

A Comparison of the Long Valley and Valles Caldera Hydrothermal Systems in the Western United States

Shawn Wheelock
Indiana University, Bloomington, Indiana

Abstract.

There are three major Pleistocene silicic calderas in the western United States: Yellowstone, Long Valley, and Valles (Grande). The Valles is the oldest and most mature, while the Yellowstone is the youngest and least mature. Maturity is measured by the degree to which the magma chamber has cooled and permeability of materials is lost due to subsidence and cementation of pore spaces by recrystallization of minerals contained in the fluids. The Long Valley caldera has undergone four main periods in its evolution with the waxing and waning of the magma chamber. Its highest activity was 300 thousand years ago, which produced the large evaporite plains across much of the Mojave Desert. Today it is relatively cool at 218° C and is of modest intensity. The Valles caldera has a much longer, but less violent history of volcanism. Its hydrothermal system has slowed because its magma chamber has almost entirely crystallized, but still penetrates to 2-3 km in the basin where it is heated to temperatures of 300° C. The reasons why this temperature is higher than that of the Long Valley caldera are examined.

I. Introduction

Pleistocene calderas from silicic eruptions are fairly common throughout the world, and many of them continue to be hydrothermally active to this day, having retained their heat for hundreds of thousands of years. (Sorey 1985). There are three main ones present in the continental United States. In order of amount of volcanic ejecta, they are the Yellowstone caldera in Wyoming, the Long Valley caldera in California, and the Valles (Grande) caldera in New Mexico.

The Long Valley caldera was primarily produced when the Bishop Tuff was erupted, approximately 730 ka. This was a plinian eruption that ejected approximately 600 km³ of highly silicic rhyolite magma (Sorey et al. 1991). In contrast, the Valles caldera formed 1.14 Ma. It was produced when 300 km³ of rhyolite was erupted to become the Bandelier Tuff (Goff et al. 1992). Both of these systems are considered to

be in a 'mature' stage, which is to say that volcanism has slowed and the permeability of the aquifer materials is slowly being lost to subsidence and crystallization of minerals contained in the fluids (Bailey et al. 1976, Goff et al. 1992).

Their nature is markedly different than that of the 600 ka old Yellowstone caldera (Sorey 1985). Yellowstone is being continually supplied with heat due to it being over a hot spot, with deep mantle melt feeding it (U.S.G.S. 2003). In contrast, the Long Valley and Valles calderas arise from regional tectonics and have their magma source being from relatively shallow in the mantle. In the present treatment, only the latter two will be considered. This is due to the fact that the origins of the Yellowstone caldera are so fundamentally different. The bulk of the discussion will be on the Long Valley caldera, with the Valles caldera presented for contrast. Additionally, data are much more abundant for the former than the latter.

II. Long Valley Caldera – Geologic Setting

The Long Valley caldera is located on the eastern flank of the Sierra-Nevada mountain range, in East-Central California. It is at the tectonic boundary between the Basin and Range province, which includes almost all of Nevada, and the Sierra-Nevada pluton. Volcanism began in this region approximately 3.2 Ma (Blackwell 1985). Figure (1) shows the caldera.

