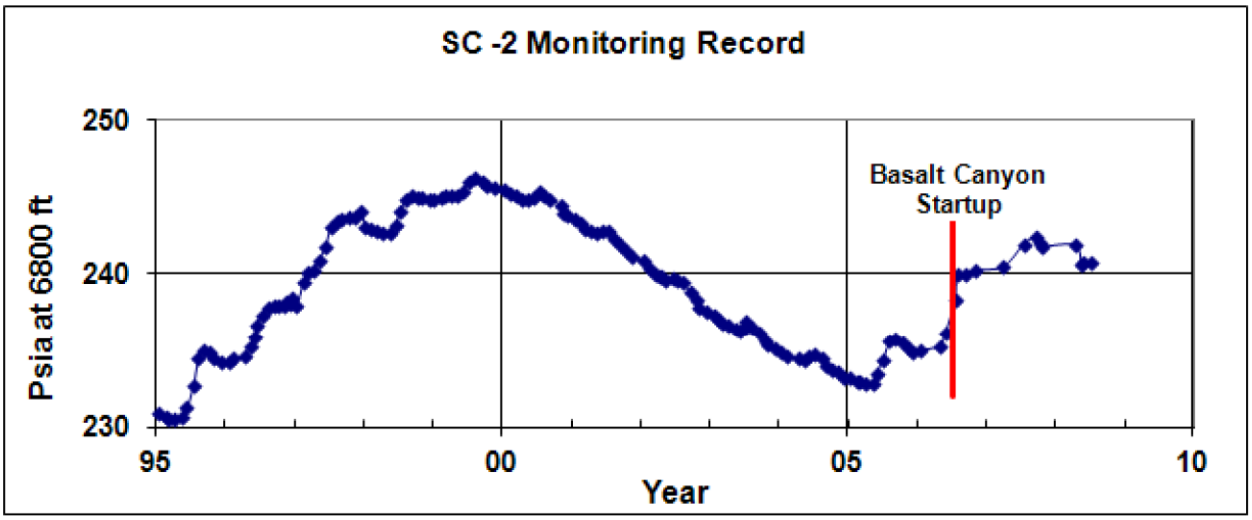
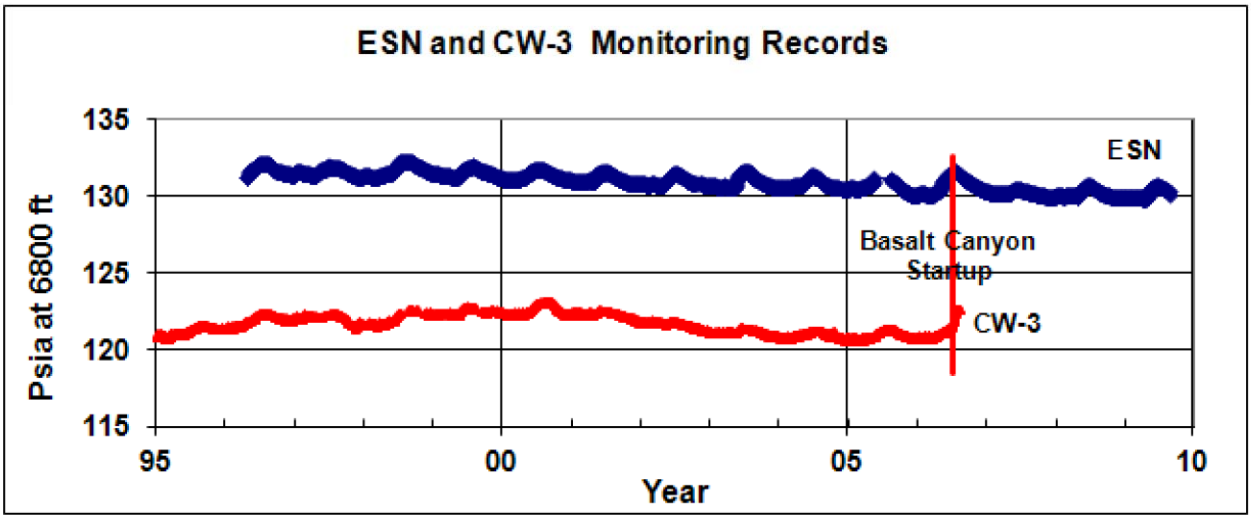


Figure 16 - Comparative hydrographs for shallow non-thermal groundwater monitoring wells M-14, ESN, SC-2, 1995-2010.



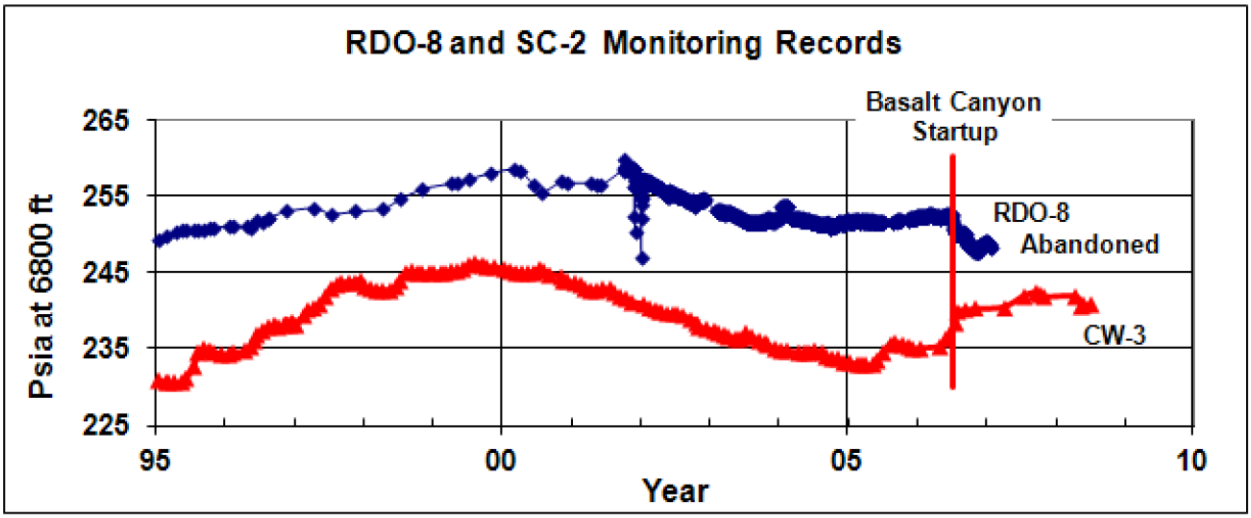


Figure 17 - Comparative hydrographs for groundwater monitoring wells ESN and SC-2 and thermal monitoring wells CW-3 and RDO-8, 1995-2010.

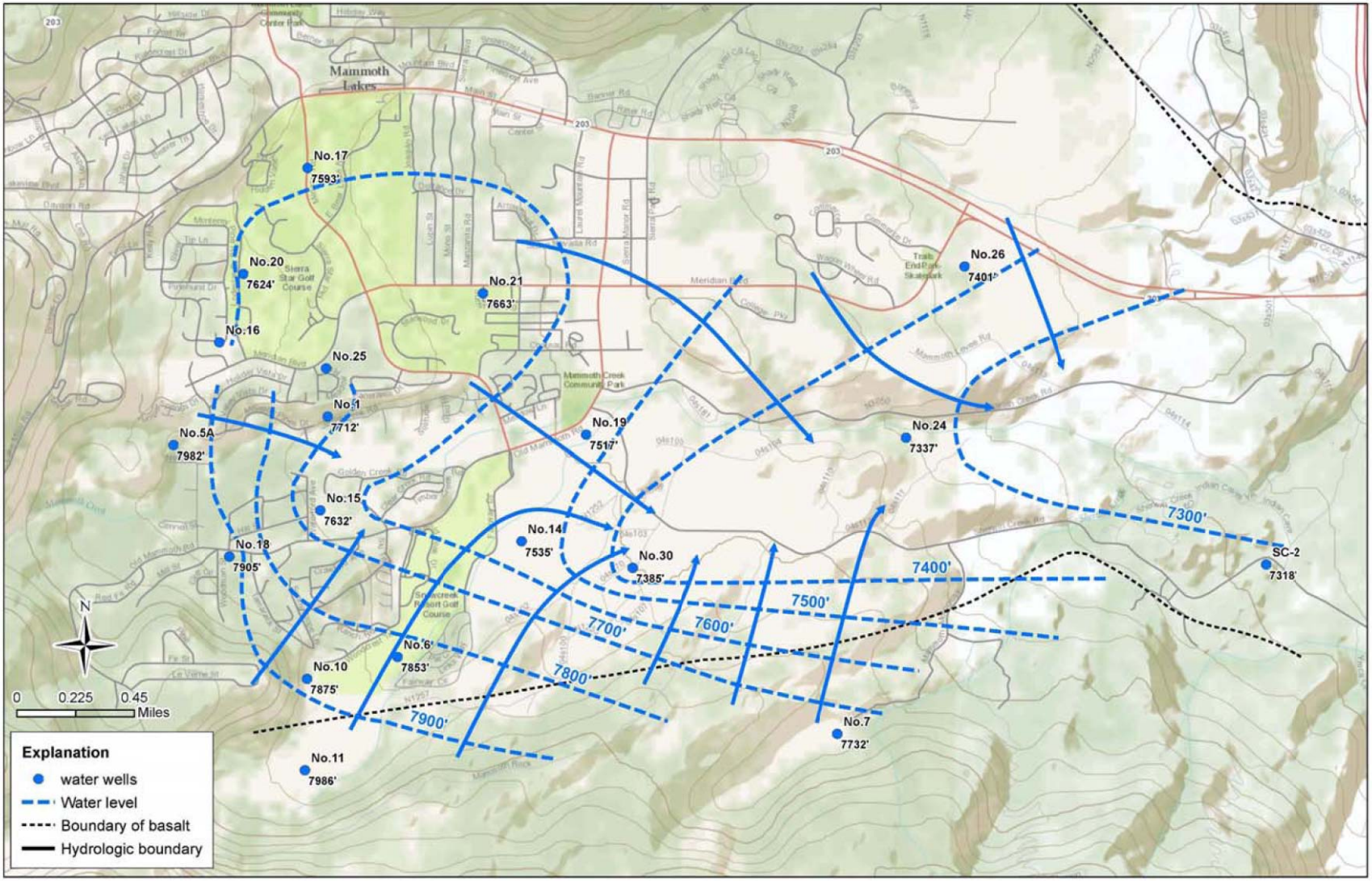
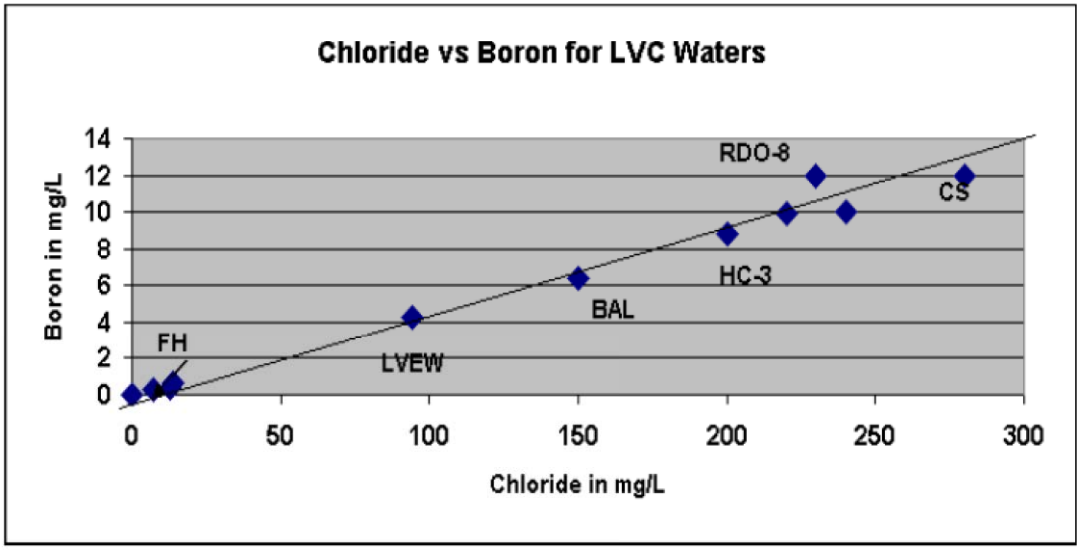


