TECHNICAL REPORT

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PHASE 2 AND 3 SLIM HOLE DRILLING AND TESTING AT THE LAKE CITY, CALIFORNIA GEOTHERMAL FIELD

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ABSTRACT

During Phases 2 and 3 of the Lake City GRED II project two slim holes were cored to depths of 1728 and 4727 ft. Injection and production tests with temperature and pressure logging were performed on the OH-1 and LCSH-5 core holes. OH-1 was permanently modified by cementing an NQ tubing string in place below a depth of 947 ft.

The LCSH-1a hole was drilled in Quaternary blue clay to a depth of 1727 ft and reached a temperature of 193 °F at a depth of 1649 ft. This hole failed to find evidence of a shallow geothermal system east of the Mud Volcano but the conductive temperature profile indicates temperatures near 325 °F could be present below depth of 4000 ft.

The LCSH-5 hole was drilled to a depth of 4727 ft and encountered a significant shallow permeability between depths of 1443 and 1923 ft and below 3955 ft. LCSH-5 drilled impermeable Quaternary fanglomerate to a depth of 1270 ft. Below 1270 ft the rocks consist primarily of Tertiary sedimentary rocks. The most significant formation deep in LCSH-5 appears to be a series of poikoilitic mafic lava flows below a depth of 4244 ft that host the major deep permeable fracture encountered. The maximum static temperature deep in LCSH-5 is 323 °F and the maximum flowing temperature is 329 °F. This hole extended the known length of the geothermal system by ¾ of a mile toward the north and is located over ½ mile north of the northernmost hot spring.

The OH-1 hole was briefly flow tested prior to cementing the NQ rods in place. This flow test confirmed the zone at 947 ft is the dominant permeability in the hole.

The waters produced during testing of OH-1 and LCSH-5 are generally intermediate in character between the deep geothermal water produced by the Phipps #2 well and the thermal springs. Geothermometers applied to deeper fluids tend to predict higher subsurface temperatures with the maximum being 382 °F from the Phipps #2 well.

The Lake City geothermal system can be viewed as having shallow (elevation > 4000 ft and temperatures of 270 to 310 °F), intermediate (elevation 2800 to 3700 ft and temperatures 270 to 320 °F) and deep (elevations < 1000 ft and temperatures 323 to 337 °F) components. In the south part of the field, near Phipps #2 the shallow and deep components are present. In the central part of the field, near OH-1 the shallow and intermediate components are present and presumably the deep component is also present. In the north part of the field, the intermediate and deep components are present. Most or all of the fractures in the core have dips between 45 degrees and vertical and no strong stratigraphic control on the resource has yet been demonstrated.

Conceptually, the Lake City geothermal resource seems to be located along the north-south trending range front in a relatively wide zone of fractured rock. The individual fractures do not seem to be associated with any readily identifiable fault. In fact, no major hydraulically conductive faults were identified by the core drilling.

INTRODUCTION

This is the final report for phases 2 and 3 of the Lake City GRED II project. Phase one consisted of performing geological, geophysical, geochemical, and well testing and logging work to further understand the resource and to pick the location for future slim holes. The work performed in phase 1 demonstrated that the Lake City geothermal system has a natural heat output comparable to several other Basin and Range geothermal systems producing 10 to 20 MW of electricity and has one well that appears capable of commercial production rates, the 337 °F Phipps #2 well. It also showed that the shallow Lake City thermal anomaly extended a significant distance east and north of the thermal springs offering new potential targets to evaluate with slim holes.

However, the phase 1 work was not extensive enough to allow the development of a comprehensive or unique conceptual model of the overall geothermal resource. The phase 1 work was performed in calendar years 2003 and 2004 with the phase 1 final report being submitted to the Dept. of Energy in May 2004.

Phase 2 of the work consisted of drilling and logging two slim holes, LCSH-1a and LCSH-5, and performing additional geological and well testing work on an already existing slim hole, OH-1 during 2005. Phase 3 consisted of flow testing the LCSH-5 slim hole in June 2005. Based on the phase 2 and 3 work a large diameter exploration well is being drilled in the fall of 2005 at Lake City.

BACKGROUND

The Lake City geothermal field is one of only five geothermal fields in the Basin and Range Province not in production that have existing large diameter wells capable of producing commercial quantities of hot water with a temperature over 300 °F. The other idle fields are Raft River, Cove Fort, Rye Patch, and Fish Lake Valley. The Phipps #2 well at Lake City was drilled in 1972, redrilled in 1974, tested in 1975, and retested in 2003. Prior to 2003 there had been little exploration of the Lake City geothermal field, other than the drilling of a cluster of mostly unsuccessful and now abandoned wells in the southern part of the geothermal area, and some low cost geophysical surveys.

To obtain a better understanding of the geothermal system so that additional exploratory wells could be successfully drilled in other parts of the geothermal area, an integrated exploration program was proposed to the Department of Energy through the GRED II program by Lake City Geothermal, LLC, then a subsidiary of NGP Power Corp in May 2003. This proposal was selected for $330,000 of Federal cost-shared funding and the proposed phase 1 program was largely completed by May 2004, with the exception of cementing a tubing string in the OH-1 core hole (Benoit, 2004) and performing a long-term flow test of the Phipps #2 well. The long-term flow test of the Phipps #2 well was largely stymied by permitting problems, specifically an inability to permit the discharge of geothermal fluid from Phipps #2 into the lowermost reaches of Mill Creek, a drinking water source further upstream. This work program was performed by Dick Benoit as principal investigator and overall project organizer, David Blackwell and Jason McKenna of Southern Methodist University, Colin Goranson, and Steve Wesnousky, Chris Sladek, and Greg Arehart of the University of Nevada at Reno, and Dwight Carey of

Environmental Management Associates. A number of other individuals played lesser technical roles in completing this phase 1 program.

Based on the success of phase 1 the Department of Energy awarded an additional $848,032 of cost shared funding for the drilling and testing of two slim holes as phase 2. In the spring of 2005 the Department of Energy contributed an additional $100,000 for the completion and flow testing of slim hole LCSH-5.

The technical phase 2 team consisted of the phase 1 team with the addition of Louis Capuano of ThermaSource and Joe Moore of the Energy and Geoscience Institute, and the deletion of the University of Nevada at Reno members. All of the key team members in phase 2 have 25 to 35 years of experience in their respective fields in the geothermal industry. At the commencement of phase 2 Lake City Geothermal, LLC was sold by NGP Power Corp. to Amp Resources, LLC., which resulted in a delay of 3 to 4 months in the start of the slim hole drilling.

REGIONAL GEOLOGY

The Lake City geothermal field is located along the western margin of Surprise Valley, the westernmost major graben in the Basin and Range province (Figure 1). Surprise Valley is viewed as being transitional between the Modoc Plateau to the west and the Basin and Range Province to the east. The controlling geothermal structure is the active Surprise Valley fault zone separating the eastern edge of the Warner Mountains from Surprise Valley (Wesnousky, 2003). Vertical movement across the Surprise Valley fault zone is at least 11,800 ft and perhaps as much as 14,000 ft in the past 14 million years (Duffield and McKee, 1986, Hedel, 1980, 1981, Slossen, 1974). Surprise Valley is a deep graben with 6720 ft of valley fill being documented in the Surprise Valley 1-ST well. Exposed bedrock in the area consists exclusively of Tertiary volcanic and volcaniclastic rocks within the Warner Mountains having a total thickness greater than 10,000 ft. No pre-Tertiary rocks are exposed anywhere near Surprise Valley.

LOCAL GEOLOGY

The topography of the Lake City geothermal field is shown on Figure 2, along with six slim hole locations that were permitted by the Calif. Division of Oil, Gas, and Geothermal Resources for phase 2. A seventh possible slim hole (site 1) was initially proposed but was not permitted.

The most comprehensive mapping of bedrock exposures near the geothermal field is a Masters thesis (Martz, 1970) which lumped all of the rocks exposed on the east face of the Warner Mtns above the geothermal field into the > 2500 foot thick Soldier Creek Volcanics Formation. This formation is defined as primarily composed of aphanitic to porphyritic basalt lava flows in the Soldier Creek type area south of the town of Lake City. However, six miles north, in the vicinity of the geothermal field the formation, consists primarily of lahars with lava flows making up less than 1/3 of the lower half of the mountain range. Martz (1970) did not focus on this part of his field area. During the early summer of 2005 Stanford University faculty and students undertook a major mapping project of the Warner Mountains. Unfortunately their mapping efforts were focused south of Lake City and did not include the face of the range directly above the geothermal field. Results of this mapping are not available in time for inclusion in this report. Stanford personnel spent 3 days logging the core from the LCSH-5 slim hole (Miller et al., 2005).

Underlying the Soldier Creek Volcanics Martz defines four additional Tertiary Formations (Lost Woods, Deep Creek, Steamboat, and McCulley Ranch in order of increasing age). These underlying formations consist of thick mud flows and finer grained sedimentary rocks with interbedded volcanic flows and tuffs.

Low on the faces of the Warner Mountains above the geothermal field there are relatively few outcrops and slope angles at the base of the range are quite gentle by normal Basin and Range standards. The Tertiary rocks erode easily creating relatively few bedrock exposures with the exception of the harder lava flows. The alluvial fans at the base of the range also have gentle slopes with relatively few surfaces covered by large boulders. Outcrops in stream channels and the deeper gullies show Tertiary bedrock extending to the front of the range. No bedrock is exposed in gullies east of the range front, with the possible exception of the probable Hot Hill landslide.

The most prominent bedrock exposures along the base of the Warner Mountains adjoining the geothermal field are the highly mineralized outcroppings in the Highway 1 road cut at Hot Hill and a distinctive tan fine-grained ash layer approximately 50 ft thick that is seen in canyons and gullies from the bottom of the gully directly west of the Hapgood ranch house in the SW ¼ of Section 12 to at least as far south as the town of Lake City where it forms a prominent cliff band near an elevation of 5200 ft (GeothermEx, 1975). This ash supports the lowest major waterfall in Powley Creek. The overall dip of this ash layer is 20 degrees toward the west with a gentle northerly component of dip.

Soft mudflows with interbedded mafic lava flows are the dominant units overlying the tan ash. These softer rocks generate relatively few outcrops so the lava flows become abnormally prominent on the lower eastern face of the Warner Mountains near the geothermal field. A continuous layer of lava flows 100 to 200 feet thick creates an obvious nearly continuous bench extending from just south of Boyd Creek to south of Powley Creek between elevations of 5500 and 5700 ft (Figure 2). This mafic lava sequence and the tan tuff layer rule out the possibility that east-west trending cross faults with significant vertical offsets cut through the geothermal field and into the east face of the Warner Mountains adjacent to the geothermal field.

The mineralized outcropping defining Hot Hill (NW ¼ of Section 13), previously named the Hapgood lobe (GeothermEx, 1975), may be interpreted in a couple of different manners. GeothermEx described it as "an erosion-resistant, silicified explosion breccia, and forms a prominent shoreline terrace. It may be an ancient volcanic vent". This feature also has the classical lobate morphology of a landslide with a gently dipping top surface and steeply dipping sides and within the road cut is highly broken. This possible landslide appears to be quite old and stable. Its upper surface has been smoothed most likely by Lake Surprise and has a well developed soil. Its north side is covered by a sand deposit which was deposited in Lake Surprise.

A prospectors pit on the top of the eastern end of the hill (just west of the highway) is composed of a blue green ash flow tuff. Part of this tuff may be the ash layer running along the base of the range.

Hedel (1980, 1981) showed Hot Hill as being a bedrock protrusion extending sharply east of the range by running the range-front fault around the eastern margin of Hot Hill. This is the only such feature shown along the entire 53 mile strike length of the fault by Hedel. Unfortunately Hedel provided no commentary on this feature. Similarly Wesnousky (2003), who was reviewing Hedel's work, did not comment on this other than to verbally agree that it strongly resembles an old landslide. Figure 3 shows the Surprise Valley fault passing on the order of ¼ mile to the west of the toe of Hot Hill but more work is needed to conclusively verify this interpretation

The Surprise Valley fault has been mapped and interpreted as a major east-dipping normal fault by numerous workers (Martz, 1970, Hedel, 1980 and 1981, Duffield and McKee, 1986, Wesnousky, 2003, and Miller et al., 2005). Hedel (1980, 1981) treated the entire 53 mile length of the fault as a single fault with a common rupture history. Wesnousky (2003) noted that a large change in the overall character of the faulting a few miles south of Lake City suggests that the fault consists of two segments with different rupture histories. The northern segment of the fault (which includes the Lake City geothermal field) is modified by numerous wave cut shoreline features and may not have ruptured since the desiccation of Lake Surprise beginning approximately 13,070 years ago. The southern segment shows two or more major events in the past 11,000 years (Hedel, 1980).