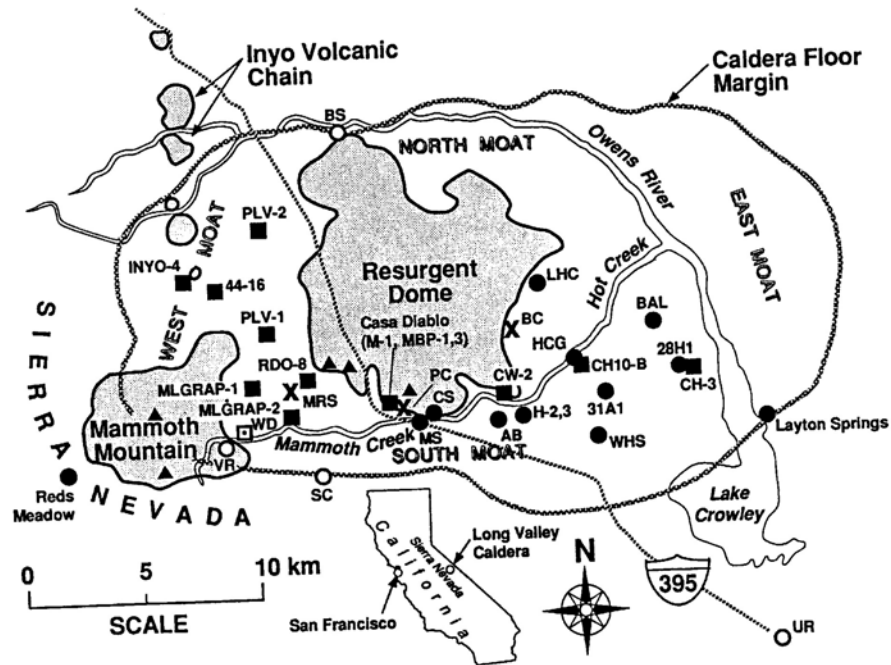


Figure 1 – Taken from Sorey et al (1991), this figure shows the caldera along with major features. Circles are thermal springs. Triangles are fumaroles. Squares are prominent wells.

After the initial eruption in which it formed, there has been a long history of intracaldera volcanism. Most significant among these is at 600 ka, much of the central portion of the caldera rose to form a large resurgence dome that is 10 km in diameter, and 500 meters high (Bailey et al. 1976).

Since that time, there has been eruption of significant “moat” rhyolites, which have filled in much of the area around the dome. Volcanism has continued to the present, with rhyolitic domes, known as the Inyo craters, forming as recent as 500 years ago (White and Peterson 1991). These were phreatomagmatic eruptions, with material only coming from about 450 meters below the surface (Mastin 1991).

Since 1980, there has continued to be earthquakes and ground deformation, suggesting that the magma chamber is becoming somewhat unstable and an eruption is possible in the near future (Hopson 1991). Seismic studies in 1984 showed a magma

chamber with an approximate depth of 5km (Sanders 1984). This has likely changed in the last twenty years.

A possible cross section of the caldera is shown as figure (2).

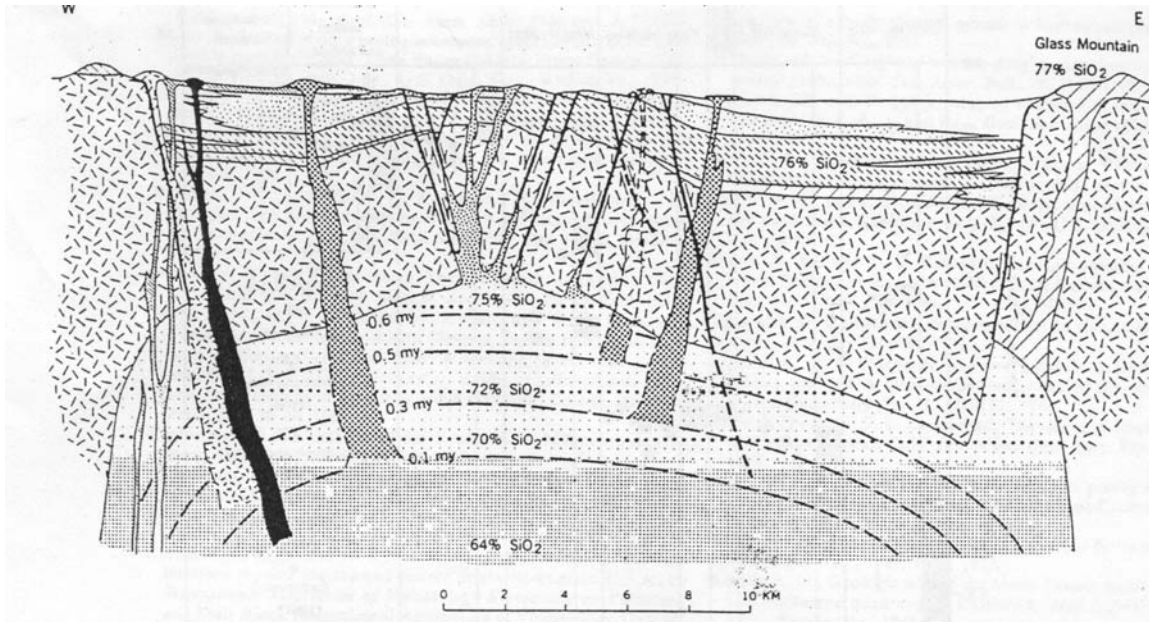


Figure 2 – Taken from Baily et al. (1976). A hypothetical cross section of the magma chamber in Long Valley