Figure 18 - Contours of water level elevations in MCWD wells of the Mammoth Basin.



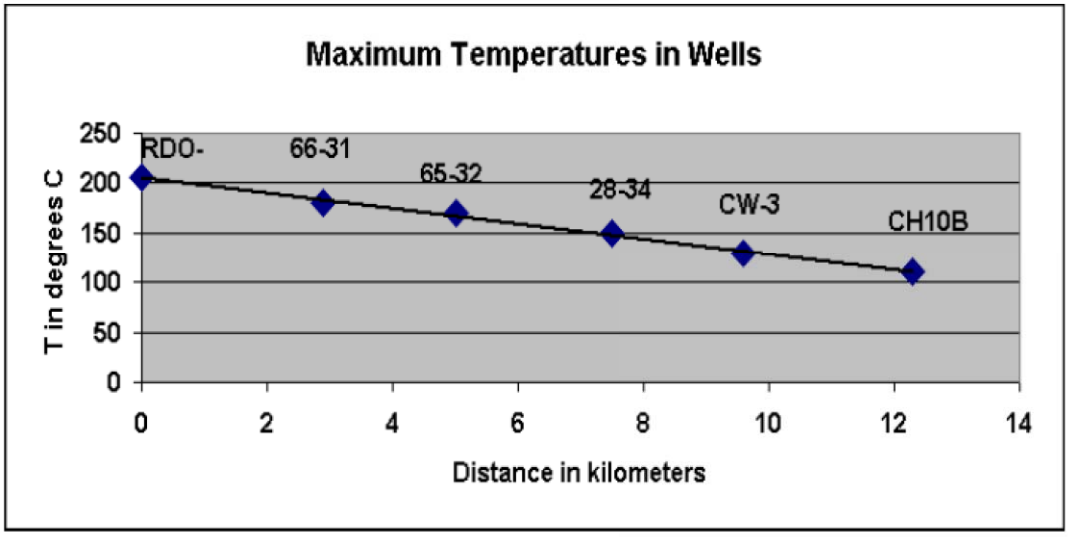


Figure 19- Cl/B ratios and temperatures for various types of cold and hot waters sampled in the Long Valley caldera.

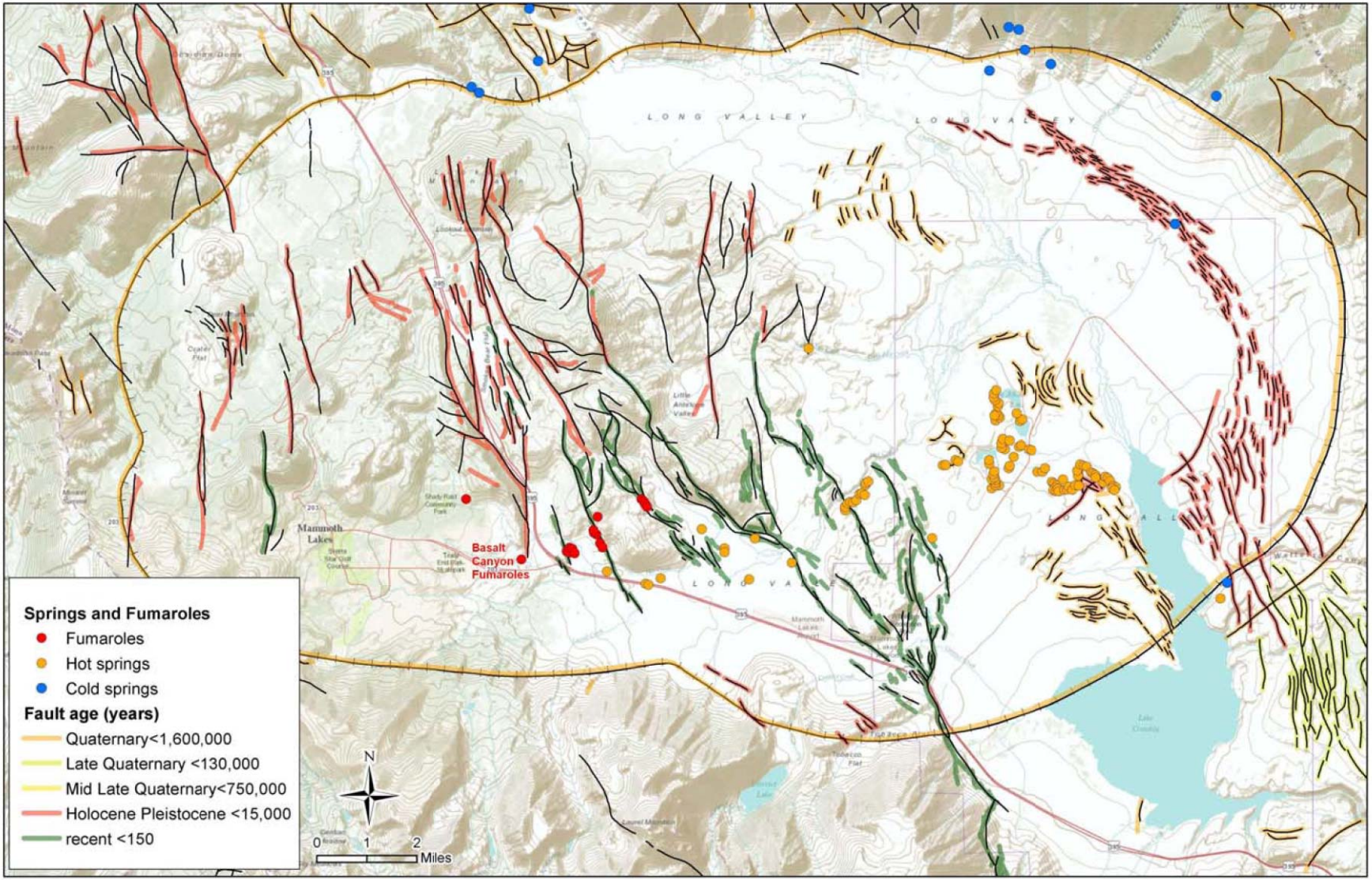


Figure 20 - Hydrothermal manifestations in Long Valley caldera.

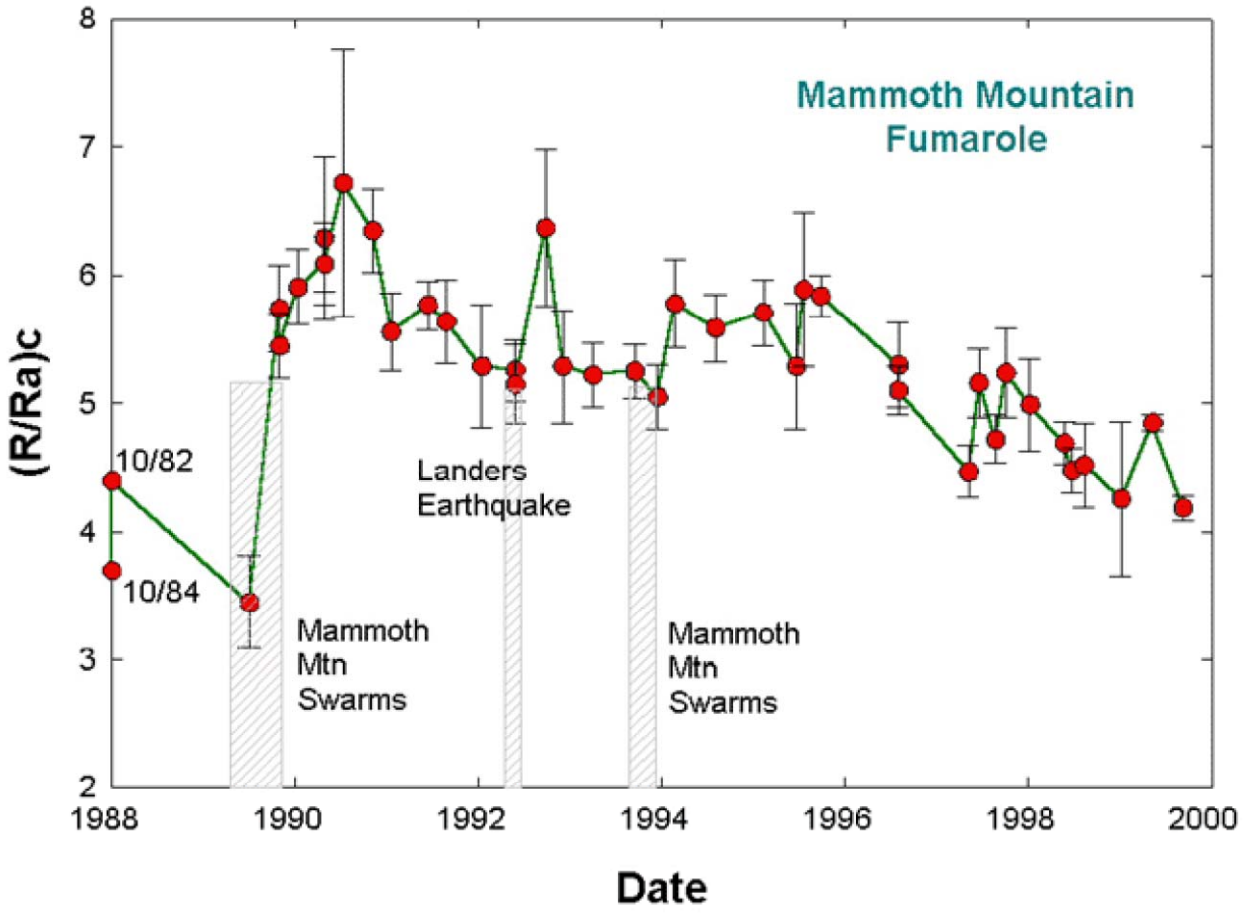


Figure 21 - Helium isotope variations in Mammoth Mountain fumaroles after earthquake swarms and potential dike injection at depth.