In the vicinity of the Lake City geothermal field the Surprise Valley fault is represented only by a change in slope angle at the upper edges of alluvial fans. Contrary to Hedel's 1980 and 1981 maps, there is no obvious fault scarp at the base of the range in the vicinity of the geothermal field. This was also the conclusion of GeothermEx (1975). Similarly, Wesnousky (2003) apparently did not clearly see fault scarps in this area on 1:24,000 colored air photos taken in 1984. Recognition of a faint or relatively old fault scarp is hindered in this area by a fairly extensive forest cover and the wave cut shoreline features. Rocks at the base of the range are for the most part deeply buried by soil and colluvium. However, within a few miles both north and south of the geothermal field there clearly are Recent fault scarps running along the front of the range (Wesnousky, 2003).

A stress redistribution model (Wesnousky, 2003) indicates that the Surprise Valley fault near the geothermal field is highly stressed due to the different rupture histories of the two fault segments. These high stresses are similar to models prepared for the Dixie Valley, Beowawe, and Bradys geothermal fields (Caskey and Wesnousky, 2000).

A second fault zone, the Lake City fault zone, trending NW-SE through the geothermal area, has been described as being 2100' wide and bounded by two more or less continuous fault traces (Hedel, 1980, 1981) (Figure 3). Hedel (1981) shows the subtle Lake City fault zone intersecting the eastern front of the Warner Mountains near LCSH-5. No thermal springs crop out along the identified strands of the Lake City fault zone and Wesnousky (2003) noted only a single possible eroded fault scarp in this area.

A detailed description and interpretation of the secondary mineral assemblages from petrographic studies of thin sections, x-ray diffraction studies, fluid inclusion studies, and fracture orientations has been prepared by Moore and Segall (2005) as part of this GRED II project. The very simplified conclusions of this study are that the Lake City geothermal system has been active for >13,000 years as determined from silica cemented Quaternary beach sands near the Phipps #2 well and that past temperatures of the geothermal system have not exceed 392 to 437 ^{o}F. Fluid inclusions trapped in quartz indicate past temperatures to be close to the measured temperatures. Evidence of higher temperatures as suggested by the localized presence of prehenite and epidote is interpreted to result from local contact metamorphism associated with intrusion of Tertiary age dikes.

LCSH-1A

LCSH-1a Siting

LCSH-1a is located 1.2 miles east of the Warner Mountains range front and 0.35 miles east of the mud volcano eruption area in a graveled hay corral at the end of a graveled county road (Figures 2 and 3). There is no road access to the east of the LCSH-1a site. The area is in seasonally muddy or dusty sparsely vegetated irrigated pasture land a few feet above the Upper Lake playa.

The LCSH-1a site was selected for three basic reasons. First, the shallow thermal anomaly extends significantly east of the thermal springs (Figure 3) and a 221 foot-deep temperature gradient hole (TGH-7) at this site had a gradient of 10.75 ^{o}F/100 ft (Figure 5). This allowed the possibility of a buried or hidden normal fault, most likely dipping to the east, allowing thermal water to rise steeply up to the thermal springs. TGH-7 had some artesian flow which disturbed the profile above a depth of 120 ft. Second, a number of previous workers had hypothesized such a fault or faults (see Conceptual Modeling Section). Such a fault (if it exists) could be a very attractive production or injection target significantly extending the size of the resource. Third, the site sits within a possible jurisdictional wetland which could extend for many miles along the western margin of Upper Alkali Lake. The LCSH-1a location is the only place within the eastern part of the Lake City thermal anomaly where there was a combination of existing all weather access and a graveled pad large enough to support a drilling operation during the winter months. This location was the only place where drilling could be permitted without involving the lengthy Corps of Engineers wetlands delineation process.

A significant challenge of the LCSH-1a site was the shallow water table which prohibited the use of a sump. Excess mud and cement had to be hauled off the location. This gave core drilling with its relatively small mud system an operational advantage over conventional rotary drilling.

LCSH-1a Drilling History

The LCSH-1a hole was spudded on Dec. 27, 2007 by Lee Conner, the local water well driller in Surprise Valley. One hundred feet of 10 inch casing was installed in a 15 inch hole as a conductor pipe. Three cubic yards of cement were pumped down through the casing and back up to the surface but the cement settled back down about 25 ft so 1000 pounds of cement were pumped down through a 1inch pipe set at 25 ft in the annulus. This brought returns back to the surface but the cement later settled down about one foot so a second very small top job was performed. Very little drilling work was performed between Dec. 30 and January 12 due to cold snowy conditions.

On January 11 and 12 a 9 7/8 inch hole was drilled to 460 ft before the mud system froze. On January 17 drilled resumed to 500 ft and 7 inch casing was run into the hole and hung from the 10 inch conductor pipe. While shutdown overnight before cementing, the hole began to flow about 20 gpm of water with methane gas. Six cubic yards of cement were pumped down through the 7 inch casing but there were no returns to the surface. The top of the cement appeared to be 125 ft below the surface and two top cementing jobs were performed on January 23 and 24 to get cement to the surface in the annulus between the 7 inch casing and the 10 inch conductor pipe. On January 25 Lee Conner ran in the well to 440 ft, encountered cement and drilled it out to 480 ft. On January 26 Lee Conner moved his equipment off the LCSH-1a location.

On January 27 Boart-Longyear began moving core drilling equipment on location and started to rig up. On January 29 the BOP test was witnessed by personnel from the Calif. Div. of Oil, Gas, and Geothermal Resources (CDOGGR). PQ coring (4.827 inch hole diameter and 3.345 inch core diameter) began on the evening of January 30. Coring was more or less continuous with no significant problems or events until the morning of Feb. 12 when circulation was stopped at 1045 hours so a temperature log could be run. At the completion of this logging at 1830 hours drilling temporarily resumed but was terminated in an orderly fashion on Sunday morning Feb. 13 at a depth of 1728 ft (Figure 4).

Boart-Longyear cored a total of 1233 ft of hole with only 800 ft of core recovered giving 65% recovery. The remaining 35% of the core was simply washed away by the bit. This poor recovery rate was the principal cause of the relatively slow drilling as frequently the soft and sticky core would not remain in the core barrel. There were no major changes in core recovery percentages between the upper and bottom parts of the hole. The core recovery for each shift was highly variable ranging from 18.75% to 100% (for only one shift). The drilling rate averaged only 60 feet per 12 hour shift for the first six shifts of drilling between depths from 486 ft to 854 ft. The drilling rate gradually diminished to an average of 37 feet per shift for the last 5 shifts of drilling between depths of 1506 ft and 1721 ft.

Decision to Terminate Drilling at a Depth of 1728 Feet

The decision to terminate drilling at a depth of 1728 ft was based on several concerns. Perhaps most important was the slow and declining penetration rate. A casing point near a depth of 2000 ft was being approached which would require running about $40,000 of 4 ½ inch casing with an expensive silica flour cement job. The core consisted of soft clay in the bottom of the hole which would not make for a strong casing shoe. There was no compelling reason to expect stronger rocks in the next 300 ft for a stronger shoe. In hindsight, this hole could have been drilled more quickly with a rotary rig but the cost of handling and removing a much larger volume of cuttings and mud in the winter would have increased substantially. By terminating the hole without cementing in the 4 ½ inch casing the option is preserved for reentering the hole at a future date with a rotary rig.

The abundant clay also argued against an east-dipping normal fault with a significant offset supplying thermal fluid to the Lake City hot springs. A major buried normal fault in this area should have shed some coarse debris, which was not found. It is still possible there is a fault at greater depth but such a fault may be more difficult to precisely locate.

The temperatures in the hole were not particularly encouraging. The maximum reading thermometer (MRT) data obtained during drilling above a depth of 1650 ft had temperatures less than 120 °F (Figure 5). These, data were obtained when the core barrels were recovered but there was no waiting time for the thermometers to heat up. The temperature gradient calculated from these data was about 4 °F/100 ft, disconcertingly low and close to the regional thermal background. With this MRT information, drilling and circulation was temporarily ceased on Feb 12 with the hole at a depth of 1681 ft to obtain a temperature log. Unfortunately the SMU logging equipment failed to operate due to a damaged cable. As a substitute plan, a series of runs with three maximum reading thermometers to depths of 200, 800, 1200, and 1665 ft with 20 minute stabilization periods was performed. These data confirmed a relatively low overall temperature gradient but did record higher absolute temperatures, with a maximum of 178 °F being recorded at a depth of 1665 ft (Figure 5). With these temperature data in hand the final decision to terminate drilling was made on Feb. 13 with the hole at a depth of 1728 ft. The 2 3/8 inch completion tubing was installed and filled with water on Feb. 14.

LCSH-1a Geology

In 1959 the Nevada Thermal Power Company (Magma) drilled the Parman 2 well approximately 1750 ft northwest of LCSH-1a (Figure 3) to a depth of 1968 ft at a cost of $10,008 in 5 days. Parman 2 was drilled only a few hundred feet east of the Lake City hot springs. No temperature log was ever obtained from Parman 2, but it had mud circulating temperatures as high as 156 °F.

The 1959 lithologic log of Parman 2, prepared by "G. M." showed clay stone and siltstone with minor "volcanic wacke" to a depth of 1240 ft. Below a depth of 1240 ft the descriptions include the terms volcanic, rhyolite, agglomerate, pyroclastic, brecciated lava, conglomerate, and scoria suggesting the Parman 2 well had penetrated into Tertiary rocks similar to those exposed in the Warner Mountains. The presence of pyrite and calcite in the descriptions suggests that Parman 2 penetrated rocks that are or have been in contact with geothermal fluids. This lithologic log suggested Surprise Valley graben was quite shallow at least as far east as Parman 2. However, given that Parman 2 was drilled in only 73.5 rotating hours (26.8 ft/hr) only soft formations must have been penetrated. Certainly rocks similar to the cores recovered from OH-1 and LCSH-5 would not have drilled this quickly. Therefore, the Parman 2 lithologic log must now be viewed with a high degree of skepticism. A more likely interpretation of the Parman 2 lithologic log may be that below a depth of 1240 ft the well penetrated some coarser Quaternary volcaniclastic sediments shed from the east side of the Warner Mountains. The shallow temperature-gradient holes drilled at Lake City as part of phase 1 of this GRED project encountered progressively coarser Quaternary alluvium as the range front was approached.

LCSH-1a encountered close to 100% exceptionally soft, massive, sticky, blue Quaternary clay. There are some thin very fine sandier intervals. No significant amounts of pyrite or calcite were seen in the core. In short, the LCSH-1a core has not hosted a geothermal fluid. The thickness of the clay at the LCSH-1a site is not known with any certainty however, the Surprise Valley 1 ST hole, drilled by Gulf in 1973 and located about 1.4 miles south-southeast of LCSH-1a (Figure 3), and about 2000 feet further from the range front, penetrated 6720 ft of fine grained valley fill sediments as shown on the Exploration Logging Inc. mud log. It is possible that fine grained sedimentary rocks may extend beneath the LCSH-1a site for many hundreds of feet. Given the monotonous stratigraphy encountered in LCSH-1a no gamma ray log was made in the hole and no geologic studies, other than photographs of the core were conducted.

LCSH-1a Temperature Logs

The first temperature log to be run was with Southern Methodist University portable probe #128 on March 11, following 25 days of stabilization time (Figure 5). The probe only has enough cable to reach a depth of 1332 ft. Spicer logged the well on March 13. Unfortunately the Spicer memory tool was not functioning properly, especially at temperatures above 200 ^{o}F with a divergence to slightly higher temperatures. Halliburton (while at Lake City for other logging) ran a survey on March 24 and produced results generally within 1 ^{o}F of the SMU tool.

The Halliburton temperature log reports a temperature of 192.9 ^{o}F at a depth of 1649ft. The temperature gradient of LCSH-1a near the surface is between 9 and 10 ^{o}F/100ft. With increasing depth the LCSH-1a temperature gradient decreases to about 7.5 ^{o}F/100ft, a 25 % decline. Had the temperature gradient not decreased, the temperature at 1649 ft would have been 18 to 19 ^{o}F hotter than the measured 192.9 ^{o}F.