III. Long Valley Caldera – Historical Hydrothermal System

Evidence suggests that Long Valley caldera once was once as geothermally active as some of the geyser basins in the Yellowstone caldera are today. It has since, not only cooled, but has also sealed itself up due to silicification, argillization, and zeolitization (Bailey et al. 1976). This did not occur, however, until approximately 430 ka *after* the caldera caved in.

The hydrothermal system of the caldera has undergone several major changes, waxing and waning with the size of the magma chamber. After the caldera collapsed in upon itself, one had a depression with several thousand feet of freshly erupted Bishop Tuff. Both logic and fossil geyser data indicate that this was a very active geothermal

system that was helping to rapidly cool the ash. It would, however take significant amounts of time for preferential flow paths to develop. This is, obviously, the phase that we know the least about. It is estimated that this portion of the caldera's evolution lasted for 100,000 – 200,000 years after the 730 ka eruption (Blackwell 1985).

At 600 ka, a new magma body had risen towards the surface and formed the large resurgence dome which was referred to above. Preferential flow paths had already formed in the tuff at this time, and these were undoubtedly altered by the rise of the dome and its attendant fractures. This initiated a new flow system, with surface waters infiltrating in the east, and hot geothermal waters discharging in the west. This system was likely in place for several hundred thousand years, and served to cool the magma beneath the resurgence dome and elsewhere in the caldera. It is postulated that this flow provided the saline waters that covered much of the Mojave Desert at the time (ibid).

Based upon the evaporite deposits in nearby Searles Lake, the hydrothermal system reached its maximum activity at 300 ka. There was a deep flow system in place, which is postulated to have been in good contact with the magma chamber. At this time, it was likely still molten and somewhat close to the surface (Sorey 1985). This caused the greatest amount of hydrothermal alteration that the caldera had experienced to date. The rocks became very isotopically depleted in oxygen and chloride (Sorey et al. 1991).

On a brief tangent, it is important to note that the chloride is of particular interest. A recent study has just found that the best ways to hydrologically monitor magma chamber developments is through high-chloride springs. Along with high-temperature fumaroles, they were found to be the best connected with the deep system (Ingebritsen et al. 2001).

A large part of the alteration that occurred was due to H₂S that rose from the magma chamber through fissures would react with water to form sulfuric acid. This would scour a variety of minerals from the host rock, and as the fluid cooled, would redeposit them in the form of mineral veins. Additionally, these silica rich waters would react with unconsolidated lacustrine sediments, forming an opal cement. This layer is as thick as 15 meters in places (Bailey et al. 1976).

This 300 ka figure coincides quite well with the 285 ka age of the Hot Creek rhyolite flow. It is also interesting to note that there is an increase in hydrothermal activity which correspond to the 500 ka, 300 ka, and 100 ka moat rhyolite flows, which are also believed to be derived from the main magma chamber. These data suggest that the main chamber, and not smaller magmatic intrusions, primarily drive the hydrothermal system. It follows that the flow system had to be very deep and well developed by this time (Bailey et al. 1976). The probable reason why the highest activity occurred at this time, 430 ka after the caldera formed is that it takes a significant amount of time for these deep flow systems to develop.

IV. Long Valley Caldera – Present Hydrothermal System

The present hydrothermal system has been in place for approximately 40ka. The magmatic heat source for this has been small, peripheral intrusions of silicic magma. Considering the proximity of the Sierra-Nevada range, there is bound to be very high recharge flow into the caldera. Using this, and the current rate of heat flux out of the caldera (which is, of itself, a very rough figure), it can be estimated that these intrusions had a volume of 50–100 km³ (Sorey 1985).