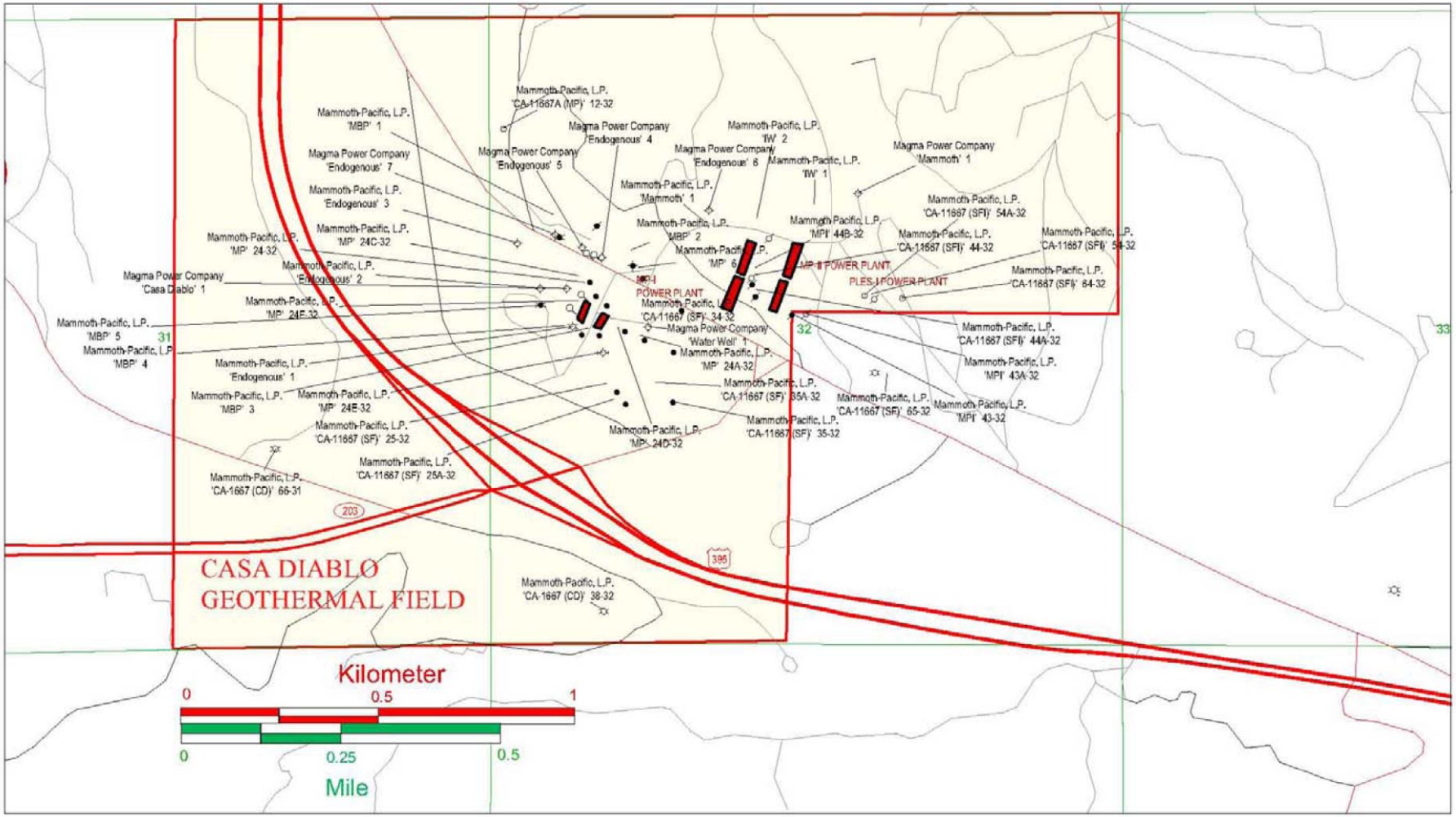


Figure 22 - Geothermal wells at Casa Diablo (after CDOGGR, 2012; ftp://ftp.consrv.ca.gov/pub/oil/maps/Geothermal/G1-1.pdf).

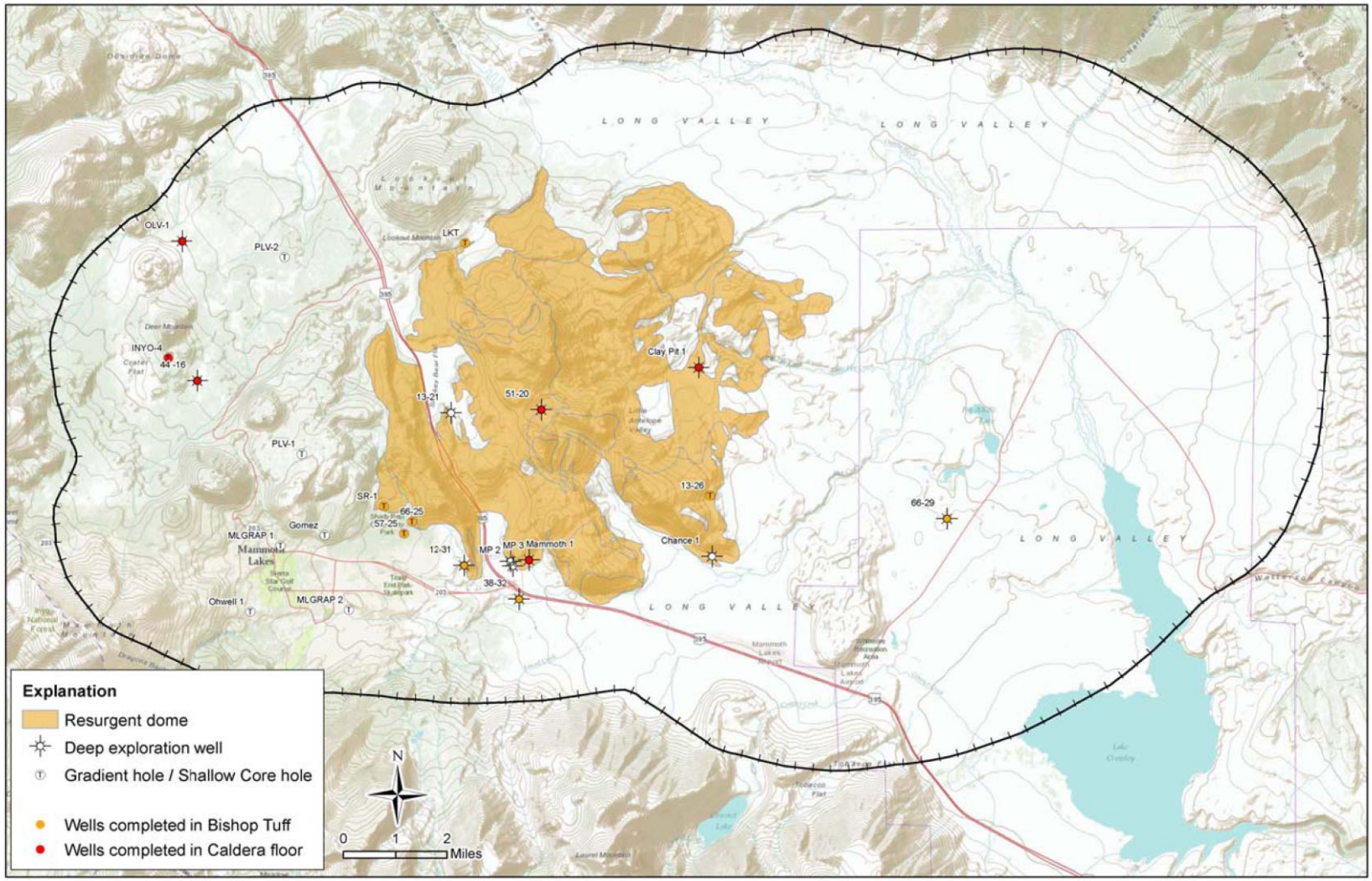
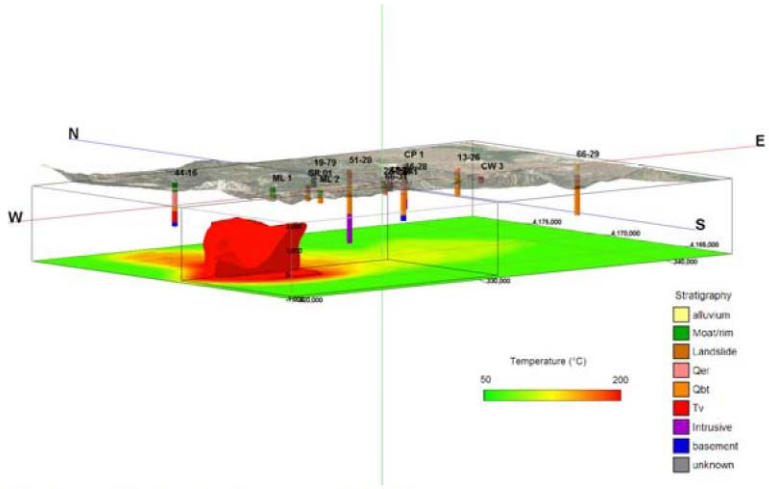
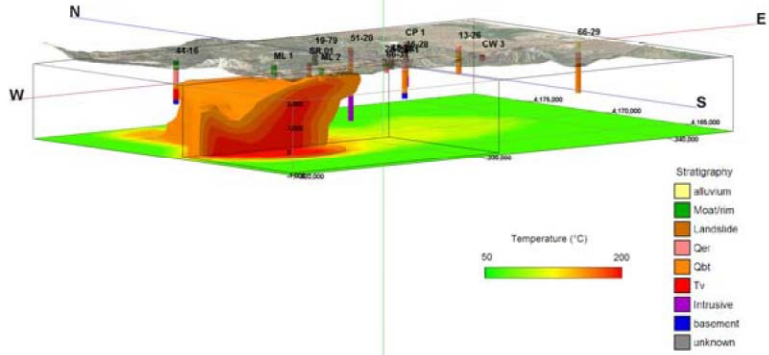