Comparison of the LCSH-1a data with the much deeper Surprise Valley1-ST well (Figure 6) offers a good indication as to what temperatures might be expected at greater depth in LCSH-1a. The Surprise Valley1-ST well has a temperature gradient that decreases from about ^{o}5 F/100ft near to surface to about 2 ^{o}F/100ft at 6500 ft; all of this in unconsolidated valley fill deposits. If LCSH-1a remains in unconsolidated valley fill deposits to significantly greater depths a similar profile of gradually declining gradient is most likely. Three possible extrapolations of the LCSH-1a temperature profile suggest a temperature of 325 ^{o}F may be found between depths of 3500 ft (most optimistic and not particularly realistic) and 5500 ft (fairly conservative) (Figure 6). The most realistic extrapolation suggests a temperature of 325 ^{o}F being reached near a depth of 4500 ft which is comparable to the depths of the other holes drilled along the range front.

LCSH-5

LCSH-5 Siting

LCSH-5 is located ½ mile north of the northernmost thermal spring and ½ mile east of the Warner Mountains range front on the overlapping alluvial fans below the mouths of Bucher and Boyd Creeks at an elevation of 4555 ft (Figure 2). LCSH-5 is about 2600 ft east of the range front where the elevation is approximately 4750 ft.

The LCSH-5 site was selected a few hundred feet west of TGH-3 because TGH-3 has a temperature gradient of 15 °F/100ft (Figure 3) and it is the furthest permitted site from the Phipps #2 well (Figure 2). The TGH-3 was easily drilled to 460 ft in 45 hours in 2003 so it was anticipated that drilling the upper part of LCSH-5 would not involve drilling through many large boulders. No alluvial boulders are present on the surface to the east of LCSH-5 but boulders are abundant to the west of the site. Also, for what it is worth, the LCSH-5 site is near where the intersection of the Lake City fault zone with the Surprise Valley fault would be located. No exploration has occurred north of LCSH-5.

Originally the LCSH-4 site (Figure 2) was preferred when the size of a possible power plant was viewed as being in the 10 to 20 MW range. The LCSH-4 site was intended to prove that the resource extends at least one mile north of the Phipps #2 well along the eastern front of the Warner Mountains. When Amp Resources purchased the project emphasis was redirected to try to demonstrate as quickly as possible that the resource might cover a larger area to be capable of producing on the order of 30 MW.

LCSH-5 Drilling History

The LCSH-5 hole was spudded on Feb. 3, 2005 by Lee Conner. Sixty feet of 10 inch casing was installed in a 14 inch hole as a conductor pipe. The top 60 feet consisted primarily of hard alluvial fan boulders that produced a very irregular hole that had to be reamed from 12 ¼ inches to 14 inches before the casing could be run in the hole. It required six days to get this part of the hole drilled, reamed, and cased. Penetration rates were often only a few feet per hour, the worst was only 8 feet in one day. Given the experience of drilling at TGH-3 a few hundred feet to the east this slow difficult drilling was not anticipated.

Drilling from 60 to 395 ft took 8 days of hard drilling through boulders. At a depth of 243 ft the bit was changed from a long toothed bit to a button bit but it still took 3 days to drill to 395 ft. The 7 inch casing was run and cemented to 395 ft with no difficulty but due to limited ability to haul cement off the location about 190 ft of cement set up inside the casing and had to be drilled out. On Feb. 21 Lee Conner moved his equipment off the location.

On Feb. 22 Boart Longyear began moving their equipment onto the site and on Feb. 24 the blowout preventer was successfully tested. PQ coring (4.827 inch hole diameter and 3.345 inch core diameter) began early on the morning of Feb. 25. Drilling progressed uneventfully until a depth of 1470 ft where circulation losses began and at 1487 ft losses were complete. The hole was drilled to 1537 ft where a 10 sack cement plug was set and full returns were regained. At 1585 ft returns were again lost and the hole was drilled to 1587 ft. The decision was made to try to regain returns and cement the 4 ½ inch casing at 1587 ft. Deeper drilling might result in additional lost circulation making cementing more difficult and expensive. Another 10 sack cement plug was set at the bottom and the hole was opened up to 6 ¼ inches with button bits to a depth of 1575 ft. The 4 ½ inch (O. D.) casing was cemented by Halliburton on March 12 with good returns to the surface.

Unfortunately, it was discovered on March 13 that the 4 ½ inch casing was accidentally run only to a depth of 1470 ft rather than the 1570 ft planned. This set off a complicated sequence of events due to the 105 ft of uncemented 6 ¼ inch hole. The HQ sized hole (3.895 inch diameter) was drilled to 1617 ft with lost circulation occurring again at 1585 ft. An 8 sack cement plug was set which brought the top of the cement up to 1521 ft. On March 15 while drilling cement at 1575 ft circulation was lost and the core barrel twisted off at about 1575 ft (the records are not very clear as to the exact depth of the fish). The core barrel was not recovered and a 7 sack cement plug was set so the core barrel would be locked in place and it could either be drilled up or whipstocked around. The top of this cement plug was found at 1568 ft and the hole was cored to a depth of 1581 ft where the core barrel and tube twisted off. This core barrel and tube were successfully fished and drilling proceeded with 5 ft core barrels (rather than the normal 10 ft barrels). At 1581 ft new formation was drilled proving the hole had sidetracked around the core barrel fish.

The sidetracked hole (labeled simply as LCSH-5 on the core boxes) was drilled with high torque to a depth of 1773 ft where circulation was lost. Drilling continued to 1979.5 ft in the sidetracked hole where there was another twist off near 1600 ft. This fish was successfully recovered but in tripping back in the hole the bit would not go below 1570 ft and when drilling at 1570 ft began cement core was recovered indicating that perhaps the lost core barrel had slipped out of the cement and fallen down the sidetracked hole and the drilling was now occurring in the original cemented hole.

Drilling below 1570 ft with no returns encountered cement to 1605 ft where there was another twist off at 1591 ft. This fish was recovered and drilling resumed to a depth of 2177 ft where there was another twist off at 1591 ft. This fish was recovered and drilling proceeded to 2253 ft where there was another twist off at 1577 ft. At this time the decision was made to install older HQ rods as temporary casing through the troublesome interval between 1577 ft and 1591 ft and to then drill ahead with NQ sized hole. This drilling below 2258 ft with NQ rods proceeded uneventfully from April 2 until several small open quartz-lined fractures were encountered below a depth of 3955 feet. Most of the hole below 1587 ft was drilled with circulation losses of 15-18 gallons per minute. On the order of one million gallons of cold drilling fluid were lost downhole during drilling.

A depth of 4257 ft was reached on April 19 and Welaco logged the hole with a temperature-pressure-spinner-gamma tool during static and injecting conditions on April 20 (Benoit, 2005a). At this time the HQ rods were in place from the surface to a depth off 2258 ft and below this there was open NQ sized hole. Static down and up logs were run several hours after drilling circulation ceased giving a maximum temperature of 322 F at the bottom of the hole (Figure 7). On these two static logs the interval between 1270 ft and 1900 ft was particularly complex. Only very minor temperature inflections were present in the deep fractured interval below 3955 ft.

The static logging was followed by injection log runs which showed little or no injectate was going below the bottom of the HQ rods at 2258 ft (Figure 7) which meant none of the open fractures drilled between 3955 ft and 4257 ft was accepting injectate. Two small inflections on the injecting downlog suggest the injectate exited the wellbore as high as a depth of 1650 ft. After the pressure falloff was measured at the end of injection a final nonequilibrium log was run up to the surface. This log showed a strong fluid flow at a depth of 1647 ft (Figure 7) and a similar complexity between 1270 and 1900 ft as seen on the static logs.

The injectivity was 0.57 gpm/psi with a pressure drop of 57.4 psi following cessation of 33 gpm of injection. This low measured injectivity was not particularly surprising as the injectate had to flow up the small annulus outside of the HQ rods for hundreds of feet to exit the wellbore.

A decision to continue drilling was made because the static temperature logs indicated that the hole was rapidly approaching isothermal conditions (indicative of a convecting reservoir) at 4257 ft and that deeper drilling might soon penetrate into more hydraulically conductive fractures. Drilling resumed on April 21 and continued into April 26 when the total depth of 4727 ft was reached. All of this additional drilling was in mafic lava flows, consistently much harder rocks than were found above a depth of 4257 ft. During this deepening additional quartz lined fractures were penetrated and there was a sharp decrease in the static fluid level in the hole suggesting one or more fractures below 4257 ft was in a different pressure regime, hopefully an integral part of the geothermal reservoir. The largest fracture, perhaps 6 inches wide as estimated by the drillers, was found at a depth of 4439 ft.

Static and injecting temperature and pressure logging were performed by Halliburton on April 27 (Figure 8) with open hole beneath a depth of 2258 ft (Benoit, 2005b, Benoit 2005c). The initial static downlog showed a smooth temperature reversal at a depth of 1695 ft, presumably representing the same hydraulically conductive fracture seen on the Welaco log at a depth of 1650 ft. The static downlog showed a sharp increase in temperature at a depth of 4470 ft (most likely the same fracture as seen at 4439 ft in the core). This is likely a major injection interval and this step was more convincingly documented on the two injecting logs (Figure 8). Below a depth of 4439 ft the temperatures increased during injection demonstrating that little or no injectate passed below 4439 ft. The Halliburton logging system was not able to record temperatures while logging up. No lubricator was used during this logging so no pressure could be applied beyond simply filling the well to the surface. The three temperature steps at 2200, 3200, and 4200 ft reflect stops for the Kuster pressure tool and demonstrate that the well was cooling during the logging at least above a depth of 4439 ft.

All of the Halliburton logs in LCSH-5 seem to be reporting thermal features a few tens of feet too deep. Near the bottom of the hole the depth difference appears to be about 30 to 40 feet with Halliburton reporting features deeper than they really are.

The injection rate prior to cessation of injection was 71.6 gpm. The pressure falloff was 184.2 psi, giving an injectivity of 0.39 gpm. This is a lower value than the 0.57 gpm/psi measured on April 20 and it was not impacted by the injectate having to flow through a small annulus between the drill rods and the formation to exit the wellbore. This strong indicates that the deeper fractures in LCSH-5 have lower permeability than the shallower fractures.

With a known temperature of 322 ^{o}F from the April 20 Welaco logging and a deep hydraulically conductive fracture evident from the April 27 Halliburton logging it was decided that the hole had accomplished its temperature and permeability goals and drilling operations were terminated at a depth of 4727 ft.

Due to the reduction of hole size at 2258 ft from HQ to NQ it was not possible to run 2 3/8 inch tubing as the originally planned completion string for temperature logging. A search for 1.9 inch tubing that could be run in the NQ sized hole confirmed that none could be located in California. Therefore, the conservative, but more costly, decision was made to keep the temporary HQ casing in the hole and run NQ rods from the bottom up into the lowest part of the HQ casing. While costing more for steel, this allowed most efficient use of the rig as it can not handle 30 ft tubing joints. It also offered the highest guarantee of getting the completion tubing to the bottom of the hole in part by not re-exposing the difficult interval near 1585 ft, and gave the largest possible hole diameter for future well testing activities.

The LCSH-5 well completion consists of uncemented HQ drill rods hanging from the surface to a depth of 2250 ft and uncemented NQ drilling rods standing on the bottom and extending up to a depth of 2226 ft (Figure 9). There are two sets of slots cut in the NQ rods between depths of 4427 and 4447 ft, and between 4707 and 4727 ft. Water can also enter or exit the drill rods where they overlap between depths of 2226 and 2250 ft. While this well completion tended to minimize costs, such as cementing, and preserved numerous future options for modifying the wellbore, it also had the consequence of allowing flows both within and outside the core rods making future temperature interpretations more ambiguous.

LCSH-5 Geology

Slow rotary drilling to 395 ft penetrated very bouldery brown alluvial fan deposits. Below 395 ft the core is poorly consolidated to a depth of approximately 501 ft. Between 501 and 1270 ft the core is generally lithified with the same brown to reddish brown matrix fanglomerate as seen above 501 ft (Figure 10). The mudflows penetrated below 1270 ft have a grey to black matrix and are more indurated. Thin section analysis of the fanglomerate shows pore filling zeolites to be present below a depth of 431 ft. This has lead Moore and Segall (2005) to suggest that the Quaternary/Tertiary contact in LCSH-5 is shallower than 431 ft and they arbitrarily chose half the depth, 216 ft, as the contact depth. Digital photos of each core box were taken and are attached as 3 CDs to this report.

The fanglomerate/bedrock contact at 1270 ft (elevation of 3285 ft) is defined by the top of a light colored, very fine-grained, rhyolitic lava flow. This rhyolite varies in color from white to lt. green to medium green to a purplish brown. It is highly sheared and often feels slippery like talc but is much firmer. This contact is very sharp and shows up sharply on the gamma ray log (Figure 10) with a tripling of the count rate. If the top of the rhyolite represents the range-front fault it has a dip of only 30 degrees (Miller et al., 2005).