It is assumed that the heat source for the present system is the same as that which has driven the eruptions of the Inyo craters, but there is no geothermal flow close to the craters (Mastin 1991). The location of this heat source that created the craters and drives the fluid flow today is still somewhat unknown. Isotopic evidence suggest that the flow originates in the metamorphosed country rock beneath the western portion of the caldera (Sorey et al. 1991). Additionally, a test well drilled by the Unocal company in the western portion of the caldera has found that it is 218°C near the top of the bishop tuff, about 1080 meters in depth. It is estimated that the maximum temperature near the magma chamber is 248° C (Mastin 1991). 218° C is the highest temperature that has been found in boreholes as of the 1991 writing of the article. As was noted in the introduction, seismic studies also show the presence of a magma chamber in this area.

Strontium isotopic data suggest that the waters are in contact with the basement complex long enough to be able to equilibrate with the surrounding metasedimentary materials (Goff et al. 1991). This is interesting when one considers that the flow rates in these aquifers is quite high – estimated at 100-200 meters per year in a confined aquifer (Blackwell 1985).

This would indicate that the deep flow is porous in nature, and once it rises, much of it is along fractures and faults as opposed to porous media flow. This would seem consistent with the fact that most of the hot springs and fumaroles occur along north to northwest trending faults. Indeed the hottest springs occur near the two main faults which bound the graben (Bailey et al. 1976). This system likely consists of thin zones of hot water which flow laterally from west, where the magma chamber is, to the east, and head towards the surface when it intersects secondary porosity (Sorey 1985). Electrical

investigations also confirm that most of the past and present flow is controlled by fractures systems formed by Sierra faulting (Stanley et al. 1976).

Groundwater flow is a very effective tool for the system to dissipate heat. Just 3000 years ago, it is estimated that the heat flux was one to two orders of magnitude greater than is presently observed. One of the reasons it is so efficient is that the water is not recirculating. It is estimated that half of the hot water in the system has been discharged, only to be replaced by cold, mountain runoff (Blackwell 1985). Some scientists place the amount of discharge from the system at 200 – 300 kg/sec (Olmsted 1978). The rate of current heat dissipation was estimated to be 2.9×10^8 Watts. These figures place it between the intense flux of the mantle plume powered Yellowstone caldera and the low from of Valles Grande (Sorey 1985).

V. Valles (Grande) Caldera – Geologic Setting

The Valles caldera formed in the Jemez Volcanic Field. This string of volcanism runs along the intersection of the Jemez volcanic lineament and the Rio Grande rift zone. Figure (3) shows the geographical placement. The rift system runs from southern Colorado, through New Mexico and down to Mexico, and began actively rifting approximately 30 Ma. Volcanism in the Jemez field occurred between 13 and 0.13 Ma, and consisted mostly of rhyolites, although there is a modest amount of basalt. Elsewhere in the lineament, the abundance of the two is reversed (Goff and Grigsby 1982, Goff et al. 1992).