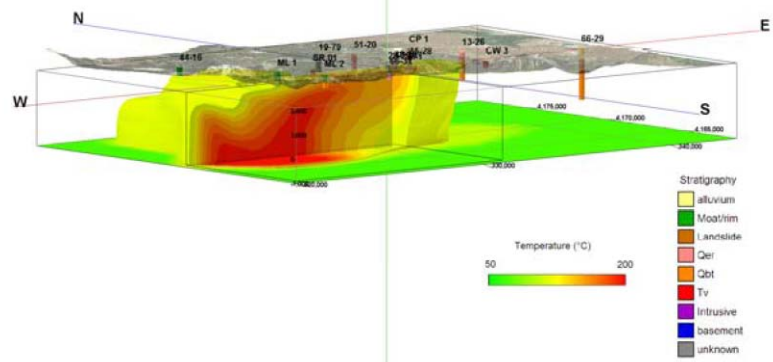
Figure 23 - Long Valley wells penetrating the Bishop Tuff (orange) or the caldera floor (red).



A) Long Valley isotherms - 190°C



B) Long Valley isotherms - 150°C



C) Long Valley isotherms - 100°C

Figure 24 - Temperature distribution in Long Valley Caldera from geothermal well records (CDOGGR) or published temperature data (Farrar and others, 2010).

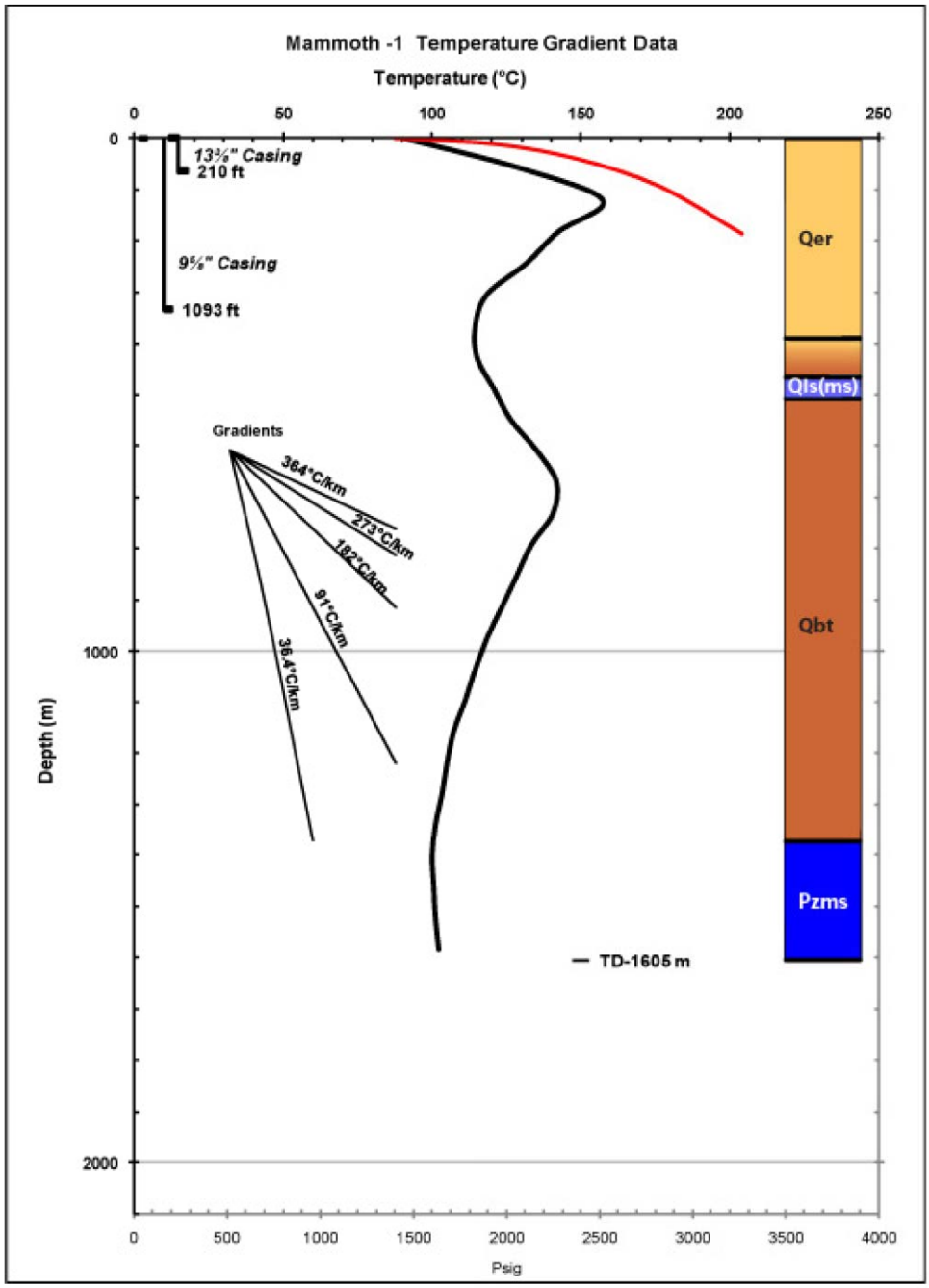
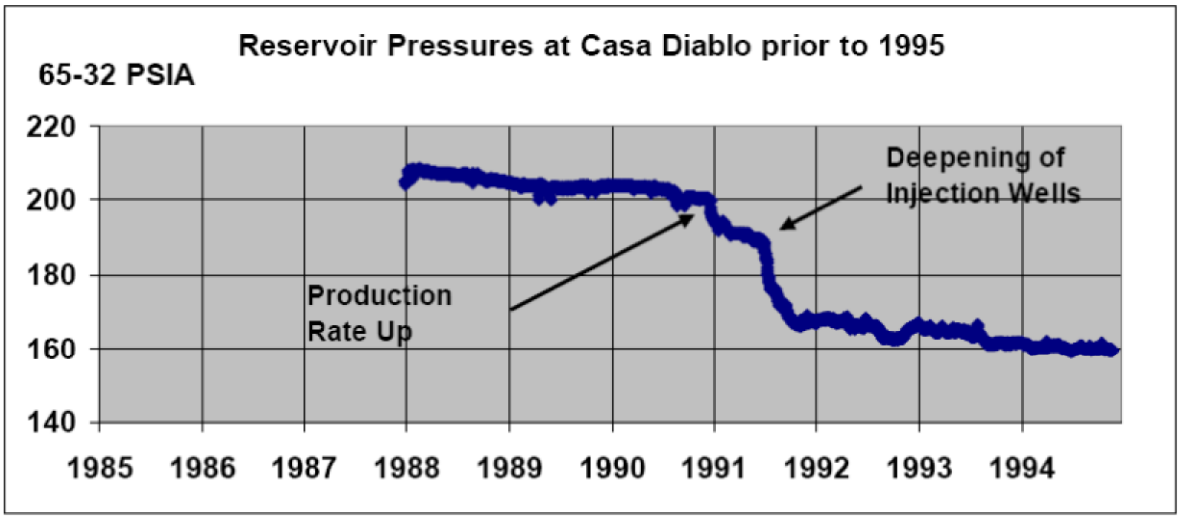


Figure 25 - Wellbore schematic for Unocal Mammoth -1 at Casa Diablo.



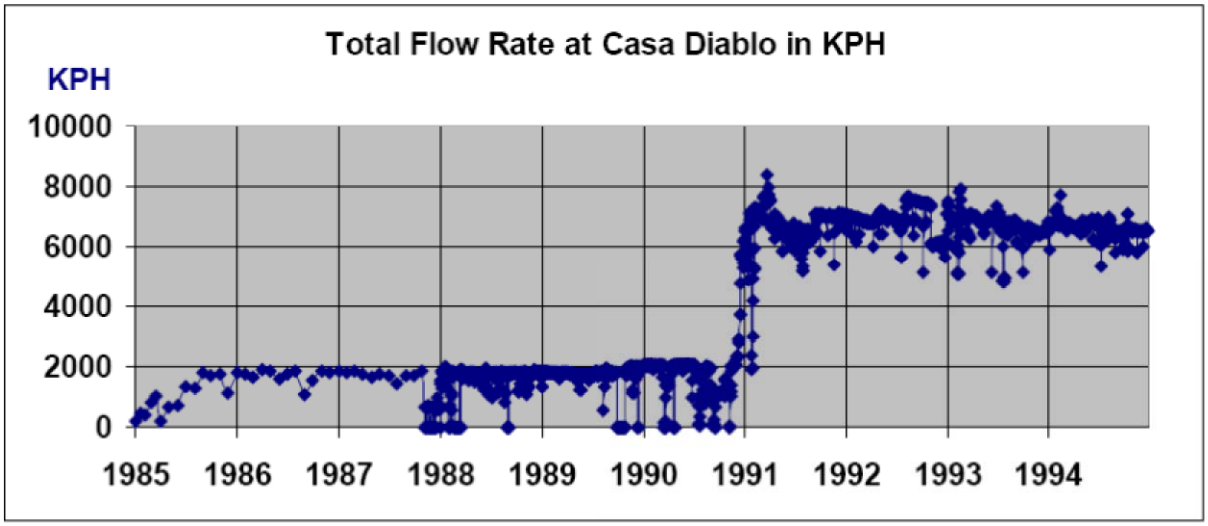


Figure 26 - Total flow rate and production reservoir pressure at Casa Diablo from 1985 to 1995.