The rhyolite flow represents the top of a 786 foot thick series of silicic and mafic lava flows extending to a depth of 2056' with lesser amounts of lahar and volcaniclastic layers. The lava flows generally display moderate to strong alteration with partial to complete destruction of the mafic minerals (Moore and Segall, 2005). Most of the highly permeable fractures in LCSH-5 are located within this mostly volcanic unit (Figure 10) which has the most abundant veining in the entire hole (Moore and Segall, 2005) with some intervals containing as much as 20% vein material.

Between the bottom of the mafic lava flows at 2056 ft and 4244 ft the Tertiary rocks are primarily sedimentary; debris flow sequences up to 353 ft thick, sandstones, siltstones and mudstones (Figure 10). There are two distinctly different types of mud flows. Above a depth of 3402 ft the mudflows contain very poorly sorted sub angular cobbles up to 2 feet in diameter of Tertiary volcanic and sedimentary rocks in a dirty appearing matrix. Below 3402 ft the cobbles are smaller, well rounded, better sorted and can be composed of pre-Tertiary granite, quartzite, and shale in a cleaner appearing matrix. No pre-Tertiary cobbles are present above a depth of 3402 ft. This overall unit can be described as generally being fairly soft with some of the mudstones even below 4000 ft being soft enough to gouge with a fingernail. There is little in the way of open or permeable fractures in this diverse 2188 foot-thick sedimentary interval.

Below a depth of 4244 ft the LCSH-5 rocks are distinctive firm basaltic lava flows often containing plagioclase crystals up to 1inch long, reminiscent of the poikolitic Steens basalt flows of Southeastern Oregon, with some microporphyryitic dikes. The dikes have locally created secondary epidote in the lava flows and prehenite at shallower depths (Moore and Segall, 2005). The overall thickness of this unit is unknown as its bottom was not reached above a depth of 4727 ft. No mafic lava flow sequence has previously been identified below the Tertiary sedimentary rocks (Duffield and McKee, 1986) so this is the first time these particular rocks have been identified. This unit contains the major deep permeable fractures encountered at 4439 ft (Figure 8).

LCSH-5 Flow Testing on May 31 and June 1

The first flow test of LCSH-5 on May 31 and June 1 was a minimal test intended only to demonstrate at the lowest possible cost that the well was capable of unassisted flow and to collect some water samples for possible analyses (Benoit, 2005d). Prior to the flow test a static temperature log was run by Halliburton on May 25. The well was kicked off by blowing air through 399 ft of 1" black pipe hanging from the wellhead. It took almost two hours of blowing before the well heated up enough to flow unassisted. The 1" pipe remained hanging in the well during this flow test. The wellhead and flow line were 2 inches in diameter and the flow rate through the HQ rods was visually estimated to be about 40 gpm. After the well warmed up the annulus outside the HQ rods also began to flow at a rate of about 5 gpm. About 50,000 gallons of fluid was produced during this initial test.

Shortly after it was realized the well would sustain flow it was shut in and the wellhead modified to better measure the pressure. The well was kicked off again and flowed overnight. Three sets of chemical samples were collected from the main flow through the HQ rods and from the annulus flow but only the latest samples were eventually analyzed.

As soon as possible following both shut-ins of the well during this flow test nonequilibrium temperature logs were run with the SMU portable logging equipment to a depth of 1476 ft. These logs (Figure 11) show active fluid flow outside of the 4 ½" casing at depths of 65 ft, 1270 ft and 350 to 400 ft.

LCSH-5 Flow Testing on June 16 and 17

LCSH-5 was retested on June 16 and 17 with a 3 inch wellhead and flow line and the ability to strip the 1" pipe out of the well while it was flowing. This allowed flowing temperature and pressure logs to be obtained. Prior to disturbing the well a static temperature and pressure log was run by Halliburton on June 16 (Figure 12). The results were so surprising that a second static log was immediately run to replicate the details of the first log (Benoit and Goranson, 2005). Unfortunately, the Halliburton logging system would not record data while logging up so only the down logs are presented.

The well was kicked off starting at 1510 hours on June 16 with air through 1 inch pipe hanging to a depth of 210 ft in about 1 1/2 hours. As soon as it was certain the well was flowing without air assistance the 1inch pipe was removed and the first flowing temperature log was run starting at 1730 hours. This flowing log also produced such unexpected results (the temperature change between 3390 and 3490 ft and the temperature oscillations near the bottom of the hole) that a second flowing log was run starting at 2130 hours to confirm the results and it did so.

After the second flowing log was completed, the annulus was allowed to flow and it did so at a rate of 5 to 10 gpm. The flow through the main flow line was measured at about 60 gpm with a wellhead pressure of about 15 psig.

The third and fourth flowing logs were run on the morning of June 17 and two sets of chemical samples were collected about 5 hours apart from the annulus and main flow line.

The well was shut-in at 1320 hours with the temperature and pressure tool hanging at a depth of 2300 ft until 1520 hours to record the pressure buildup data. The pressure buildup was 50.6 psi in 1.5 hours (Benoit and Goranson, 2005) giving a productivity of 1.18 gpm/psi based on a 60 gpm flow rate. This is a low productivity but it is undoubtedly influenced by the completion of the well which requires fluid entering the well to flow for hundreds of feet through a small annulus before either reaching the surface or entering the HQ rods. Recompleting LCSH-5 so that fluid can more easily enter the well should significantly improve its measured productivity.

A nonequilibrium log was then run from the surface to total depth before injection of cold water began at 1609 hours. A final log was then run during injection of cold water and this was completed at 1725 hours and the tool was moved to a depth of 4450 ft to hang and obtain pressure falloff data. The injection rate prior to stopping injection was 60 gpm. After stopping injection the downhole pressure decreased by 56 psi which gives an injectivity of 1.07 gpm/psi (Benoit and Goranson, 2005). This injectivity is very close to the productivity of 1.18 gpm/psi measured earlier in the day. This injectivity of 1.07 gpm/psi is significantly above the values of 0.57 gpm/psi and 0.39 gpm/psi measured on April 20 and 27 for the individual shallow and deep zones respectively. Again, this is a low injectivity but it is being impacted by the completion of the slim hole. If the HQ and NQ rods could be removed from the well, the injectivity and productivity would certainly show a significant increase.

Injection of the second water truck load was completed at 1737 hours and at 1759 hours the tool began its trip up to the surface. This injection log was the only log run on June 16 and 17 that did not record the temperature oscillations near the bottom of the hole.

LCSH-5 Static Temperature Logs

Five temperature logs have been run in LCSH-5 while it was in a static or idle condition. The most recent was run on August 22 by Colin Williams of the U. S. Geological Survey. Prior to obtaining these logs the well had been static for periods of several hours to two months following its last disturbance. These logs show a complex and relatively slow evolution of vertically moving fluid controlling temperatures below a depth of 1500 ft (Figure 13).

The April 20 and 27 static logs were run only several hours after drilling ceased and are very transient in their overall nature. These two logs have considerable character between depths of 1270 and 1650 ft that document lateral flows but lack isothermal intervals defining vertical flows within or near the wellbore.

The May 25 log showed a much subdued temperature overturn compared to the April 27 log showing vertical fluid flow development within or near the wellbore and a bottomhole temperature of 317.8 °F. Water is clearly flowing down the wellbore from a depth of 1500 ft and exiting the major fractures at 1647 ft below a depth of 1500 ft.

On June 16, another Halliburton static log was run fifteen days after the well was flow tested for one day (Figure 13). This log unexpectedly showed much greater vertical fluid movement within the wellbore than the previous logs. It also showed unexpected features such as temperatures as high as 323 °F much shallower than previously measured in the well and temperature "noise" or oscillations of as much as 7 °F near the bottom of the well. These oscillations were confirmed by making a second static logging pass that precisely duplicated the oscillations.

The final static log was run on August 16 after the well had been idle for 65 days. As usual for LCSH-5, the Aug. 16 log is significantly different from the previous logs. The August 16 log shows higher temperatures between depths of 1500 and 2500 ft and lacks the noise or oscillations of the June 16 log, demonstrating that much of the detail of the June 16 logs were transitional in nature or have been obliterated by a flow of water within the wellbore that commenced after June 16. Future static logs of LCSH-5 will probably be somewhat different from the Aug. 16 USGS log. The most significant features deep on the August 16 log are the three small but sharp temperature inflections at 4025, 4439, and 4568 ft (Figure 14). These represent permeable intervals where water is either entering and/or exiting the wellbore. There is a progressive decline in temperature from a maximum of 323.1 °F at a depth of 3858 ft to 320.1 °F at 4700 ft suggesting that the true formation temperatures are declining near the bottom of the well.

There currently are no truly static temperature logs from LCSH-5 that represent the true formation temperatures over the length of the hole. The true formation temperatures are being masked by fluid movement below a depth of 1500 ft. The maximum reading thermometer data collected during drilling may give some indication of the true formation temperatures (Figure 13). Two types of MRT data are presented on Figure 13, data from allowing the thermometers to hang and equilibrate for 10 minutes and for 30 minutes. The ten minute hangs are up to 20 °F cooler than the 30 minute hangs. The MRT data are difficult to interpret due to considerable lost circulation below a depth of 1470 ft and the possibility of a shallow temperature overturn. The lack of increase in MRT temperatures between 1400 and 2200 ft might be indicative of no increase or perhaps even a decrease of true formation temperatures in this depth interval. The MRT data might also be hinting at a decline in formation temperatures deep in the well.

Unfortunately, the lack of a truly static log from LCSH-5 is a significant hindrance in understanding the geothermal system in the vicinity of LCSH-5. For instance, no truly credible temperature cross sections can be constructed through this well. Without thermal cross sections no complete or unique models can be developed in this part of the geothermal field. Without a good model drilling target selection becomes much riskier. To obtain a true equilibrium temperature log of LCSH-5 will require recompleting the well, a task outside the scope of this project.

The LCSH-5 temperature profiles do show that there are no active shallow flows of thermal water nearby. This is in agreement with the absence of nearby hot springs. Instead the active flows are below a depth of 1470 ft.

LCSH-5 Permeability

There are multiple permeable intervals in LCSH-5 as defined by lost circulation, fracturing and veining in the core, and inflections on temperature profiles. The permeable intervals can be grossly separated into a cooler upper zone above a depth of 2000 ft and a hotter lower zone is below a depth of 3955 ft.

Lost Circulation

During drilling the shallowest lost circulation was noted at a depth of 1470 ft with complete losses at 1487 ft. This correlates closely with the top of an isothermal segment of the temperature log where fluid is entering the well and flowing down to a depth of 1650 ft during static conditions (Figure 13). A cement plug cured this zone and drilling resumed until circulation was lost a second time at 1585 ft. A cement plug also cured this zone. After the 4 inch casing was set at 1483 ft circulation was lost again at 1773 ft. Following the setting of the uncemented HQ casing at 2258 ft circulation was maintained to a depth of 2317 ft. Below 2317 ft only tiny amounts of drilling fluid ever returned to the surface and the fluid level was reported as being about 50 ft below the surface. At a depth of 4439 ft a six inch void was encountered and the water level dropped another ±200 ft to as much as 280 ft below the surface during drilling. Fluid levels under static conditions has been measured between depths of 167 ft shortly after drilling to 64 ft.

Fracturing and Veining in the Cores

This report makes no attempt to go into the detailed mineralogy of the veining and fracturing as described by Moore and Segall (2005); it merely notes the depths of the most significant sections in the core.

Calcite veining extends up into the Quaternary fanglomerate formation where small rims are present around cobbles in the mud flows. The uppermost veinlets are present as shallow as 614 ft. However, calcite veining is not common or abundant above a depth of 1270 ft. There are abundant calcite veins between depths of 1387-1397, 1443-1502 (with particular abundance between 1443 and 1459 ft), 1561-1587 ft, 1645-1651 ft (Figure 15), 1759-1777 ft, and 1919-1922 ft. Some of these fractures are quite steeply dipping but there are also a number of fractures and veins with shallower dips. The dips in the shallower, softer and more rubbly fractured intervals are not as well defined by the core as the deeper fractures. It is not possible to tell just from the core alone which of these shallow intervals are most permeable or important.

Between 1922 ft and 3955 ft there are few veins and little or no open space associated with these small veins generally separated by 50 ft to 200 ft of barren rock. Completely sealed hairline cracks are relatively common throughout the hole.

