Helium Isotope Systematics of Long Valley Caldera, California

G.A. Suemnicht¹, B.M. Kennedy² and W.C. Evans³

Mailing address, ¹EGS Consulting Inc., ²Lawrence Berkeley Laboratory, ³US Geological Survey
E-mail address, gsuemnicht@envgeo.com

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ABSTRACT

Long Valley Caldera supports an active hydrothermal system that has varied through time. The current hydrothermal system has probably been active in the western part of the caldera for only the last 45,000 years. 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. The highest temperatures of 218°C were encountered in a well in the western caldera moat. Geothermal plants at Casa Diablo in the southern caldera moat currently generate 40 MWe (gross) from moderate temperature (170°C) shallow (200m) hydrothermal outflow injecting spent fluid into deeper (750m) permeable zones in the underlying Bishop Tuff. The shallow hydrothermal system that supplies geothermal production and surface manifestations is more than 7 km from the apparent upwelling source region and significantly removed from eruptive centers in the western caldera moat that represent the largest volume of magmatic input into the caldera over the last 200,000 years. Apart from elevated ³He/⁴He ratios, magmatic signatures are generally lacking in Long Valley hydrothermal fluids. There are no volcanic-type fumaroles with temperatures far above the boiling point or with high-temperature magmatic volatiles (CO, SO₂, halogen gases etc.). The most significant change in surface manifestations was a dramatic increase in ³He/⁴He in a fumarole on the north side of Mammoth Mountain four months after the onset of seismic swarm activity. Helium isotope compositions within the rest of the shallow hydrothermal system have remained relatively stable. The highest ³He/⁴He levels are detected in relatively low temperature outflow springs in the far eastern part of the caldera.

We suggest that magmatic volatile input occurs within the current geothermal system in the western caldera. Intense alteration and circulation within the deep permeable western metamorphic basement complex adds significant radiogenic ⁴He and sets a relatively constant ³He/⁴He level for more distant outflow at lower elevations to the east. Impermeable metamorphic rocks underlying the shallow outflow limit further magmatic volatile input. Surface manifestations with higher helium isotope ratios are distributed along the deeply penetrative Hilton Creek fault in the eastern caldera far from obvious recent magmatic input. The prevailing distribution of helium isotopes and the absence of evidence for other magmatic volatiles is related more to the separation between the upflow and outflow of the hydrothermal system than increased magmatic input within the central caldera where there is little, if any, heat flow evidence for new significant volumes of magma in the crust.

Figure 1: Generalized Long Valley geology and distribution of the Bishop Tuff (after USGS).

1. INTRODUCTION

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 (Figure 1). The caldera is a 17 X 32 km (10 X 20 mi) depression created by the eruption of an estimated 600 km³ of Bishop Tuff 760,000 years ago (Bailey and others, 1976; Bailey, 2004; Hildreth, 2004). Post-collapse eruptions have continued to fill the caldera over the last 600,000 years (Bailey and others, 1976; Bailey, 2004; Hildreth, 2004). The
youngest Moat Rhyolites erupted ~100,000 years ago during a period of more voluminous basaltic and andesitic flows in the western caldera. The most recent eruptions occurred 500-600 years ago along the Mono-Inyo volcanic chain extending from the western caldera moat northward to Mono Lake (Figure 1). The caldera began a period of unrest in the late 1970s that included earthquake swarms, approximately 80 cm of inflation centered on the resurgent dome, changes in fumarole discharge and CO2 emissions around the flanks of Mammoth Mountain. Detecting and anticipating potential eruption precursors motivated a caldera-wide program of monitoring that has included analysis of helium and inorganic carbon isotopes to evaluate the potential of magma input beneath the caldera.