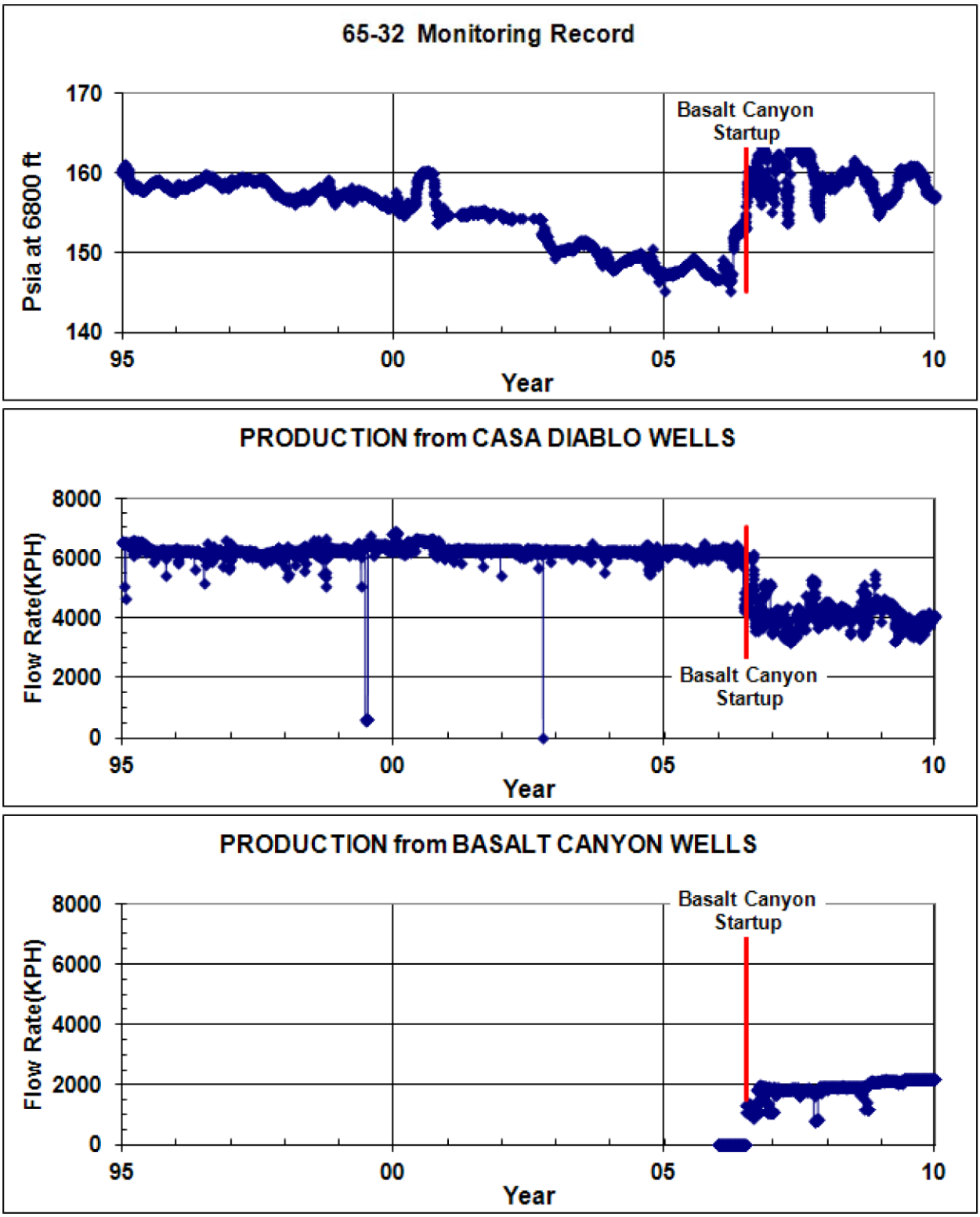


Figure 27 - Mass flow from Casa Diablo wells versus pressures in well 65-32 from 1995 to 2010.

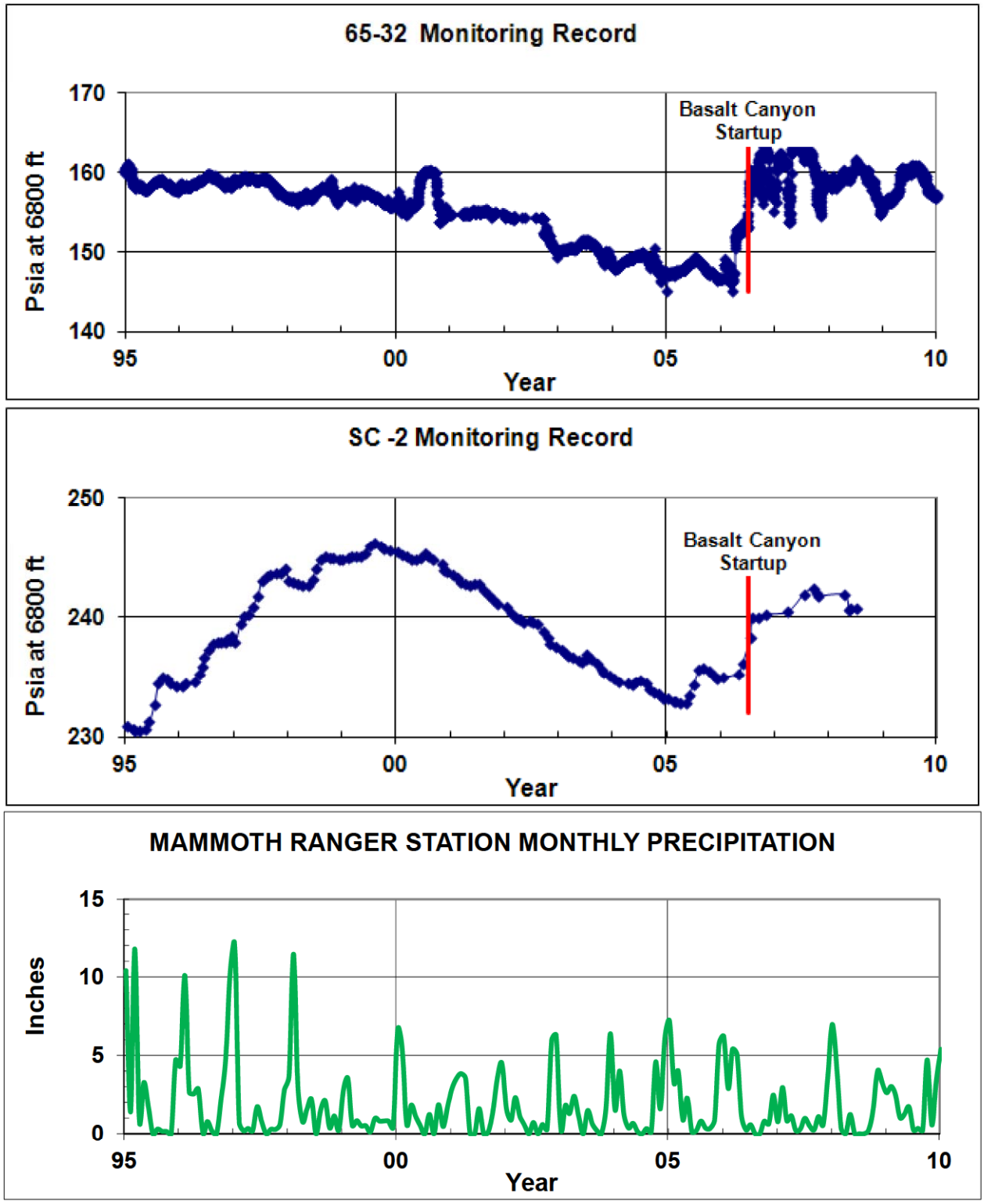


Figure 28 - Comparisons of seasonal variations in pressure and water level in thermal monitor wells 65-32 at Casa Diablo, non-thermal wells SC-2 in the Mammoth Groundwater Basin and monthly precipitation, 1995-2010.