Below a depth of 3955.5 ft several discrete fractures, filled or lined with quartz were cored. The most significant of the deep fractures is at a depth of 4439 ft where the drillers reported a 6 inch void (Figure 16). One side of the fracture had quartz crystals up to ¼ inch long while the other side had much smaller crystals. The sides of the fracture dip about 45 degrees. The upper side of the fracture was sandstone while the lower side is andesite, suggesting could be a minor fault. This fracture is the most permeable of the deeper fractures as shown on the April 27 Halliburton injection temperature logs (Figure 8). Other deep interesting fracture intervals with abundant secondary mineralization in the core are located at 3955 -3971, 3988 - 4024, 4165 - 4168, 4335- 4336, and 4562- 4563 ft.

The deep fractures are hosted by three different rock types, sandstone, mud or debris flows, and most importantly mafic lava flows and dikes. These fractures are also are more clearly defined in the cores with steep dips of 45 degrees to vertical.

These fractures do not show any strong evidence for significant offset across them as might be expected if they were part of a major fault system. Also these fractures are relatively distant from each other. If a major permeable fault or fault zone were penetrated a denser concentration of fractures could be expected.

Static Temperature Logs

These data have previously been described (Figure 13).

Injection Temperature Logs

Three injection tests with temperature log runs have been performed on LCSH-5 (Figure 17). The first test was on April 20 with the hole at a depth of 4257 ft and uncemented HQ rods in place to a depth of 2258' (Benoit 2005 a). There was open hole below a depth of

2258 ft. After the hole was deepened to 4727 ft and additional fractures were exposed, the hole was injection tested and logged on April 27 (Benoit, 2005b). The hole was in the same basic condition as on April 20 with uncemented HQ rods to 2258 ft and open hole below. On June 17 the third injection log was performed with the hole completed as shown on Figure 9.

The three logs on Figure 17 differ considerably in their gross character but a closer examination of their more detailed character shows the same shallow and deep permeable features. The April 20 log shows no fluid going below a depth of 2250'. The injectate rose behind the HQ rods and exited the wellbore at shallower depths. The April 27 and June 17 logs show sharper inflections at depths near 1600 and 1500 ft. This shows that in all three injection tests fluid was able to exit the HQ rods and flow up the HQ annulus for 750 ft before exiting the wellbore. These flows extend almost up to the bottom of the cemented casing at 1470 ft. The amount or percentage of fluid flowing up the HQ annulus during the April 27 and June 17 injection tests is not known.

Similarly, near the bottom of the well the June 17 injection log has three clear inflections at 4300, 4480, and 4617 ft (remember that these values are about 40 ft too deep due to the Halliburton depth measurement error) which correlate closely with small and large inflections on the April 27 injection log. The current well completion has impacted the overall character of the June 17 injection log as there now appears to be no single major injection zone shown by a sharp increase in temperature but the same overall processes and injection zones were active on both logs. As the very bottom of the hole was cooled during the June 17 test, injectate was flowing out the slots between 4707 and 4727 ft and then moving up the annulus outside the NQ rods up to at least 4620 ft giving the curved temperature profile similar to that seen just above a depth of 2200 ft on the April 20 log.

The major injection intervals on June 17 appear to be at 4480 ft, which most likely is the fracture seen in the core at 4439 ft and at 4620 ft which is probably really at 4580 ft, remembering the previously mentioned Halliburton depth discrepancy. This is suspiciously close to a significant fracture seen in the core between 4562 and 4563 ft. The reason for the sharp decrease in the injecting temperature gradient below a depth of 4300 ft is uncertain but it does show up on both of the deepest injecting logs.

Flowing Temperature Logs

The only flowing logs from LCSH-5 were obtained with the uncemented NQ rods lining the bottom half of the hole (Figure 9). This allows fluid flows both inside and outside of the HQ and NQ tubings, adding considerable ambiguity to the analysis of the logs. The flowing temperature logs are all quite noisy below a depth of about 1250 ft.

The simplest feature to interpret on the flowing logs below the flash points (near a depth of 200 ft) is the sharp 9.5 °F temperature change near a depth of 2250 ft which must represent mixing of fluids with two different temperatures at the bottom of the HQ rods (Figure 12). Cooler water must be flowing down the outside of the HQ rods and mixing with hotter water rising outside and/or inside the NQ rods. Fluid flowing down the outside of the HQ rods effectively turns this part of the hole into a counter flow heat exchanger. The sharp inflection in the flowing logs at a depth of 1950 ft is the likely place for a major inflow to the HQ annulus, or at least the deepest inflow. The relatively low temperature gradient in the flowing logs between 1950 and 2250 ft represents the counter flow heat exchanger effect (Figure 12).

Between depths of 1950 and about 1650 ft there is an interval with a higher flowing temperature gradient which is difficult to interpret as it is not known what flows may be occurring in the annulus. Above a depth of 1650 ft the temperature gradient decreases for uncertain reasons. Perhaps there are additional inflows into the HQ annulus at and above 1650 ft.

The location(s) of the deeper and hotter inflow(s) are not obvious on the June 16 and 17 flowing temperature logs (Figure 12) and it is beyond the time frame of this report to develop a flow model which does not have significant conflicts with the temperature logs and core record. Some of the problems developing a consistent model follow.

The most striking features of the flowing logs below a depth of 2250 ft are the obvious 7 ^{o}F temperature decline between depths of 3390 and 3490 ft and the presence of repeatable large and very sharp temperature oscillations particularly below a depth of 3490 ft. The temperature decline between 3390 and 3490 ft was recorded only on the June 16 and 17 temperature logs, making it a transient feature. A few very small temperature inflections can be seen on the May 25 temperature log (when it is plotted at a greatly expanded scale) that correlate with some, but by no means all, of the June 16 and 17 temperature oscillations.

All of the larger oscillations have been precisely repeated on four June 16 and 17 flowing and static logs leaving no opportunity to ascribe this to an equipment problem. These oscillations demonstrate that there was no vertical flow in the well below a depth of 3490 ft on June 16 and 17. This is surprising given the presence of the open fractures and the injection into the fracture at 4439 ft on April 27 and the fractures at 4439 ft and 4580 ft immediately following the June 16 flow test (Figure 17). The temperature oscillations either represent some transient phenomena within the wellbore or were washed out by flows within the wellbore during the U. S. Geological Survey log in August.

Between a depth of 3200 and 3390 ft there are some repeatable oscillating temperatures with as much as 2 ^{o}F variation. This makes it unlikely that there was any significant flow in the well below a depth of 3200 ft. This is at odds with a possible interpretation that the deeper fluid might be entering the well at and above a depth of 3440 to 3480 ft. This is the depth interval below which the static temperatures in June were greater than the flowing temperatures and above which the flowing temperatures were greater than the static temperatures (Figure 12). A review of the core between depths of 3400 and 3500 ft showed no significant fractures or secondary mineralization to support permeability here. If there is a permeable fracture here it is the only fracture in the well which is not easily recognizable in the core.

Between 2250 and 3200 ft the flowing logs do not present obvious locations for fluid inflows. Also, there were no obvious open fractured and mineralized intervals in the core in this depth range. Picking these fluid-entry locations is complicated by the fact there may be annular flow within this interval and perhaps there is no flow within the NQ rods.

Below 2300 ft there is a temperature increase to a depth of 2630 ft. Below 2630 ft the temperature shows a very slight decrease. By itself, this can be interpreted that no significant inflow of fluid rose from below a depth of 2630 ft during the June 16 and 17 flow test as it would have had to gain temperature while rising up the wellbore.

The various types of evidence for permeability in well LCSH-5 are summarized on Table 1.

TABLE 1
LCSH-5 Evidence of Permeability

Depth	Lost Circulation	Core Fractures	Static Temperature Logs	Injection Temperature Logs	Flowing Temperature Logs
50-100 ft			Fig. 11		
350-400 ft			Fig. 11		
1270 ft			Fig. 13		
1443-1502 ft	X	X	Fig. 13	Fig. 7	
1561-1587 ft	X	X	Fig. 7		
1645-1651 ft		Fig. 15	Fig. 7, 8, 13	Fig. 7, 8, 12	Fig. 12
1759-1777 ft	X	X	Fig. 7		
1919-1922 ft		X	Fig. 7		Fig. 12
2317 ft	X				
3955-3971 ft		X			
3988-4023 ft		X	Fig. 14	Fig; 7	
4165-4168 ft		X			
4335-4336 ft		X			
4439 ft		Fig. 16	Fig. 8, 14, 17	Fig. 8, 12, 17	
4562-4563 ft		X	Fig. 14	Fig. 17	

Table 1 does not specifically note which of the individual fractures are most important. Qualitatively the fractures at 1650 and 1920 ft seem to be the most important shallow fractures based on the all the evidence. Fractures behind the casing and fractures for which have only limited character on the injection and production logs are most likely of little or no significance. The most significant deep fracture seems to be at 4439 ft with the fracture at 4562 ft being the second most important.

LCSH-5 Productivity and Injectivity Summary

The three injectivity tests and one productivity test have been previously described. The productivity and injectivity data from these four tests are summarized on Table 2.

All of the data show relatively low productivity or injectivity but it must be remembered that during all of these tests fluid flowed for several hundred feet in the small annuli outside the drill rods. This will create large pressure drops which will limit the amount of fluid that can be produced or injected. A more efficient wellbore should result in substantially larger injection and production rates. Another factor to keep in mind is that all of the tests were of very short duration, ranging from a few hours to one day.

TABLE 2
LCSH-5 Productivity and Injectivity Summary

Date	Well Completion	Inj. Rate (gpm)	Prod. Rate (gpm)	Downhole Pressure Change (psi)	Productivity (gpm/psi)	Injectivity (gpm/psi)
4-19	HQ rods to 2258 ft and open hole below, TD = 4257 ft	33		57.4		0.57
4-17	HQ rods to 2258 ft and open hole below, TD = 4727 ft	76		184.2		0.39
6-17	HQ rods to 2258 ft and NQ rods 2226-4727 ft, TD = 4257 ft		60	50.6	1.18	
6-17	HQ rods to 2258 ft and NQ rods 2226-4727 ft, TD = 4257 ft	60		56		1.07

LCSH-5 Structural Setting

The simplest structural analysis of LCSH-5 is to pick depths where faults might cross the wellbore and connect them to surface features. The most obvious possible depth for a fault location is the fanglomerate/rhyolite contact at 1270 ft (Miller et al., 2005). While the cores show a large amount of shearing in the top of the rhyolite there was no major permeability as defined by lost circulation. If the top of the rhyolite represents a planar fault with its surface trace at the range front, the dip of the fault is 31 degrees (Figure 18). A dip of 31 degrees seems quite low for a major range-front fault but is but this dip is almost twice as steep as the face of the lower part of the range and it has found favor with the Stanford University workers (Miller et al., 2005). If the range-front fault passes beneath the bottom of LCSH-5 then its dip must exceed 63 degrees, presuming LCSH-5 is a vertical well. No directional surveys were run in LCSH-5 but there were no drilling problems suggestive of a highly deviated hole.

If a second major normal fault east of the range front is postulated, this fault shows little or no evidence of crossing the LCSH-5 wellbore (Figure 18). No major faults were evident in the LCSH-5 cores. Only discrete relatively small scale fractures were seen in the core. No thick zones of shattered rock with several closely spaced fractures were cut. Although faults and contacts are shown on Figure 18 it needs to be remembered that these are conceptual in nature.

OH-1

OH-1 was not originally part of the slim hole drilling project but it was an integral part of phase 1 of the Lake City GRED project. After it was recognized that there would be very little to be gained by detailed analysis of the Quaternary lacustrine clay encountered in LCSH-1a, it was decided that Joe Moore would substitute the OH-1 core for LCSH-1a core and each OH-1 core box was digitally photographed. Also, OH-1 was flow tested and its NQ rods were grouted in place during phase 2.

OH-1 Siting

OH-1 is on a location previously permitted by Trans Pacific Geothermal Corp in 1992 about 1 mile north-northeast of the Phipps #2 discovery well at the northern end of the hot springs (Figure 3). It was drilled at this location basically due to rapidity of permitting and ease of access (Dennis Trexler personal comm.). It is located in pasture land at an elevation of 4540 ft about 400 ft east of the toe of a large apparent landslide approximately ¼ mile east of the projected surface trace of the range front beneath the landslide (Figure 3).