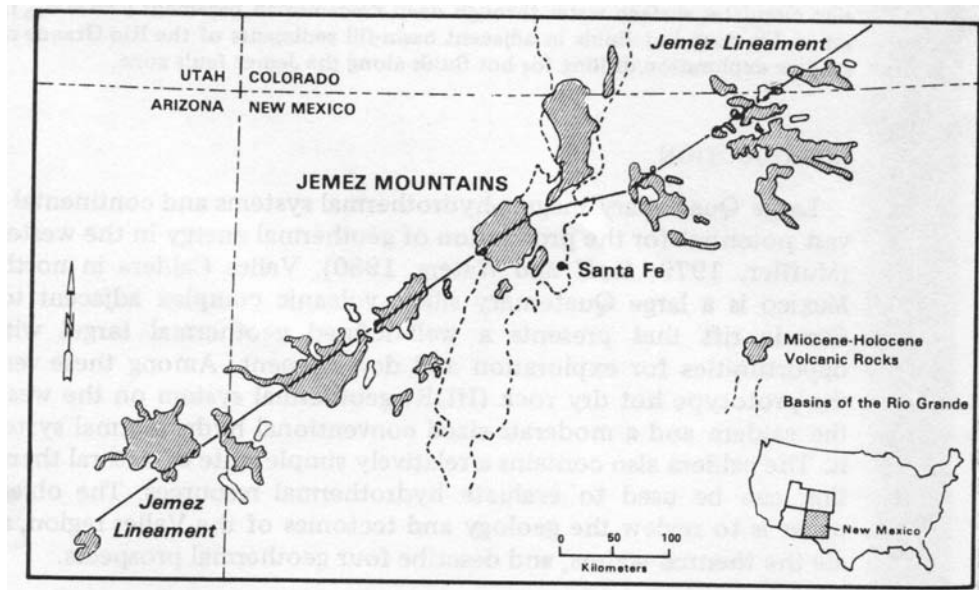


Figure 3 – Taken from Goff et al. (1992)

The Valles caldera is the youngest of several Quaternary calderas in the field. In fact, it partially obscures the much smaller Toledo caldera to its northeast. This superposition is also the reason why the floor of the caldera is very asymmetric. Following it, there were only minor volcanic events in the field, and, of course, within the caldera (ibid.). The caldera is shown in Figure (4).

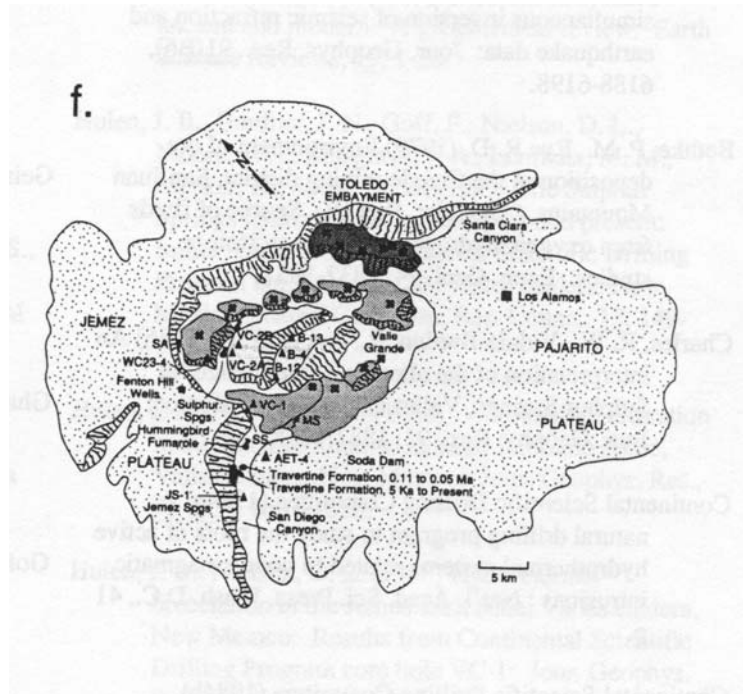


Figure 4 - Taken from Goff et al. (1992)

One hundred thousand years after the creation of the caldera, there was a resurgence forming a dome in the center of the caldera. Some of this magma reached the surface, forming moat rhyolites, just as in the Long Valley Caldera. These small flows continued until approximately 130 ka, when all volcanism in the chain ceased. Data from Union Oil Company test wells has shown that there are likely few magmatic intrusions into the resurgence dome. Thus all of this late volcanism was confined to moat flows (ibid.).

Today, some models estimate that the Valles pluton has virtually finished crystallizing leaving only scattered pockets of molten material at depths of five to six kilometers (Kolstad and McGetchin 1978, Suhr 1981, Goff et al. 1992)

VI. Valles (Grande) Caldera – Hydrothermal System

The Valles hydrothermal system was originally very hot. It is estimated that at 1 Ma, as shallow as 400 meters, the temperature of the fluids was 300° C. Today fluids at this temperature can still be found, but they occur 2 –3 km below the surface (Goff and Grigsby 1982, Goff et al. 1992). Figure (5) shows a cross section of the caldera along with prominent flow paths of fluids in the system.