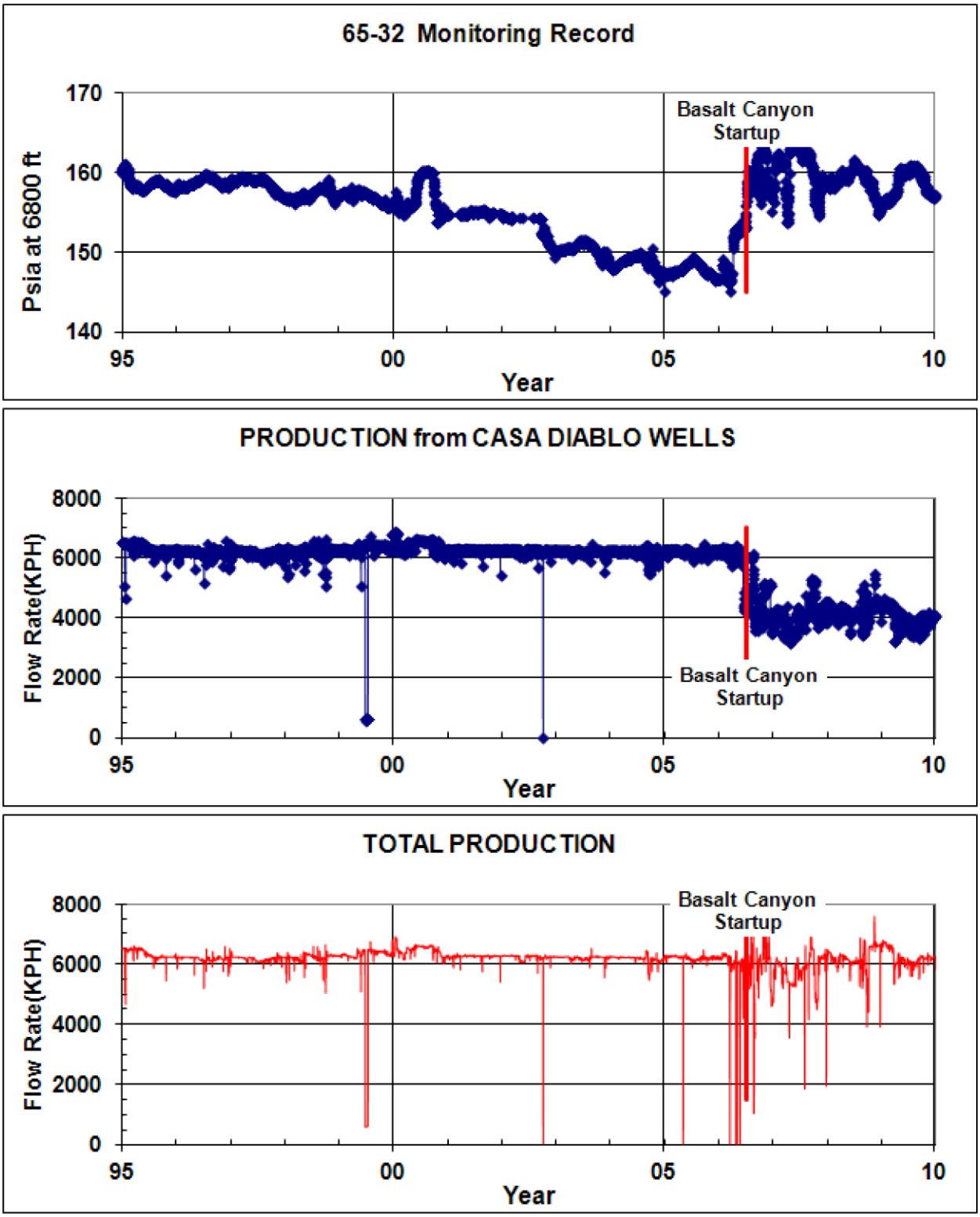
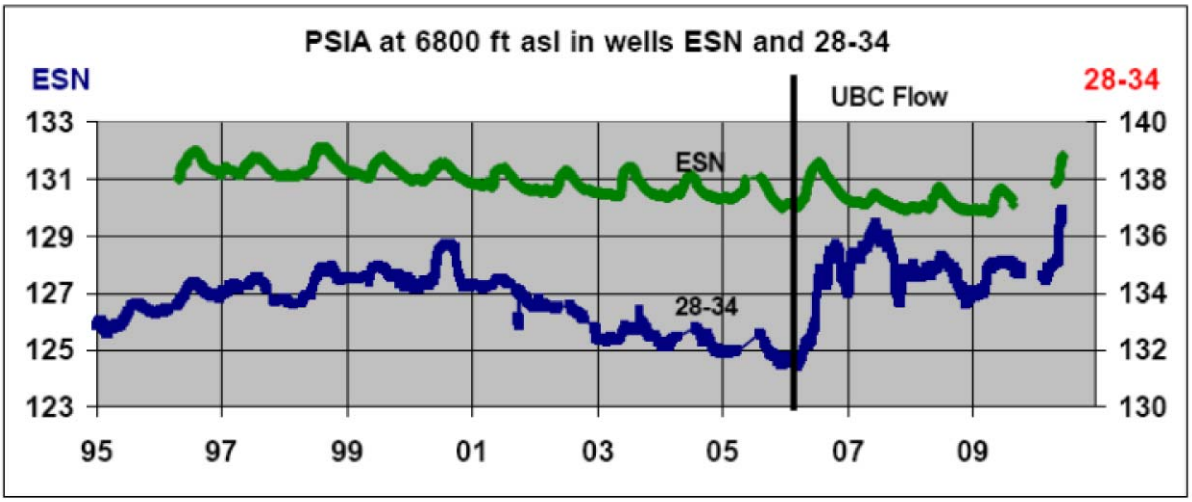


Figure 29 – Total mass flow to the Casa Diablo power plants versus pressures in well 65-32 from 1995 until 2010.



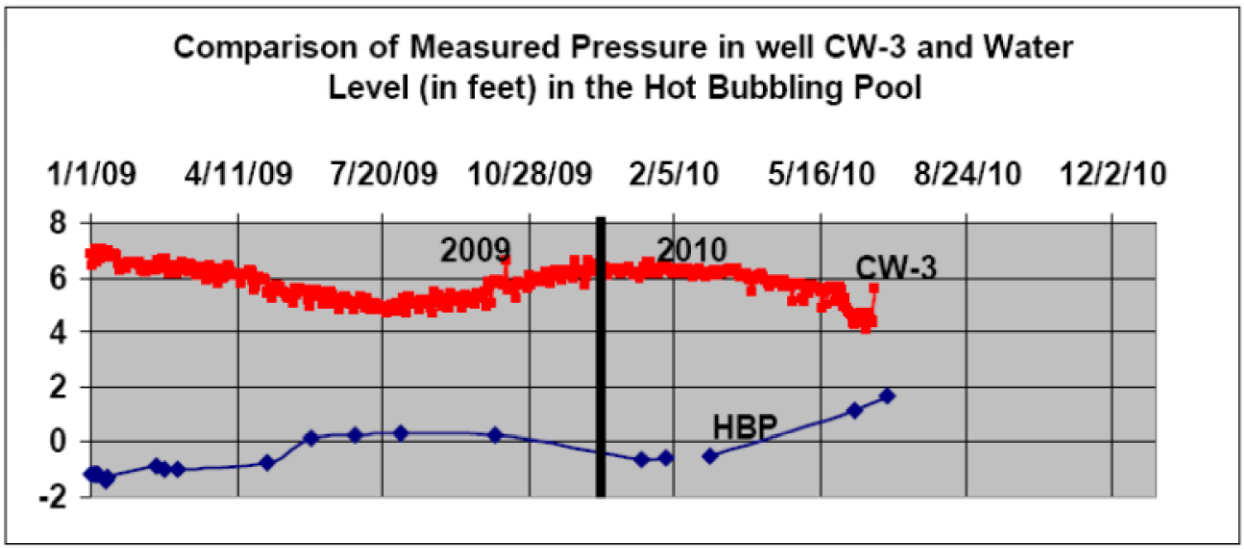


Figure 30 - Long-term plots of pressures in wells ESN (Elementary School New) and 28-34 and CW-3 and Hot Bubbling Pool from 1995-2010 relative to the onset of production from Basalt Canyon (2006)

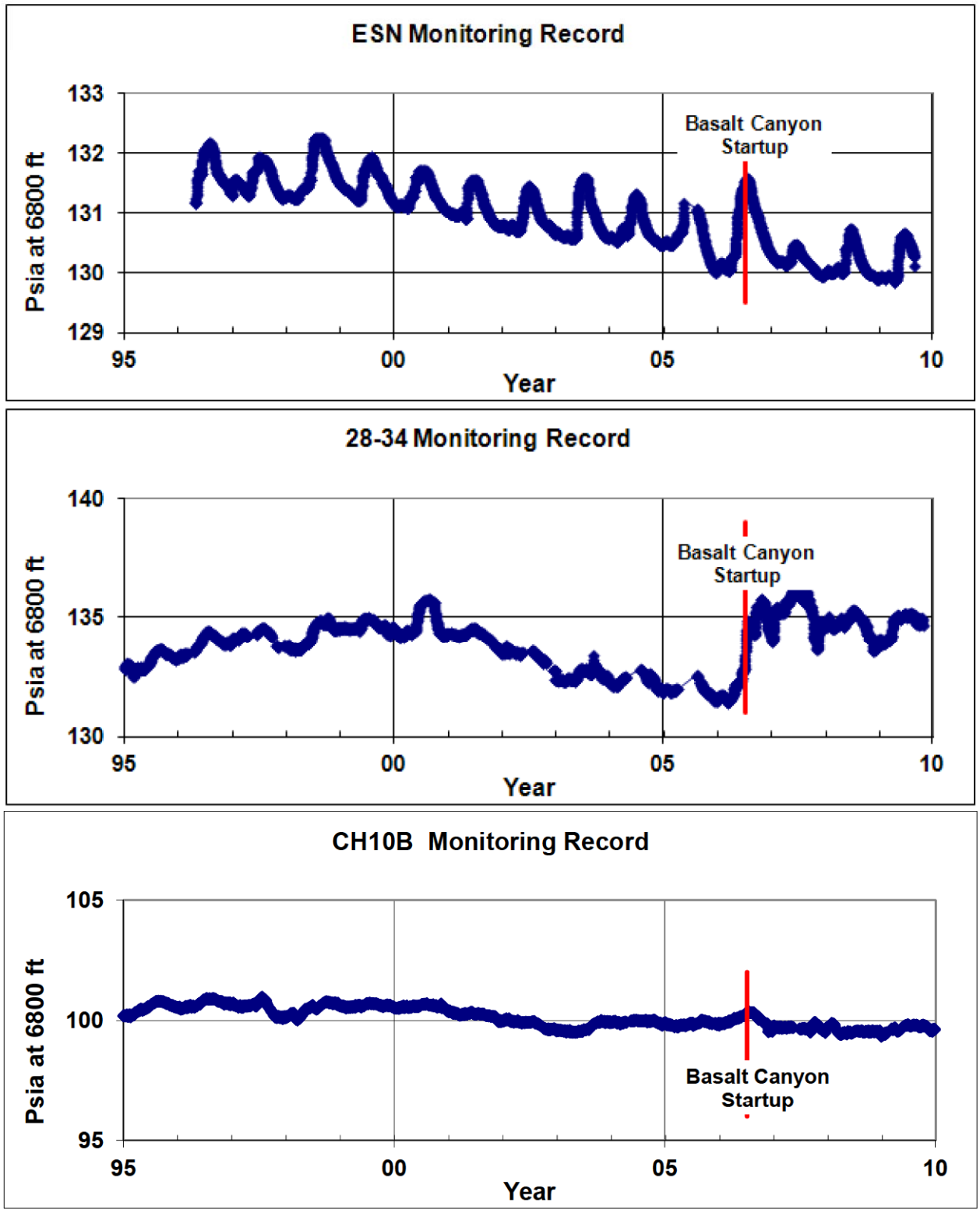
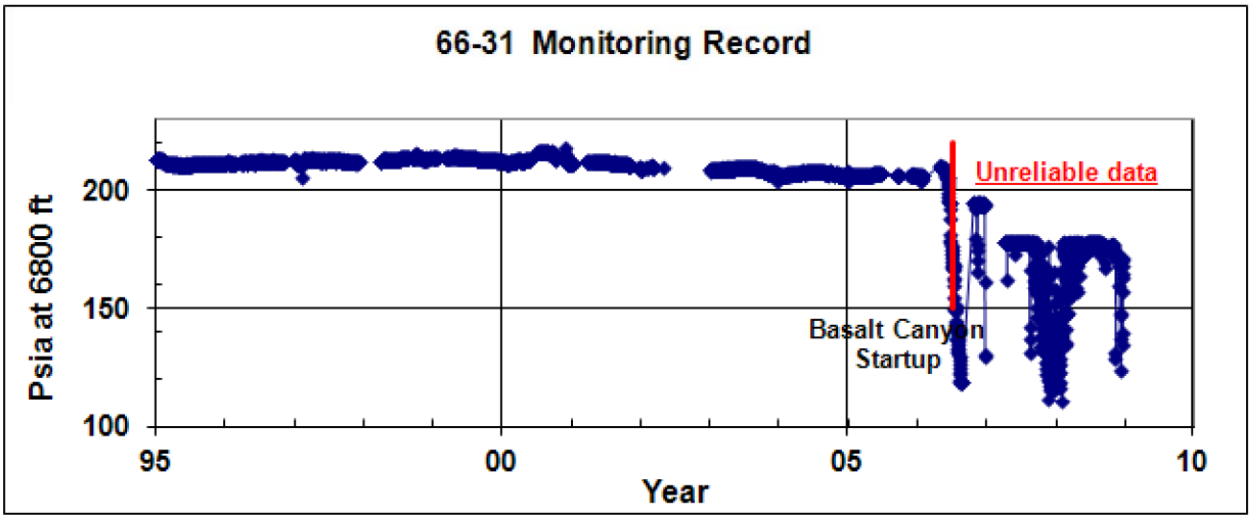


Figure 31 - Pressure histories of ESN, 28-34 and CH 10B 10 km east of Casa Diablo 1995-2010.