OH-1 Drilling History

OH-1 was drilled to a depth of 3436ft in 36 days by Boart Longyear in 2002. At completion OH-1 had 7 inch casing cemented to a depth of 56 ft, 4 ½ inch casing cemented to a depth of 310 ft and NQ core rods (2 3/8 inch I. D.) hanging in a HQ sized hole (3.83 inch diameter) to a depth of 3220 ft. The bottom ten feet of the NQ core rods was slotted. During drilling there were identified lost circulation zones at depth of 144 ft, 265, 270, and 368 ft. Other unrecognized lost circulation intervals, such as a major zone at 947 ft are also present. The bottom 200 feet of the hole is in a reddish brown pebbly mudstone that was difficult to drill with sticking, caving, torque, and twisting off problems. These difficulties are attributed to swelling smectite rich clay by Goranson (2003). At completion, the NQ rods would not go below a depth of 3220 ft.

OH-1 Geology

An exceptionally detailed 59 page description of the OH-1 core was prepared by Hardyman (2002) but no brief lithologic log was prepared and no attempt was made to define the Quaternary/Tertiary contact. A generalized lithologic log of OH-1 is shown on Figure 10. OH-1 is located east of two unnamed creeks that originate on the face of the mountain range, have not developed deep canyons, and have not created large alluvial fans below their mouths (Figure 3).

Above a depth of 263 ft the core is generally rough with a relatively soft and poorly consolidated appearance suggesting a Quaternary age. The rocks are sandstones, siltstones, and mudstones in sharp contrast to the very coarse fanglomerate found in LCSH-5. Below 263 ft the core is generally smooth and firm, but can locally be extensively fractured. Tertiary volcanic bedrock is clearly the lithology below a depth of 263 ft but the Tertiary-Quaternary contact may be shallower. Below a depth of 241 ft core recovery was close to 100%. Above a depth of 241 ft there were three intervals of greatly reduced core recovery. The gamma log of OH-1 (Figure 10) shows a sharp increase in gamma ray activity below a depth of 60 to 70 ft that could also represent the Quaternary/Tertiary contact. If so, this would be the thinnest Quaternary alluvial sequence yet penetrated at Lake City.

Between depths of approximately 260 and 2427 ft the Tertiary rocks are primarily muddy debris flows separated by finer-grained volcaniclastic sediment units, consisting primarily of sandstone with lesser gravel and siltstone. There are no obvious layers or horizons within this sequence that serve as clear stratigraphic markers. The most significant veining occurs between depths of 941 and 951 ft in OH-1 (Moore and Segall, 2005).

The most distinctive rocks in OH-1 are found between 2427 and 2978 ft as a sequence of andesitic lava flows separated primarily by mudflows, with lesser siltstone and sandstone. About half of this sequence is andesite. Hardyman (2002) identified one thin possible andesitic ash flow tuff between depths of 2809.5 and 2812.3 ft in OH-1. Unfortunately, none of the distinctive units or formations noted in LCSH-5 are present in OH-1.

Between 2978 and 3388 ft the lithology is dominated by siltstone, sandstone, and mudstone, with the massive mudstone being a striking dark brown to chocolate brown color. The very bottom of the hole between 3388 and 3435 ft is in a mudflow (lahar).

Additional discussion of the petrographic studies, secondary mineral assemblages, x-ray diffraction studies, fluid inclusion systematics, and fracture orientations in OH-1 can be found in Moore and Segall (2005).

OH-1 Flow Testing

OH-1 was briefly kicked off in February to verify that it would sustain flow. It was then tested for 6 ¼ hours on March 12 by initially flowing through the NQ rods and later by flowing through the annulus outside of the NQ rods (Goranson, 2005). This was not long enough for complete thermal stabilization of the well. Flow rates were throttled back to about 46 gpm while first flowing through the NQ rods and were about 34 gpm while later flowing through the annulus. The productivity index is 7.6 gpm/psi which is substantially greater than the productivity or injectivity of LCSH-5 with a similar completion.

The Spartek memory tool utilized for the static log prior to the initiation of flow produced unrealistically high temperatures that have proven impossible to correct or adjust. Therefore, a Kuster temperature tool (providing fewer data) was also used to obtain flowing temperature logs. The flowing Kuster logs (Figure 19) show a pattern that is consistent with most or all of the produced fluid entering the well at a depth of 947 ft. When the well was flowed through the NQ rods the fluid had to enter the well at 947 ft and flow down the outside of the rods to a depth below 3200 ft where it could enter the slots in the rods and then flow up the inside of the rods. This created a long heat exchanger between 947 ft and 3200 ft which resulted in an overall warming of the produced fluid. While flowing through the NQ rods the temperatures at 200 ft, the approximate flash point depth, were 286 ^{o}F, or 14 ^{o}F hotter than the static temperature at 947 feet.

While flowing through the annulus the temperature below the flash point was 280.5 ^{o}F. This decline is expected as the fluid was able to directly flow to the surface after entering the well. It is interesting to note that the flowing annulus temperature is 8 ^{o}F hotter than the static temperature of 272 ^{o}F at a depth of 947 ft. Either hotter fluid is entering the annulus at shallow depths or perhaps under flowing conditions the zone at 947 ft increases its temperature by several degrees.

OH-1 Grouting and Confirmation Testing

The day after OH-1 was flow tested the NQ rods were uneventfully grouted in place by Halliburton with 130 sacks of high-temperature cement giving a volume of 209.3 cubic feet. This should have been enough cement to bring cement up to the surface as the theoretical annulus volume was 151.6 cubic feet. There were no returns of water or cement to the surface and no pressure buildup in the annulus indicating that all the displaced water and the excess cement flowed out of the well at the 947 ft permeable zone. This grouting was successful to the extent that no fluid could be pumped into the NQ rods following the cementing.

Following the March 13, 2005 grouting Halliburton returned to OH-1 on March 24 to run a static log. This log and an August 2005 U. S. Geological Survey log show no change in the static temperature profile (Figure 20). Therefore, there was no downflow masking the true formation temperatures deep in OH-1. As the maximum reading thermometer (MRT) temperatures of 330 to 355 °F can not be found in a static condition it must be concluded that either these MRT data are erroneous. Therefore, the MRT values above 330 °F reported during the drilling of OH-1 were erroneous.

On April 6 a step rate injectivity test was performed on OH-1 to determine what impact the grouting may have had on the ability of the hole to accept fluid. This test demonstrated that the injectivity of OH-1 had actually increased by about 20 gpm as compared to the previous injectivity tests on Nov. 11, 2003 (Figure 21). The two tests were performed in an identical manner with the same equipment and personnel. Perhaps the flow testing of OH-1 removed some debris partially clogging the fracture at 947 ft. During the injection into the annulus on April 6 a temperature log run with the SMU portable equipment again showed all the injectate exiting the hole at a depth of 947 ft (Figure 22).

OH-1 Static Temperature Logs

The various OH-1 static temperature logs all closely agree with each other and show a complex temperature profile. In detail there are a couple of shallow thermal aquifers with a maximum temperature of 287 °F above a depth of 300 ft which are in agreement with the presence of thermal springs several hundred feet east of OH-1 (Figure 20).

At intermediate depths there are also strong indications of fluid movement at depths of 947 and 1480 ft. Below about 1600 ft there is limited evidence of active fluid movement with the well having a positive temperature gradient to its total measured depth. Presumably if the well were deepened, it would encounter somewhat higher temperatures before becoming isothermal in a deeper fracture network.

OH-1 Permeability

Permeability in OH-1 is mostly, if not entirely, confined to the upper part of the hole. During drilling, circulation was lost at a depth of 144 ft while reaming the core hole with a rock bit. At this time the core hole was 315 ft deep. The 4 ½ inch casing was set to 310 ft with returns but circulation was lost somewhere between 368 and 428 ft after drilling out from the 4 ½ inch casing shoe and apparently never was regained. While the dominant fracture in the well is at a depth of 947 ft, there are no specific drillers comments about the 947 ft depth other than to note fractured rock was resulting in some short core runs during the shift. In the core box containing the core from 947 ft there is a wooden block noting a 1 ft void at that depth (Figure 23). In appearance the fractured interval in OH-1 is quite similar to that seen at shallow depths in LCSH-5 (Figure 15).

Evidence of intense hydrothermal alteration extends to within 50 feet of the surface as evidenced by soft red oxidized clay-rich intervals. Calcite veining is present below a depth of 163 ft and secondary silica is first noted at a depth of 246 ft. This mineralogy is consistent with a very high near surface temperature gradient that reaches a temperature of 283.5 °F at a depth of 190 ft. A temperature maximum of 287.5 °F is present at a depth of 285 ft. Mineralogicaly, the most important permeable interval in the well appears to be at a depth of 947 ft due to an abundance of drusy quartz and pyramidal quartz crystals associated with this interval (Moore and Segall, 2005). Why this productive interval is a relatively cool section in the well (Fig. 20) is unclear but it does suggest that under "static" conditions there is some downflow through this zone. The major permeable zone at 947 ft is located at the contact between a sandstone unit above and a coarse mudflow below but the exact nature of this contact is unclear. It may be a normal fault but it is clearly not part of a major fault with hundreds of feet of offset.

Temperature logs of OH-1 during and shortly after injection show evidence of rapid fluid movement in two zones between 250 and 350 ft and smaller amounts of fluid movement at shallower depths (Figure 24). The Dec. 4, 2003 logs on Figure 24 were obtained immediately following injection while the April 6, 2005 logs were obtained during injection.

OH-1 Structural Setting

The cores suggest the bottom of the Quaternary alluvium in OH-1 is at a maximum depth of 263'. The gamma ray log may be indicating that Tertiary rocks are as shallow as 50 or 60 feet below the surface. Whether the range-front fault is located a few hundred feet west of OH-1 or ¼ mile west of OH-1 there is a shallow bedrock bench of some sort underlying OH-1.

If OH-1 crossed any major normal faults they are most likely to be present either near 947 ft or near a depth of 300 ft.

CORRELATIONS BETWEEN WELLS

Correlations Between LCSH-5 and OH-1

Even though OH-1 and LCSH-5 are only ¾ mile apart in a north-south direction there is no obvious stratigraphic correlation between the two holes (Figure 10). The fine grained light colored rhyolitic unit between 1270 and 1391 ft in LCSH-5 is not present in OH-1. The mudflow with pre-Tertiary cobbles between 3402 and 3669 ft in LCSH-5 is not present in OH-1. And lastly, the mafic poikolitic lava flows below 4244 ft in LCSH-5 are not present in OH-1. OH-1 may simply have not been deep enough to penetrate these rocks.

The only obvious unit for correlation purposes in OH-1 is the andesitic sequence between 2427 and 2978 ft. These OH-1 andesites do not look like the andesites or mafic lavas in

LCSH-5 and are located either much deeper or much shallower than the mafic lavas in LCSH-5, requiring either large dips or faults to explain offsets. In LCSH-5 the upper andesite lies between depths of 1349 and 2056 ft while in OH-1 the andesitic unit depth interval is 2427 – 2978 ft. Correlating the tops or bottoms of these requires a southward deepening of 922 to 1078 ft in a horizontal distance of ¾ mile. North-south dips like these are not seen in the rocks on the east face of the Warner Mountains, in fact there is gentle northward dip component.

Attempting to correlate the top of the andesitic unit in OH-1 at 2427 ft with the top of deep mafic lava flows in LCSH-5 at 4244 ft results in an even less credible 1817 ft offset. As no large dips or fault offsets are visible in the range in this area it becomes more difficult to credibly propose such structures.

Any correlations to be made between the formations encountered in LCSH-5 and OH-1 apparently will need to be based on the sedimentary units. This will require considerably more time and effort than has been dedicated to this question to date. The local geology penetrated by OH-1 and LCSH-5 may not lend itself to obvious stratigraphic markers.

Correlations Between the Phipps #2 Well and OH-1

The lithologic descriptions of the Phipps #2 cuttings (Zebal, 1973, 1979) are very brief (samples were apparently collected only every 30 ft) and are inconsistent with the gamma ray log. Igneous names such as rhyolite, andesite, etc. have apparently been applied to sedimentary rocks, (GeothermEx, 1991).

Comparing the Phipps #2 gamma ray log with the OH-1 gamma ray log shows a reasonable amount of similarity at shallow depths in both holes suggesting similar formations were penetrated (Figure 10). Perhaps the step down in gamma ray activity at 600 ft in Phipps #2 and at 947 ft in OH-1 might be equivalent. Deeper in the two holes there are no obvious correlations.