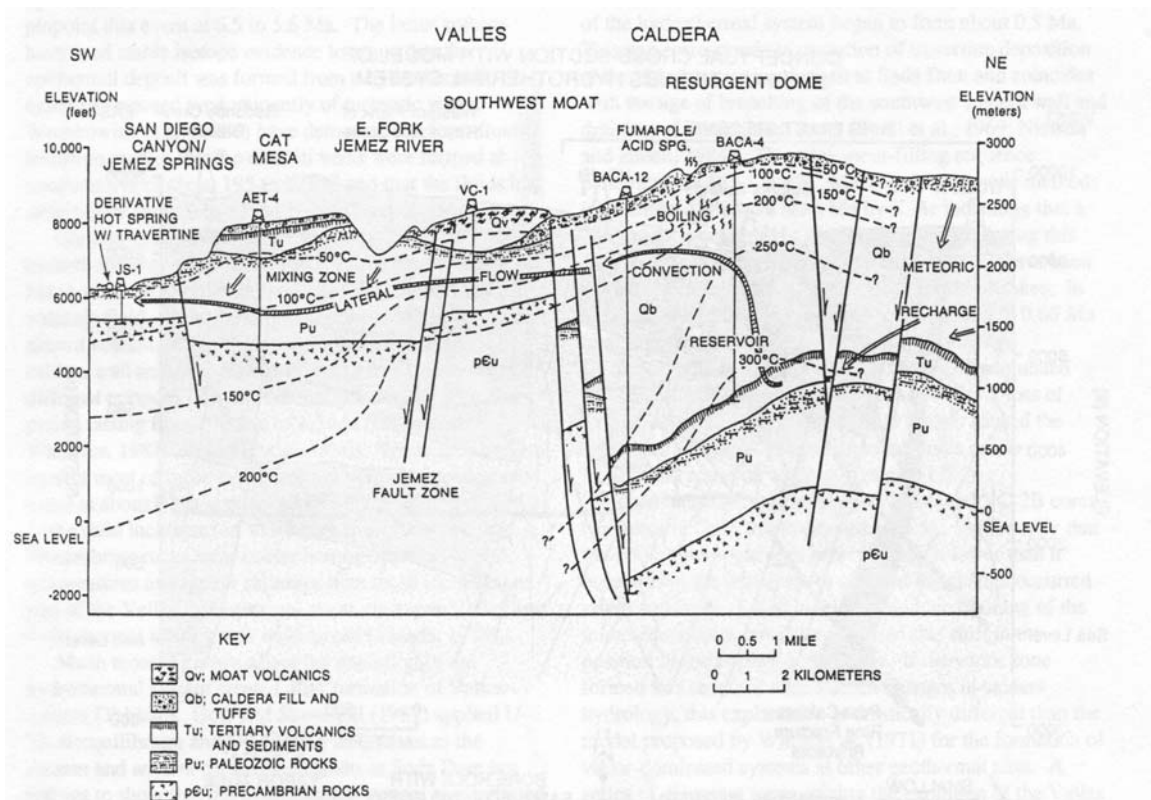


Figure 5 - taken from Goff et al. (1992)

The flow system, as said above, originates at least 2-3 kilometers in depth, where chemical data suggest that it equilibrates with the surrounding rocks. This is not connate water, but is almost entirely the result of recharge. $\delta^{18}\text{O}$ data reveal that these are

meteoric waters, falling very close to the meteoric water line when the $\delta^{18}\text{O}$ and $\delta^{16}\text{O}$ data are plotted against each other (Goff and Grigsby 1982, Goff et al. 1992). Tritium data suggests that the residence times of these waters is between 3 and 10 thousand years (Shevenell 1990). This would also point to a fairly high flow rate, which is likely the combination of both porous media and fracture flow. This is, however, significantly slower than the modeled results of Blackwell (1985) which indicated that waters in the Long Valley caldera were moving at 100 –200 meters per *year*.