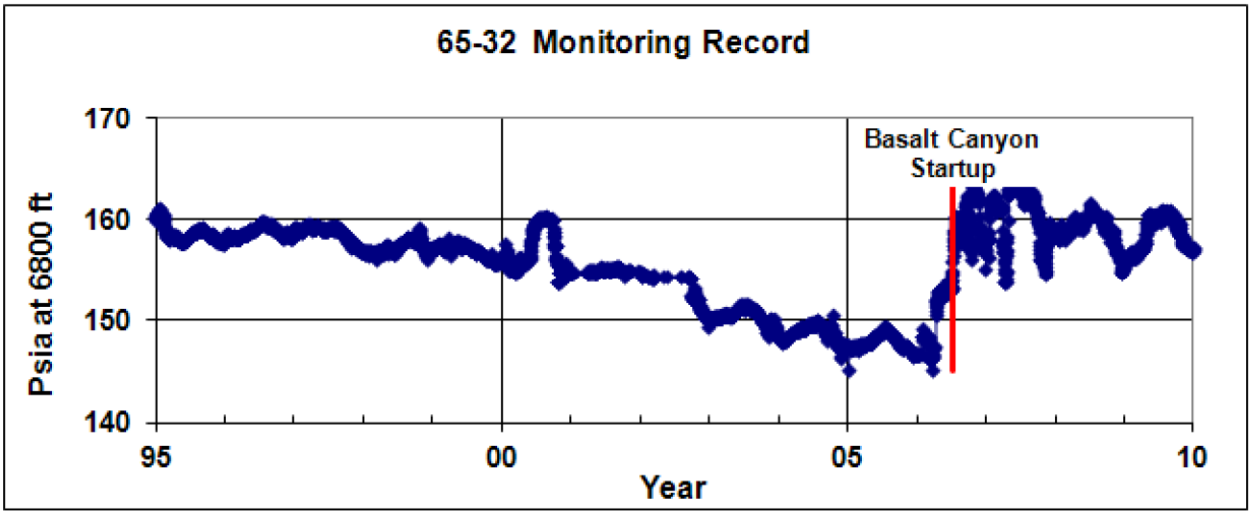


Figure 32- - Long-term pressure histories in geothermal monitoring wells 66-31 and 65-32, 1995-2010 (unreliable data noted).

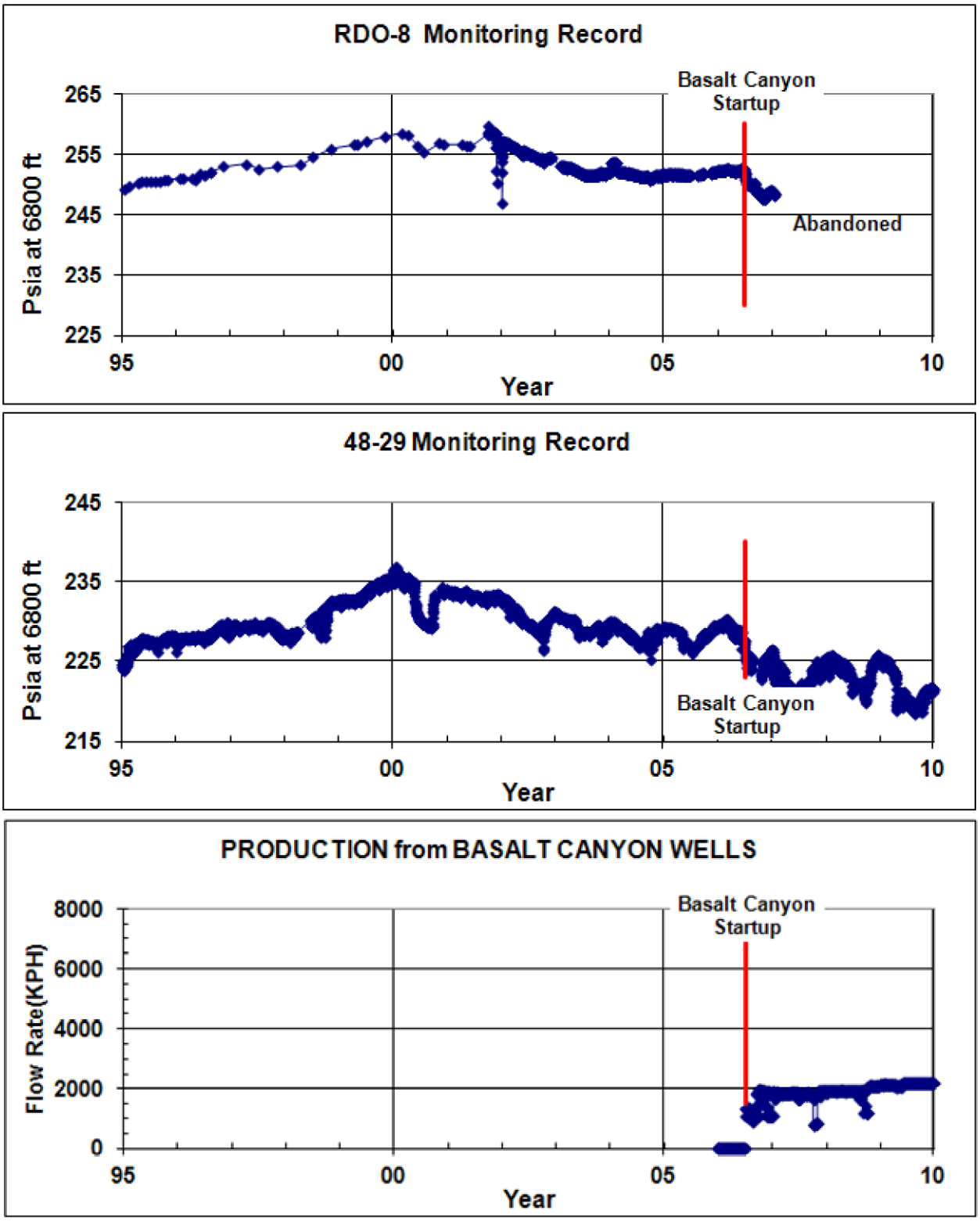


Figure 33 - long-term pressure histories of geothermal monitoring wells RDO-8 and 48-29 completed in the deeper Bishop Tuff injection reservoir in Long Valley, 1995-2010.

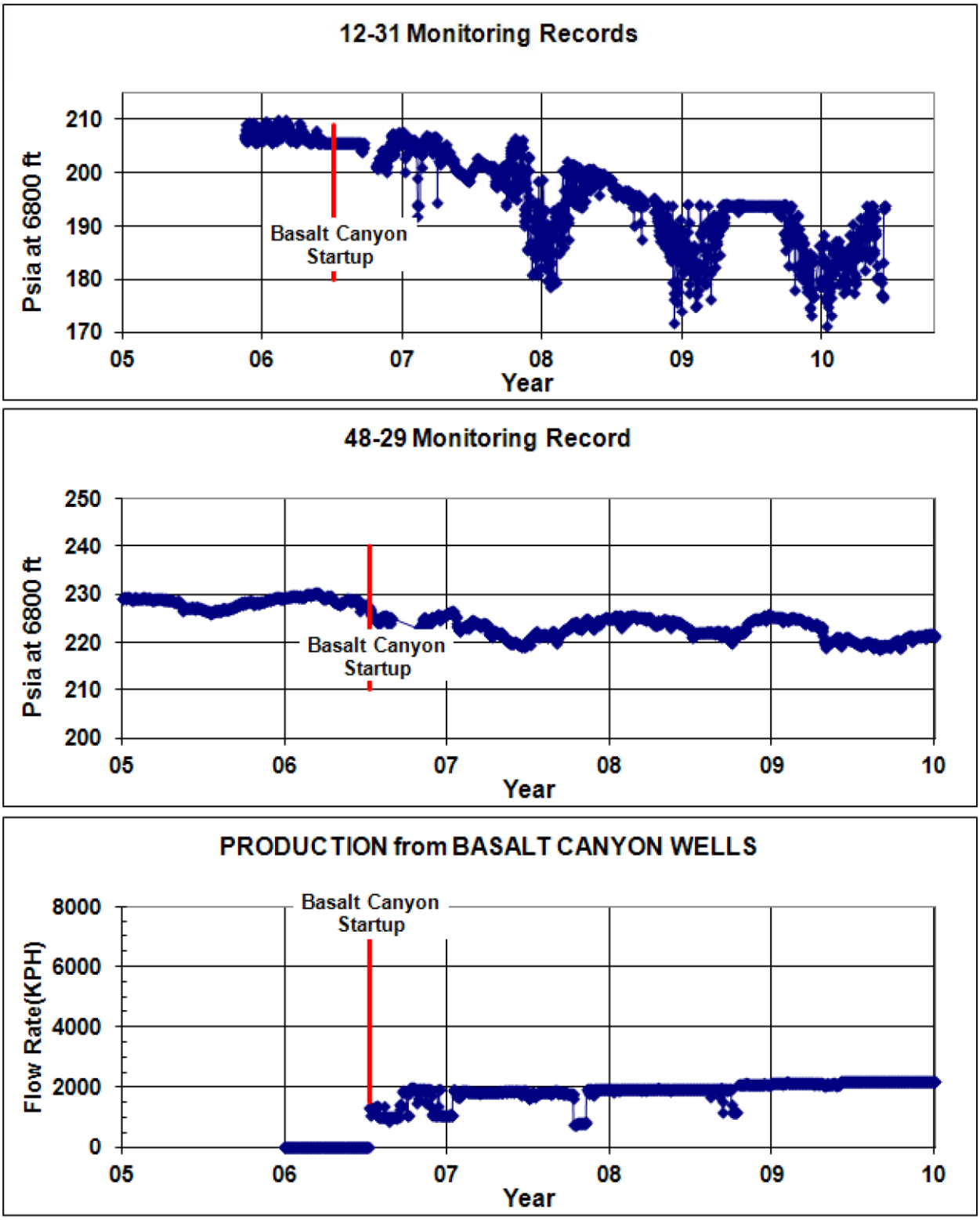


Figure 34 - Pressure monitoring data 2005-2010 for geothermal monitoring wells12-31 completed in western Bishop Tuff production reservoir in the Basalt Canyon area and 48-29 completed in the eastern Bishop Tuff injection reservoir north of Casa Diablo.