2. HYDROTHERMAL SYSTEM

The Long Valley hydrothermal system has varied through time (Bailey and others, 1976, Sorey and others, 1978; 1991) supporting an intense hydrothermal system from 300,000 to 130,000 years ago succeeded 45,000 years ago by the current active hydrothermal system. Surface manifestations include fumarolic discharge at higher elevations west of the Resurgent Dome and hot springs at lower elevations to the east (Figure 2). Thermal waters are near neutral Na-HCO3-CI type, with CI concentrations of 200-300 mg/L and dissolved solids ~1300 mg/L. Hydrothermal manifestations are notably absent in the western caldera (Bailey and others, 1976); however, high-temperature alteration mineral assemblages <100,000 years in the west moat were deposited by hydrothermal outflow along penetrative faults in the western caldera (Suemnicht and Varga, 1988; Martini, 2002). Nearly all active surface manifestations occur within the southern part of the caldera (Figure 2) and as much as 80% of the current hydrothermal outflow occurs at Hot Creek on the edge of the Resurgent Dome in the southeastern moat along splay of the active Hilton Creek fault system. Geochemical estimates of source reservoir temperatures range from 200°C – 280°C (Sorey and others, 1978; 1991; Mariner and Wiley, 1976). The hottest well in the caldera is Unocal well 44-16 approximately 1 km (0.6 mi.) west of the Inyo Craters (Figure 3) with temperatures of 218°C (424°F) at 1100m (3600ft) (Suemnicht, 1987).

The present hydrothermal system sustains 40 MWe (gross) of geothermal production at Casa Diablo in the southern caldera moat (Figure 3). Relatively shallow (~200m) wells supply ~630 L/sec (~10,000 gal/min) of moderate temperature (170°C) fluids to three binary power plants. Data from wells penetrating the intracaldera Bishop Tuff and into the Sierran metamorphic floor of the caldera reveal that the principal geothermal reservoir in Long Valley is not located directly beneath the Resurgent Dome but instead, is supplied by outflow from an upwelling source in the western caldera (Figure 4). The current pattern of outflow and active surface manifestations in the southern caldera moat is the result of fracturing and faulting that opened many older outflow zones at lower elevations in the south central portion of the caldera. Strontium isotope relationships indicate that at least part of the source reservoir originates from the metamorphic rocks that comprise the western caldera floor (Goff and others, 1991).

3. HELIUM ISOTOPES

Surface thermal features and produced geothermal fluids in Long Valley do not have magmatic characteristics. None of the fumarole temperatures is far above the boiling point (for the elevation) and none of the hot springs have elevated levels of high-temperature magmatic volatiles such as CO, SO2, or halogen gases (Cl, F) (Farrar and others, 1985, 1987; Sorey and others, 1984, 1985). Nearly three decades of monitoring hot springs, fumaroles and geothermal wells in and around the caldera has yet to detect radical changes in fluid chemistry or helium isotope compositions. The R/Ra helium ratios in hydrothermal fluids are generally within the range of the helium isotope compositions of olivine extracted from Long Valley moat basalts and regional basalts.
(Dodson et al., 1998; Figure 5). The exceptions are Little Hot Creek and Big Alkali Lake in the eastern caldera that showed an apparent transient helium isotope response potentially related to early (1982) caldera-wide seismic activity (Hilton, 1996), and a fumarole on the north face of Mammoth Mountain where temperatures, flow rates, helium isotopic compositions and hydrogen sulfide increased in apparent response to a swarm of seismic events in 1989 (Sorey et al., 1993; Farrar et al., 1995; Sorey et al., 1998).

Figure 3: Well locations and detail of wells penetrating the Bishop Tuff and Paleozoic metamorphic rocks.

Figure 4: 3-D isotherms across Long Valley Caldera from upwelling western source to outflow in the southeastern caldera moat.

The enigma of the distribution of helium isotope compositions within Long Valley caldera is the apparent separation between helium isotope ratios of 5-6 Ra in distant comparatively low temperature outflow springs compared with moderate to low ratios (R/Ra ~ 4) around the probable high temperature upflow zone of the current geothermal system. The highest helium isotopic ratios (~5-6.5 Ra) occur in the eastern portion of the caldera in thermal fluids associated with splays of the recently active Hilton Creek Fault system (Hot Creek, Big Alkali Lake and Little Hot Creek, Figures 2.5 (red symbols) and 6). In some cases, helium ratios approach or exceed the west moat basalt olivine compositions. The asymmetric distribution of helium is particularly puzzling since lower R/Ra values are distributed within the area of the most recent eruptive events in the western caldera, within an area of intense
Seismic activity in the southwestern caldera moat and within the upwelling source area for the caldera’s hydrothermal system. Only the distal eastern features respond with transient increases in R/Ra during periods of seismic unrest. (Hilton, 1996). The Long Valley Exploratory Well (LVEW) drilled by the U.S. DOE is the deepest well within the caldera reaching 2997m (9832ft) within the caldera’s resurgent dome in the central part of the uplift noted during the period of caldera unrest (Hill, 2006; McConnell and others, 1992). The maximum temperature at 3km in LVEW was 104°C, which is substantially less than expected for a conductive regime above a shallow or relatively recent magma chamber at 5-7 km (Farrar and others, 2003). The estimated volume of new magma intrusion within the central caldera is only 0.03 - 0.22 km³ (Langbein, 2003; Battaglia and others, 1999) and, based on the deep drilling results from the LVEW well, there is no heat flow evidence of an extensive active magma body within the center of recent uplift.