LAKE CITY STATIC TEMPERATURE PROFILES

The three deeper holes within ½ mile or so of the range front have very high near-surface temperature gradients and abnormally complex profiles (Figures 25 and 26) indicative of active three dimensional fluid movement. OH-1 and Phipps #2 have shallow overturns but the amount of temperature loss below the overturns is small only exceeding 10 °F near Phipps #2. This implies that the lateral flow component of the geothermal system may relatively small compared to some other major Northern Nevada geothermal systems, the flow system has been active for a long time, or that possibly larger overturns are masked by convective flows beneath the aquifer.

There is clearly a shallow lateral flow system with temperatures as high as 310 °F between elevations of 4000 and 4300 ft near Phipps #2, and OH-1 (Figure 27). This lateral flow as interpreted on Figure 27 flows toward the east from the immediate vicinity of the range front over a strike length of about one mile. There is no evidence for this aquifer extending east of the hot springs and it probably does not extend either north of south of the hot springs (Figure 3) by any significant distance. Evidence of shallow lateral flow at

LCSH-5 is very limited, being found only as small inflections on the May 31 and June 1 SMU logs obtained immediately after the well was shut-in (Figure 11). It is likely that there is a deeper lateral flow system near LCSH-5 between elevations of 2800 and 3100 ft (Figures 13 and 26) but this would most likely be a separate aquifer. Below an elevation of 2000 ft there is no evidence of lateral flow in the temperature profiles.

Phipps #2 has the hottest static and flowing temperatures measured at Lake City at 337 °F below an elevation of 700 ft. LCSH-5 has a maximum static temperature of 323 °F and a maximum flowing temperature of 329 °F representing a 8 to 14 °F decrease in temperature toward the north. It is not clear how much of this decrease is related to LCSH-5 being north of Phipps #2 or is related to LCSH-5 being further east of the range front or some combination of both directions. OH-1 apparently was not drilled quite deep enough to penetrate into the deep resource. The bottom hole temperature in OH-1 is 327 °F with a positive gradient. Temperatures several hundred feet below the bottom of OH-1 could be close to the 337 °F measured in Phipps #2.

NATURE OF FRACTURING

Permeable fractures have been recognized and defined in three widely spaced holes at Lake City; OH-1, LCSH-5, and Phipps #2. (Phipps #1 and Parman #1 also encountered permeable fractures but these are not included in this discussion due to an absence of data on these fractures.) Of these three, the fractures in the Phipps #2 well are the least understood, being documented only by flowing temperature and spinner logs (Goranson, 2003, Benoit, 2003) and a gamma ray log.

The most significant Phipps #2 productive fractures are located at depths >4900 ft, 4825 ft, 4700 – 4550 ft, and 4495 ft. There are other fractures above a depth of 4000 ft in or near the Phipps #2 well as indicated by the stair stepped static temperature profile, but none of these contributed to the flow from the well. In contrast to OH-1 and perhaps LCSH-5, no single fracture in Phipps #2 is dominant. There is no way to estimate the apertures of these fractures or their orientations as there is a slotted liner to the bottom of the well. The gamma ray log shows Phipps #2 below 4500 ft to be fairly homogeneous with a fairly high gamma ray activity of 30 to 40 API units (Figure 10). If these rocks are volcanic they would likely be rhyolitic and therefore are in a different rock type from the OH-1 and LCSH-5 fractures. If these rocks are sedimentary they might be called mudstones but it is very unlikely that mudstones would be the most productive interval in the well. There is a sharp change in gamma ray activity immediately above 4500 ft with these rocks having gamma ray activities of about 15-30 API units. Again, if these rocks are volcanic they would be described as andesitic or basaltic.

There are a number of fractured intervals in the OH-1 core above a depth of 950 ft. Above a depth of 400' there is considerable veining, secondary mineralization, and hydrothermal alteration. The single major fracture in OH-1, described as a 1 ft void by the drillers, is at a depth of 947 ft. Heavy veining and smaller subsidiary fractures extend from 939 to 953 ft (Figure 23). The dip of the major fracture at 947 ft can not be reconstructed from the core photograph but calcite veins a couple of feet above 947 ft dip at 45 to 60 degrees. Sandstone is on both sides of the major fracture but only a few feet deeper at 953 ft there is a sharp change in lithology to a mudflow. This opens the possibility that this fractured interval is associated with a small fault. The gamma ray log (Figure 10) shows a sharp change in counts at 950 ft with sandstone above and a mudflow below.

LCSH-5 contains a complex permeable interval between depths of 1270 and 1920 ft. It almost appears that the fanglomerate might be acting as a classical cap rock here.

The single major fracture deep in LCSH-5, was described as a 6 inch void by the drillers, is at a depth of 4439 ft and defines the contact between an overlying sandstone and an underlying poikoilitic andesite lava flow. There is no other veining or fracturing of the sandstone and mineralization associated with fracturing extends only a matter of inches into the lava flow. The other impermeable fractures in LCSH-5 have apertures slightly less than an inch with identical or similar rocks on opposite sides of the fractures. There is also at least tens of feet between the individual quartz lined fractures. This strongly indicates that these fractures represent intervals where the rock has broken, but not major faults. In LCSH-5 the most significant fractures deep in the hole are steeply dipping, between 50 degrees and vertical. At shallow depths in LCSH-5 there is greater variability in the fracture dips.

The fracturing in OH-1 and LCSH-5 is confined to the harder mudflows, sandstones, and lava flows. The finer siltstones and mudstones have no open fractures. The most permeable fractures in OH-1 are located at a sandstone/mudflow contact and in LCSH-5 at a sandstone/lava flow contact within a massive lava flow sequence. This may be implying that the Phipps #2 fractures are located within a thick and firm rhyolitic formation.

These three holes suggest a pattern or relatively small relatively widely spaced fractures located in the vicinity of the range front. The fractures are not confined to single lithology. There are not a few large fractures oriented defining a plane that might represent a steeply dipping normal fault.

PHIPPS #2 STRUCTURAL SETTING

The Phipps #2 well is unique in the northern Basin and Range province being located directly on the surface trace of a major range-front fault (Figure 3) and also by being productive from depths of thousands of feet. Zebal (1973) noted that the Phipps #2 well was “critically located to take advantage of nearby surface manifestations and the junction of two fault zones at a point where lake bed sediments would not be encountered.” Unfortunately, Zebal did not show the second fault zone on any maps and no other worker in the area has presented any convincing evidence of structures crossing the Surprise Valley fault zone near the Phipps #2 well.

The gamma ray log confirms that Phipps #2 was drilled in bedrock from the surface. This would be in agreement with a fault having some easterly dip having its surface trace beneath the Phipps #2 pad. This implies that as the Phipps #2 well is drilled to greater depths the further it moves away from the range-front fault.

If the fault were vertical then the Phipps #2 well should have been drilled within this fault from the wellhead to total depth. This is unlikely as the Phipps well only encountered lost circulation at a depth of 370 ft and below a depth of 3926 ft. The Phipps #2 well has only shallow and deep permeability. It is apparently missing the intermediate depth permeability seen in OH-1 and LCSH-5.

GEOCHEMISTRY

Brine chemistry samples were collected from well OH-1 during its six hour flow test on March 12, 2005 and from LCSH-5 during its May 31- June 1 and June 16-17 flow tests. One sample of highly contaminated steam condensate was collected from LCSH-5.

OH-1

OH-1 was flow tested on March 12, 2005 by flowing it through both the NQ rods and the annulus outside the NQ rods. Prior to the flow testing, two water truck loads (3600 gallons per load) of dilute cold water had been injected into the well in Nov. and Dec. 2003 and one truck load had been injected in late January 2005. The hole was flowed for 2 ½ hours in Feb. 2005. It is anticipated that most or all of the recently injected fluid was produced from the well or had ample time to flow away from the well. However, it is possible that small amounts of this injected fluid were produced during the flow test. The total volume of the OH-1 core hole is 151.6 cubic feet or 1134 gallons.

Flow through the NQ rods began at 1145 hours and stopped at 1428 hours at an average rate of 46 gpm (Goranson, 2005) producing a total of 7500 gallons. During this time there was no flow to the surface from the annulus. Fluid had to enter the NQ rods through slots in the bottom joint. The well was shut in from 1428 hours to 1445 hours. Flow through the annulus outside the NQ rods commenced at 1445 hours and continued until 1800 hours at an average rate of 35 gpm producing a total of 6825 gallons.

During flow through the NQ rods, fully flashed water samples were collected by holding a plastic pitcher at the end of the flow line at 1338 and 1425 hours. The flowing temperature profiles (Figure 19) indicate that most of the fluid entering the bottom of the NQ rods came from a depth of 947’ and flowed down the annulus to enter the bottom of the rods. The static temperature at 947’ is between 271.5 and 274.8 °F depending upon the individual temperature log utilized. During the flow testing this fluid gained 55 to 58 °F flowing down the annulus outside the NQ rods and then lost 45 °F while rising back up the inside of the rods to 947 ft. The rods acted as a long heat exchanger. The overall net gain in temperature of the fluid from 947 ft down to the bottom of the NQ rods and back up to 947’ was 10 to 14 °F. The flash percentage during flow through the rods is 8.56 % utilizing a flash point temperature of 286 °F.

During flow through the annulus, fully flashed water samples were collected by holding a plastic pitcher at the end of the flow line at 1606 and 1735 hours (Table 3). The flash percentage during flow through the annulus is 8.72 %. This flash percentage is slightly higher than when the flow was through the NQ rods in spite of the flowing temperatures between 800’ and 600’ being lower than during flow through the NQ rods. The reason for this is the Spicer memory tool showed the annular flow gaining 7 °F between depths of 800’ and 300’. While the Spicer memory tool was producing anomalously high values the differences between various readings appeared to be close to correct. Therefore, adding 7

°F to the annular flowing Kuster log gives a calculated flash temperature near 200' of 287.5 °F (Figure 19).

The Desert Research Institute performed the chemical analyses on samples that were filtered, acidified, and diluted as per standard sample preservation techniques. Field pH values from papers were 8.5. Table 3 shows the post-flash analyses with corrections back to pre-flash conditions along with dilution corrections for the silica analyses. The annulus samples are slightly more concentrated in all species except calcium and silica in the post-flash samples. The magnesium and boron contents are very similar. Perhaps the annulus samples were able to pick up small amounts of fluid from shallower fractures between depths of 500 to 300' at higher temperatures (Figure 19) that contain slightly more saline water. A less likely alternative is that the flow down the annulus picked up a small component of more dilute fluid. A third possibility is that the well was producing progressively smaller amounts of previously injected fresh water during the testing.

LCSH-5

The last set of samples collected from the May 31-June 1 flow test and two sets of samples from the June 16 and 17 flow test were analyzed by DRI (Table 4). As was the case in OH-1 samples were collected from both the HQ rods hanging in the well and from the annular flow outside these rods. The samples were collected and treated in an identical manner to those from well OH-1. The flash percentage is calculated at 8.8% on the basis of the final flowing temperature log run during the flow test. This is probably accurate for the samples collected from the HQ rods. It is less certain how accurate this is for the samples collected from the annulus, where the temperature during flowing could be somewhat different from what was measured inside the HQ rods. Prior to the flow testing approximately one million gallons of cold dilute drilling fluid was injected into LCSH-5. The May 31-June 1 flow test produced about 50,000 gallons and the June 16-17 flow test produced about 88,000 gallons so the great majority of the injected drilling fluid remains underground.

Both of the HQ rod samples and the annular samples from LCSH-5 are about 10% more saline on June 17 than on June 1 indicating that LCSH-5 regurgitated a significant fraction of dilute drilling fluid when flowed on June 1 (Table 4). For this reason, the June 1 analyses will not be further discussed. The June 17 samples, collected about 5 hours apart, show little change in composition so it is hoped that the June 17 samples are reasonably representative of the long-term flowing composition. The fluid from the LCSH-5 annulus is approximately 10 % more saline than the samples collected from the HQ rods. This is somewhat unusual as the flowing temperature logs allow at least part of the annulus fluids to have entered the wellbore at shallower depths than the fluid entering the HQ rods. Generally geothermal fluids originating at greater depths are more saline than fluids collected from shallower depths. The drilling mud was made with a very dilute fluid so this allows the deeper fluid to perhaps be more contaminated by the drilling fluid.