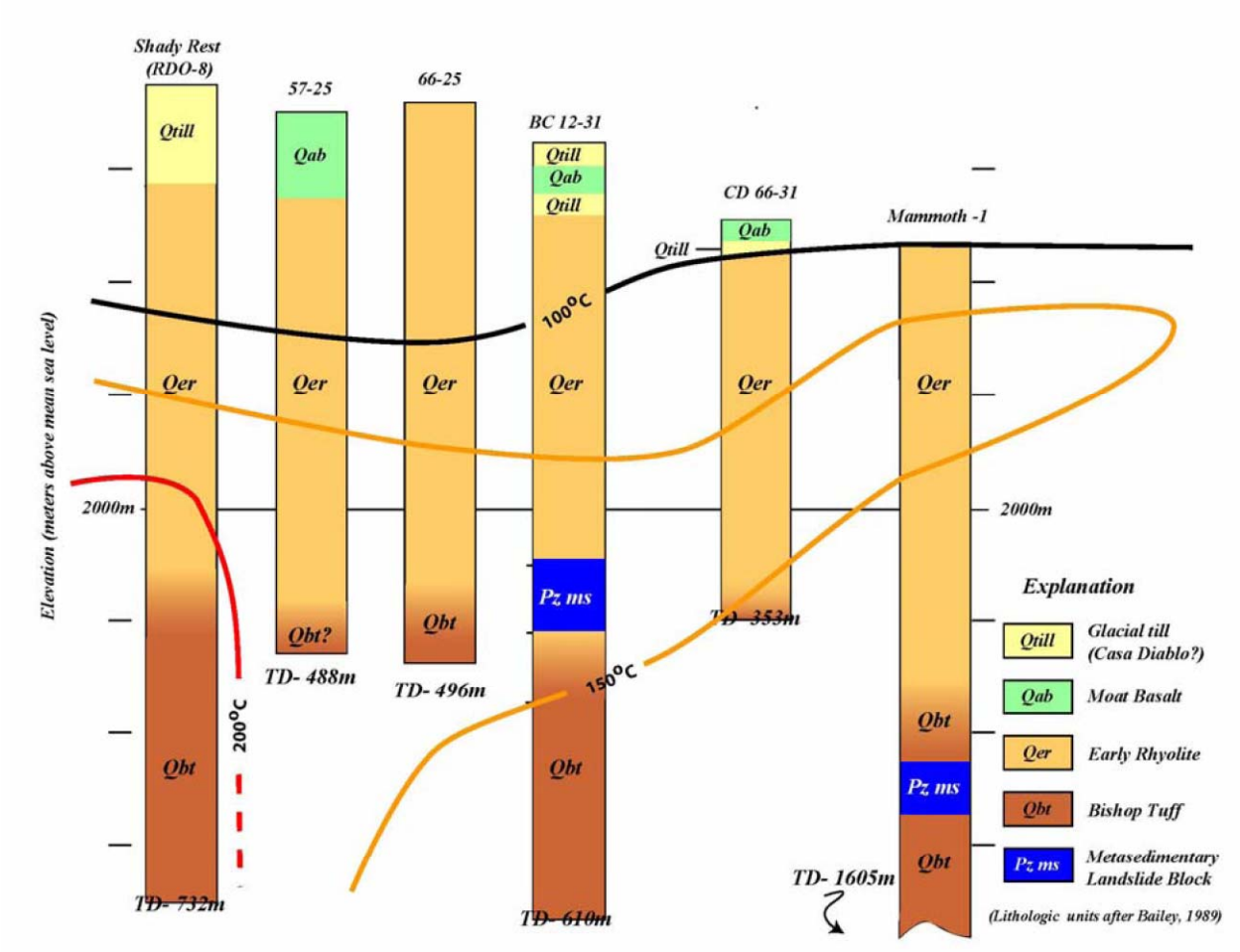


Figure 35 - Lithologic columns of western caldera wells showing a landslide block of impermeable Paleozoic rocks in wells 12-31 and Mammoth-1 but absent in corehole RDO-8 father west.

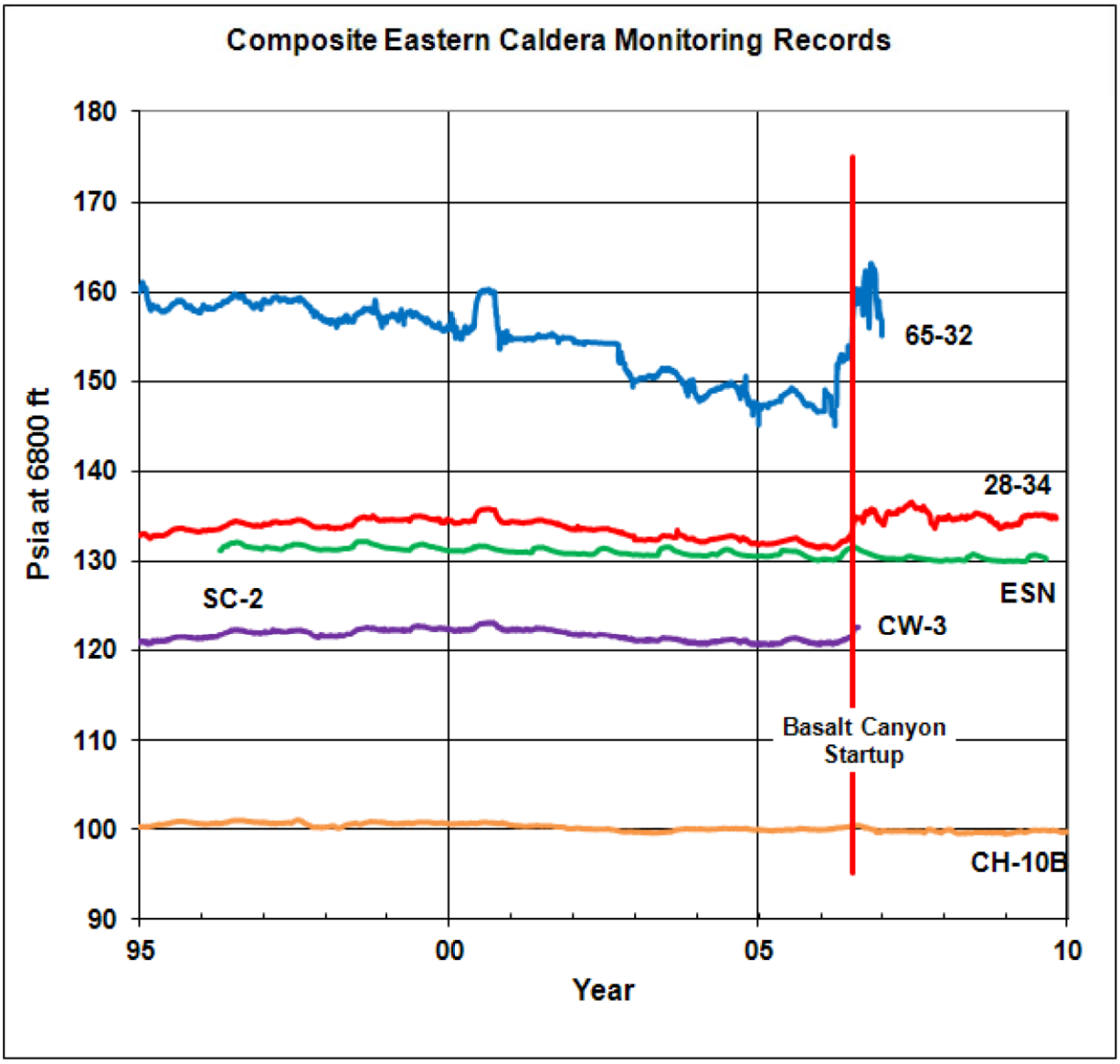


Figure 36 - Composite pressure monitoring records for eastern caldera monitoring wells.

This page intentionally left blank

Tables

Table 1 –Summary of Long Valley hydrologic monitoring data for Mammoth Creek/Hot Creek

	sample date	T	flow rate	Conductivity	pH	N	PO4	Si	Cl	Na	As	B	SO4	TDS	Northing	Easting
		°C	cfs	µS/cm		mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	mg/L	mg/L		
Mammoth Creek																
Mammoth C AB	1982	6.5		58	7	<0.7	0.06								37°37'49"	118°59'18"
Mammoth C Sherwin Rd	1982-1996	11.5		58				10	0.3		2	<10		<10	37°38'06"	118°57'57"
Mammoth Creek Flume	1983-1990	8.7	34.8	127.98				23	4.8		21	246			37°38'26"	118°53'58"
Mammoth Creek 395	1983-2008	6.5	17	122				20.9	0.48		4	14			37°38'16"	118°54'10"
Hot Creek	1996-2010		40-190												37°38'25"	118°54'02"
Hot Creek - Mammoth Creek	1982-1986	61		1301	6.3			188	193	208	2090		115	866		
Colton Spring area																
Colton Spring	1987-1991															
Fish Hatchery area																
AB		15-18	2-16													
CD		13.5-16.8	5.5-12													
H1																
H2,3		10.8-11.5	2-5													
Hot Bubbling Pool																
HBP	2008-2010	49-90		1730-1830	7.7											
Hot Creek Gorge Springs																
HCG			8.5													