Figure 5: Helium isotopic compositions for caldera thermal features as a function of time compared to olivine helium isotopic compositions for Long Valley basalts.

Long Valley geochemical data are inherently biased because all of the sampled geothermal production wells are shallow (< 500m) and surface manifestations are supplied by shallow outflow that is considerably displaced from the deep upwelling source of the hydrothermal system. The helium isotopic compositions (R/Ra ~ 3.7) of fluids from the very deep LVEW research well were indistinguishable from the other sampled features in the western caldera, including the Casa Diablo production fluids. The highest R/Ra values occur some distance from the concentration of eruptive centers in the western caldera and are the most prominent evidence of young magmatic input in Long Valley over the last ~200 ka. Heat flow data do not substantiate that ³He in the eastern part of Long Valley caldera can be attributed to recent magmatic input. The ³He content of the geothermal fluids could be diluted by radiogenic crustal ³He but degassed or within the long outflow zone in Long Valley (Sorey and others, 1998). Dilution still assumes a relatively high rate of ³He and none of the proposed mechanisms explain why the highest R/Ra values in Long Valley occur at the far distal end of the geothermal outflow plume in the most dilute moderate temperature springs.

4. CONCLUSIONS

Crustal permeability is a fundamental control in Long Valley because a thick section of impermeable metamorphic rocks comprise the deep caldera floor and the roof of the Bishop Tuff magma chamber. Oxygen isotope data (Smith and Suemnicht, 1991; McConnell and others, 1995; 1997) show that post-collapse Early Rhyolite units, the intracaldera Bishop Tuff and metamorphic floor of the caldera are consistently altered by the older 300,000 year-old hydrothermal system that circulated outward from the Resurgent Dome reaching a peak at ~ 300 ka waning by 100 ka. The LVEW well was affected by deep circulation of ~ 300°C fluids within the older hydrothermal system further reducing permeability (Mukhopadhyay, 2002; Fischer and others, 2003). The altered impermeable section of metamorphic rocks underlying Long Valley is the principal control on radiogenic helium input at a deep crustal level in Long Valley. Surface manifestations with high ³He/²He ratios within the caldera all occur east of the thick section of metamorphic rocks that comprise the west-central caldera floor along the main fault trace or intracaldera splays of the Quaternary/Recent Hilton Creek Fault (Figure 6) that Bailey (1976, 1989) interpreted as one of the principal controlling deeply penetrative tectonic elements of the caldera. Similarly, the Mammoth Mountain fumarole that experienced a sudden rapid increase of ³He input occurs along the caldera’s ring fracture system that cuts the northern face of the mountain and is a deeply penetrative fault system related to caldera collapse. Elevated magmatic volatile flux is related more to permeability than new magmatic input.

The distribution of mantle volatiles and, specifically, helium isotopes in the Long Valley is a pointed reminder that assumptions of symmetry or uniform helium isotope distribution in vigorous magmatic hydrothermal systems are not necessarily viable conceptual models. Past concepts of Long Valley assumed that the hydrothermal system was symmetrically distributed around the caldera’s Resurgent Dome, the center of the represurized Bishop Tuff magma chamber. Drilling results prove that the upwelling geothermal source in Long Valley is unrelated to the Resurgent Dome. In a similar fashion, helium isotope distribution has been used during periods of caldera unrest to infer varied magma input within a zone of uplift centered on the Resurgent Dome. There is, however, little heat flow evidence for large volume magmatic input within the central part of Long Valley. Marked increases in flow characteristics, magmatic helium and inorganic carbon accompanying seismic swarms beneath Mammoth Mountain and are direct
evidence of potential magmatic input or at least enhanced crustal permeability but the general lack of response in prominent surface manifestations elsewhere suggests changes in magma input are an unlikely causal mechanism in the central and southern caldera.

Figure 6: Configuration of basement rocks and generalized faults in and around Long Valley caldera with maximum measured 3He/4He ratios over the period 1978-2006.

REFERENCES


Suemnicht, Kennedy and Evans