Comparison of OH-1 and LCSH-5 with Other Lake City Thermal Waters

The analyzed waters from OH-1 and LCSH-5 are in general quite similar to or intermediate between most of the hot spring waters and the Phipps #2 well. (Table 5 and Figures 28 and

29). This overall similarity demonstrates that all of these thermal waters are part of a single fairly homogenous geothermal system and that there has not been extensive dilution of the thermal waters with cold shallow groundwaters (Sladek and Arehart, 2004). Similarly, there is no obvious evidence for subsurface boiling processes occurring at Lake City. The water produced from the NQ rods in OH-1 is the most dilute of the subsurface thermal waters analyzed to date while the water produced from the LCSH-5 annulus are in some species the most concentrated of the subsurface thermal waters. However, there remains the possibility that the samples collected from OH-1 and LCSH-5 were contaminated with drilling fluid or injectate. The samples collected from the OH-1 annulus and the LCGC-12 sample collected from a shallow well a few hundred feet southwest of OH-1 are virtually identical in composition.

Geothermometry

A plot of predicted Na-K-Ca temperature against the chalcedony predicted temperature (Figure 30) shows the two geothermometers giving very similar values. The quartz predicted temperature (Figure 31) gives values about 35 °F higher and while they may be more attractive they are probably less credible and won't be further discussed.

The hot spring waters, and the waters from the NQ rods in OH-1 give the lowest predicted temperatures with values 290 to 330 °F. The Phipps #2 water analysis has the highest Na-K-Ca predicted temperature of 382 °F. The two samples from LCSH-5 plot nearest the Phipps #2 sample. This is interesting because these two holes are near opposing ends of the field. A third group of samples might be defined as the OH-1 annular flow and the shallow well located near OH-1. The overall trend is that progressively deeper and hotter fluids have progressively higher predicted subsurface temperatures. The maximum Na-K-Ca temperature of 382 °F from the Phipps #2 well is 45 °F greater than the measured temperature of 337 °F. It is not yet known where temperatures approaching 380 °F might be found at Lake City if they actually are present at accessible depths. Fluid inclusion temperatures (Moore and Segall, 2005) are comparable to measured temperatures and are unlikely to have exceeded 392 to 437 °F.

CONCEPTUAL MODELS

Historic Models

Conceptual geothermal models of the Lake City geothermal system have been developed over the past 32 years and fall into three different categories, although individual models may utilize aspects of more than one of the categories. These models provide a history on how ideas on the nature of the resource evolved as new data became available.

These models can not be viewed as overly rigorous or definitive for two reasons. First, they were (and still are) based on limited data. For instance, we lack a credible lithologic log for the sole existing production well and it is uncertain what the static temperature profile in LCSH-5 might look like. There is ample opportunity for differing interpretations of the geology and geophysics, and even more basic disagreements on the quality of some of the geophysical data. All of the historic models were prepared before the 2003 to 2005 GRED II work program. Second, through no fault of their own, most of the previous model preparers spent little time in the field, generally did not have the opportunity to collect raw data or look at rocks and cuttings, and had far too little available time to come to grips with all the available details. Only GeothermEx personnel had the opportunity to spend more than two weeks in the area examining the local geology (GeothermEx, 1975).

Zebal 1973 Model

The earliest conceptual model of the Lake City geothermal system (Zebal, 1973) suggested that the geothermal system was at the intersection of what is now called the Lake City fault zone and the Surprise Valley fault zone. As it was never published, this model has received very little attention. This model suggested the Surprise Valley fault zone is "not a single linear break but rather a broad zone, several thousand feet wide, containing a major fault line and literally hundreds of minor faults." Also Zebal proposed that the hot springs emanate from the NW-SE trending Lake City fault zone, a hypothesis seriously at odds with the north-south distribution of the hot springs. At this time the extent of shallow lateral flow of thermal waters in Basin and Range geothermal systems was unrecognized. No more recent author has come up with evidence for hundreds of minor faults and the OH-1 and LCSH-5 core holes failed to find evidence of these faults. However, the existing holes do seem to show there is an extensive network of fractures in the vicinity of the range front.

Warner Range Models

The next generation models (GeothermEx, 1975, Trans-Pacific, 1990, GeothermEx, 1991, Erskine, 1992) are based on a deep permeable lava flow (?) unit dipping gently toward the west beneath the Warner Mountains allowing hot water to flow miles toward the east where it flows into the Surprise Valley fault zone. The Surprise Valley fault allows hot water from the Oligocene (?) aquifer to rise almost to the surface but stops any deep hot water flow to the east of the fault. There is a shallow lateral flow of water to get the hot water over to the hot springs. This model was developed primarily to provide an explanation of the Phipps #2 permeability deep within the range block, a considerable distance from the range front and to explain the absence of a geothermal system near the Surprise Valley 1-ST well in the valley.

The primary strength of the Warner Range model is that it provides an explanation for the Phipps #2 permeability. The primary weaknesses of this model are that it is based on one well so it is poorly constrained. Core from LCSH-5 shows the open deep fractures to all be steeply dipping, and this model does not deliver much energy to the mud volcano area to power the 1951 eruption. As a more generalized comment, stratigraphy controlled geothermal models are currently not in favor in the Basin and Range province.

According this model, successful wells would be drilled along or west of the Surprise Valley fault zone to intersect a largely horizontal sheet-like target of regional extent and the highest temperatures should be found further to the west. The western limit of drilling would be controlled by topography and access to the faces and canyons of the Warner Mountains. In spite of the weaknesses and shortage of confirmatory data, aspects of this model have attributes worthy of further consideration and testing.

Surprise Valley Fault Zone Models

The second type of conceptual model relies primarily on thermal fluid rising up the east dipping Surprise Valley fault zone and also along parallel north-south trending normal faults both located east and/or west of the Surprise Valley fault zone (Trans-Pacific, 1990, Teplow, 2002, Geo Hills Associates, 2002, Blackwell et. al., 2004). Nearly every conceptual model shows more than one north-south trending fault in the western part of Surprise Valley, but seldom are these faults shown in the same location and no modeler has yet presented a convincing analysis with multiple data sets to prove their existence and locations. Blackwell et al., (2004) demonstrate how some of the geophysical data can be interpreted in multiple ways to define faults with varying offsets in differing locations east of the range front. The fact is there is little or no surface evidence for most of these proposed north-south faults, other than along the very front of the range. Some models have prescribed great significance to a fault lying beneath the hot springs while others indicate a fault here but do not utilize it as a major flow path.

The strength of these models is that they are in overall agreement with the north-south elongation of the shallow thermal anomaly and to date the deeper drilling indicates a strong north-south elongation of the deep thermal anomaly. North-south trending faults should be fairly well oriented for creation of open space during fault movement. All of the geothermal fields in Northern Nevada appear to be located along structures that trend north-south to northeast-southwest.

The primary weakness of these models remains the ability to convincingly locate and characterize these faults, especially a fault that provides the permeability for the Phipps #2 well.

Lake City Fault Zone Models

The third type of conceptual model) postulates that thermal fluid rises primarily along steeply dipping NW-SE trending faults of the Lake City fault zone that cross the Surprise Valley fault zone and extend into the Warner Mountains. The Lake City faults have been interpreted to have created a 4000 foot wide northwesterly trending horst block with 1000' of structural uplift between the Phipps #2 and OH-1 wells (van de Kamp, 2002, Goranson, 2003). A possible strength of this model is that it might explain why no obvious correlations could be made between the rocks cored in OH-1 and LCSH-5.

There are several major weakness of this model. The individual faults within the Lake City fault zone are based on four oblique seismic lines of admittedly questionable quality. The gravity survey shows no local indication of the NW-SE structural trends. The faults are shown in different places and with different trends than were mapped by Hedel (1980, 1981) and Wesnousky (2003) from air photos. The faults are shown extending into the Warner Range. In particular, one very important fault, supposedly providing the permeability for Phipps #2, is shown in the bottom of Powley Creek. There is a well exposed 50 foot thick tan ash layer forming the lowest major waterfall in Powley Creek that shows no evidence of vertical offset. All other well known geothermal fields in Northern Nevada have a N-S to NE-SW trending structure as the controlling feature of the resource. Faults oriented in this direction are most likely to pull apart during movement.

Faults oriented NW-SE are least likely to pull apart and create open space during movement in the regional stress field.

Presuming that this model is correct, successful wells will be drilled along NW-SE trends. It has not been possible to drill temperature gradient holes in Upper Lake or within the Warner Mountains to further test this model.

These three groups of conceptual models call for three different exploration or drilling strategies and target. Most likely other restrictions on drill hole locations will be discovered as new holes are drilled. The Warner Mountains model generally suggests future wells should be drilled as far west as possible. The Surprise Valley fault models suggest that successful wells should be drilled in an elongated band generally along the range front targeting east dipping structures. The Lake City fault zone models suggest that successful wells should be drilled along a NW-SE trend targeting near vertical structures.

UPDATED CONCEPTUAL MODEL

The recharge area for the geothermal system is uncertain. The stable isotope data (Sladek and Arehart, 2004) indicate the water could be either a paleowater, perhaps from the Pleistocene Lake Surprise, or could come from relatively high elevation. Discriminating between these two possibilities is not a high priority activity. There is not enough deep information available to conclusively determine the direction of recharge to the geothermal field. GeothermEx suggested recharge from the west but it could also be coming from along the Surprise Valley fault zone or perhaps even from the east.

The amount of discharge from the geothermal field is not easy to measure but is probably on the order of a couple hundred gallons per minute. About 100 gpm can be seen on the surface flowing east from the mud volcano area (Benoit et al., 2004). Perhaps an equal amount is flowing on the surface and underground from the more northerly hot springs and there must also be some evapotranspiration losses. There may be some diffuse subsurface flow of thermal water away from the hot springs but no shallow thermal aquifers have been identified that might be moving subsurface thermal water away from the hot spring area (Figure 27).

More important than the system throughput is the amount of fluid stored in the reservoir readily available for production. At the present time there are no convincing data available to generate this number other than to note that every well drilled along the range front over a length of 1 ¾ miles to date has intersected some part(s) of the geothermal reservoir.

The Lake City geothermal field is clearly associated with a two mile long north-south trending segment of the Surprise Valley fault zone (Figure 3). Vertically the field can be subdivided into three discrete intervals. There is a sub horizontal plume of thermal water above an elevation of 4000 ft with temperatures as high as 311 ºF (Figure 26) flowing through alluvial fans and perhaps the upper most section of the Tertiary rocks from the range front to the thermal springs. This flow occurs along about a mile of the range front from a short distance south of Phipps #2 to a short distance north of OH-1 (Figure 27). The shallow permeable intervals do not appear to extend to the east of the hot springs. This shallow thermal plume is most likely too small to support a commercial power generation project by itself but perhaps parts of this plume might be utilized for injection purposes.

There are permeable intervals at intermediate depths in the northern part of the field. In OH-1 and LCSH-5 these occur between elevations of 2800 and 3700 ft with a variety of thermal signatures (Figure 26). These have temperatures from 270 °F to as high as 320 °F. Depending upon the permeability, drilling costs, and other considerations this portion of the field might be utilized for either production or injection purposes.

Below an elevation of 1000 ft the hottest and deepest resource is found with temperatures ranging from 323 to 329 °F in well LCSH-5 to 337 °F in the Phipps #2 well (Figure 26). The OH-1 hole was not deep enough to reach this deeper resource but if it were to be deepened by a few hundred feet the temperature would most likely exceed 330 °F. The top of the deeper resource may be at least locally defined by the presence of overlying sedimentary rocks (Figure 10). The deeper resource in LCSH-5 seems to be confined to a sequence of firm lava flows at least 450 ft thick. In Phipps #2 the deeper resource is most likely in a rhyolitic unit at least 450 ft thick. Either unit could be present beneath OH-1. The individual fractures in the deep permeable interval have dips between 45 degrees and vertical. The LCSH-1a temperature data suggest that temperatures over 320 °F extend on the order of a mile east of the range front at depths below 3500 ft.

The similarity of the water chemistry throughout the field indicates that these various intervals are all part of the same geothermal system and should be well interconnected. Water level data obtained during the drilling of LCSH-5 suggests that the deeper intervals have lower pressures, which is a common geothermal occurrence. The chemical geothermometers from progressively deeper fluids tend to give progressively higher predicted subsurface temperatures. The Phipps #2 water suggests the geothermal system may have temperatures as high as 382 °F, or 45 °F hotter than measured. If these higher temperatures are present the exploration to date has been unsuccessful in locating them.

The core drilling to date has not been very successful in identifying specific faults. It is not clear if LCSH-5 and OH-1 were somehow located to miss any and all major normal faults in the local areas as indicated on Figure 18, or if there simply might not be discrete faults with large offsets. It seems highly unlikely event these faults are present but unrecognized in the cores. The fact that no obvious correlations could be made between the LCSH-5 and OH-1 cores indicates that the local subsurface geology is either more complex than that exposed on the east face of the Warner Mountains or is simply not amenable to readily obvious correlations.

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