After the flow convectively rises between 500 and 600 meters, it heads almost exclusively laterally towards the caldera wall. This is the reason why the vast majority of the hot-springs and fumaroles are around the perimeter of the caldera. This flow regime has been dominant for at least 1 Ma. It is remarkable that all the moat rhyolites that erupted since the resurgence dome formed had little to no effect on the flow system. The age of this flow regime is confirmed by U-Th dating of calcite veins in travertine deposits of soda dam, south of the caldera (Goff et al. 1992).

The hot springs around the caldera are isotopically a mixture of cool surface waters, and deep hot waters. It can be confirmed that these deep waters arise from areas in which they are proximal to magma pockets by the isotopic fractionalization of helium in the waters. In general, near surface formations containing high amounts of ^3He are rare, and indicate that the material has come from within the mantle. When the water is in contact with newly crystallize material, it will equilibrate with the constituents of the rock, and that includes with helium (ibid.). The chloride content of the springs, while generally a very good technique (Ingebritsen et al. 2001), would not have efficacy here as

the Bandelier and subsequent tuffs have a chloride content, as high as 2800 PPM (Goff et al. 1992).

One significant difference from the Long Valley caldera system is that here there is a vapor zone overlying the entire hydrothermal system. It began to form 500 ka, when the caldera wall was breached and the caldera lake drained down the Jemez canyon. Now that the soil was no longer completely saturated, volatiles began to accumulate in the materials above the 200°C waters. The primary constituents of these gases are H₂O, CO₂, and H₂S. Unlike other locations in which such layers can be found, it is not a sharp interface here, instead it varies with gas output, groundwater flow, and precipitation. Close to the surface, there is a several meter thick condensation zone. This causes acid springs, mud pots and fumaroles to form across the caldera (ibid.).

As noted in the Long Valley section, the hydrogen sulfide gas reacts with water to form sulfuric acid. Bacteria can also oxidize the H₂S as part of their metabolism and produce even greater quantities of acid. This acid scouring is partially responsible for many economic mineral veins. One example is that between 25 and 125 m in depth, there are vast deposits with “molybenite mineralization in hydrothermally-brecciated quartz-sericitized tuff” (Goff et al. 1992). Elsewhere in the Jemez Mountains, there are significant deposits of phrite and even gold. The alteration style that has taken place in the caldera is advanced argillite to anhydrous calc-silicate.

VII. Conclusions

One of the strangest comparisons that can be made between the two systems is that the waters in the Valles Caldera reach 300° C at depth. This is remarkable in that it is hotter than the estimated 248° C that occurs in the Long Valley caldera by almost 20%.

The Long Valley caldera is younger, resulted from a larger eruption, and still has a very molten magma chamber, and is emitting much more heat, and yet the fluids in the Valles caldera fluids are significantly hotter. Table (1) shows the relationships between the heat flux between all three western calderas (adapted from Sorey, 1985)

Caldera (age)	Ejecta Amount (km ³)	Fluid Discharge (kg/s)	Heat Discharge (10 ⁸ W)	Heat Flux (mW m ⁻²)
Yellowstone (0.6 Ma)		3000	42	2100
Long Valley (0.7 Ma)	600	250	2.9	630
Valles (1.1 Ma)	300	35	0.75	500

Table 1

These data imply that the fracture systems likely allow the fluids to come in much closer contact with the remaining pockets of molten material, than those in the Long Valley caldera do. Another possible explanation is that since the Valles magma pocket has almost totally crystallized, that these cooled, intrusive granitic rocks are much better at holding heat in than the unconsolidated Bishop Tuff, which composes the whole lower sequence of the Long Valley caldera stratigraphy.

In fact, the crystalline basement rocks beneath the Valles caldera are so good at holding heat in, that Los Alamos National Laboratory constructed the world's largest, hot-dry-rock energy production system, in which they would drill wells and hydrofracture the rock to create reservoir space. They would then pump down surface waters to heat them and extract them to generate power (Goff and Grigsby 1982). This experiment has since been decommissioned since they were never able to turn a profit.

The general flow systems of the two calderas are very different due a variety of factors, but represent well two different stages of caldera evolution. The Valles caldera is much more mature. It has lost much of its permeability and most of its magma has

cooled. It is important to study both systems, along with immature systems such as Yellowstone to better understand the life and evolution of silicic caldera systems throughout the world.

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