

## A CASE STUDY OF THE GEOTHERMAL PROJECT AT CARSON LAKE, NEVADA

William L. Desormier  
Oxbow Power Services, Inc.  
Reno, NV 89502

### ABSTRACT

The Carson Lake thermal area is located about 18 km southeast of Fallon, Nevada. The western part of the thermal anomaly extends into the Naval Air Station located at Fallon. Although no natural surface-thermal features exist, an artesian-flowing drill hole produces hot water at 72°C.

The ground surface consists of Quaternary alluvial deposits and Tertiary volcanic rocks. The main part of the thermal anomaly is coincident with a complex horst block that is approximately nine square miles in aerial extent. Gravity, magnetics, self-potential and seismic reflection surveys assist in defining the structure and geology.

The thermal anomaly was discovered by shallow temperature-gradient drilling during the early 1970's. Subsequent shallow drilling, in the 1980's and 1990's, confirmed and further delineated the thermal anomaly. Five intermediate depth holes have been drilled within or on the flanks of the anomaly. The deepest hole, completed to a depth of 2119 meters, has a static temperature of 191°C and reportedly produced geothermal fluids. The most recent hole, located near the center of the thermal anomaly, was drilled to a depth of 427 meters. The disappointing result of over twenty years of exploration is that a commercial reservoir has yet to be discovered

### INTRODUCTION

The Carson Lake thermal area, located about 18 km southeast of Fallon, Nevada (Figure 1), was discovered by shallow temperature-gradient drilling conducted by Phillips Petroleum Company in 1973. Phillips drilled 28 temperature-gradient holes to a maximum depth of 150 meters covering an area of 5 to 6 townships.

The western part of the thermal anomaly extends into the Naval Air Station located at Fallon (Figure 2). In the late 1970's the U.S. Navy embarked on a program of evaluating selected facilities for their geothermal potential. Geothermal data from the Naval Air Station at Fallon (NASF) and some surrounding bombing ranges were first published by Bruce, 1980.

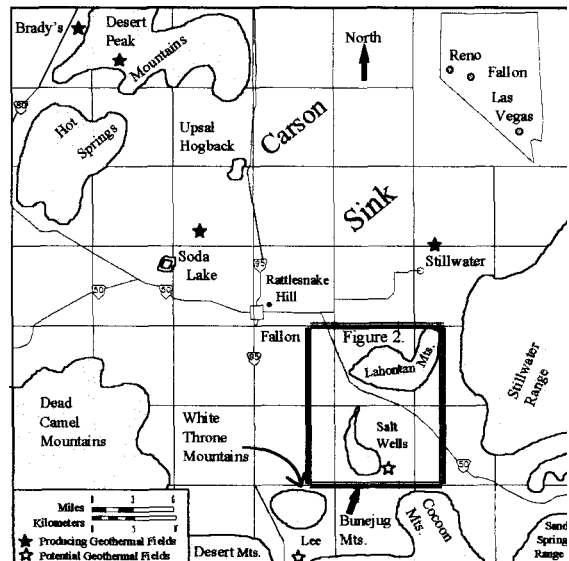


Figure 1. Location map showing the Carson Sink and Fallon area, a Nevada index map and a Figure 2 inset.

In 1980 and 1981 Unocal obtained leases on BLM acreage east of NASF and performed a significant amount of exploration work which was made public during the late 1980's. Unocal ran gravity and aeromagnetic surveys which culminated in the drilling of a 912 meter deep slim hole, 72-7 in mid 1981 (Figure 2).

Additional Navy data, including detailed gravity and ground magnetic surveys, part of an aeromagnetic survey, and results from a 616 meter observation hole (OH-1) were published by Katzenstein and Danti, 1982. In 1986 the Navy drilled OH-2, a core hole, to a depth of 1367 meters near the southeastern corner of NASF (Katzenstein and Bjornstad, 1987). During 1989 and 1990 Bxbow drilled 13 additional shallow temperature-radiant holes from 60 to 150 meters deep to further outline and define the thermal anomaly.

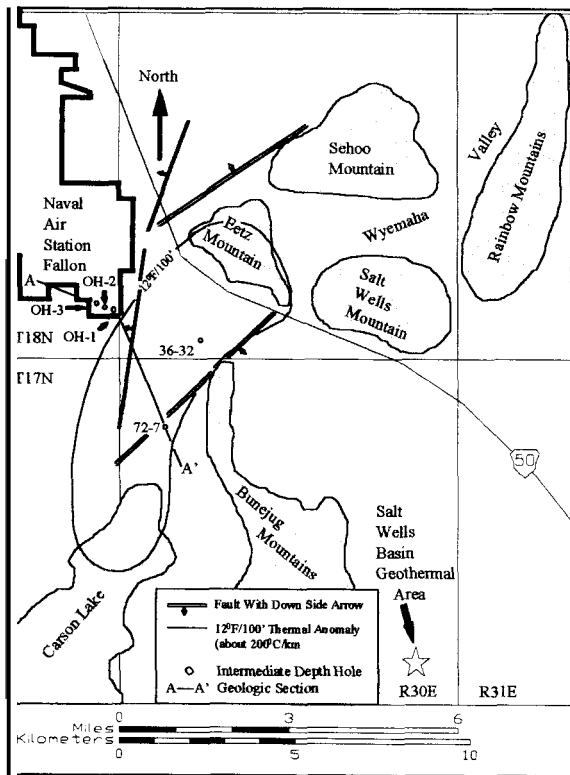


Figure 2. Carson Lake area showing proximity to the Naval Air Station at Fallon, the thermal anomaly, several fault traces, intermediate-depth drill-hole locations and geologic cross section A-A'.

In 1993, the Navy drilled OH-3, a production-type slim hole, to a depth of 2119 meters at a location northwest of hole OH-2 (Combs et al., 1995). During a short duration test the slim hole was lowered. However, the results reportedly were disappointing because of suspected cold water entry. The maximum static temperature of 191°C at 2119 meters suggests that a commercial reservoir at a similar temperature may be found in the area, perhaps at shallower depths.

During the early to mid 1990's self-potential surveys were conducted at the Carson Lake project, the previous geophysical data were reviewed and the results were published by Ross, et al., 1996. During Ross's review of the previous geophysical data the public domain gravity and aeromagnetic data were reprocessed and interpreted.

The residual Bouguer gravity results reported by Ross, et al., 1996, show a general north-south contour trend with a 20 mGal decrease from the east toward the center of the basin on the west. The westerly decrease in gravity reflects a rapid thickening of less dense alluvial and lacustrine sediments toward the center of the basin. Numerical modeling for some of the data defines steeply dipping surfaces that apparently reflect offset and erosion along high-angle normal faults which trend northeast to easterly.

The aeromagnetic data were integrated with the gravity data and were presented in the form of a structural interpretation map as Figure 5 in Ross, et al., 1996. The structures interpreted from the aeromagnetic data correspond closely with north and northeast trending structures interpreted from the gravity data. Several east-west structures were also inferred from the data.

The self-potential (SP) survey identified ten well defined anomalies within the area of the shallow thermal anomaly. Several of the SP anomalies occur near interpreted structures and structural intersections, and according to Ross, et al., 1996, may indicate upflow zones of thermal fluids to the near subsurface.

In 1996, 36-32, was completed to a depth of 427 meters near the center of the northern part of the thermal anomaly (Figure 2). Unexpected slow drilling due to harder, more competent rocks and other drilling problems contributed to only completing one test hole rather than the two to three holes originally planned. The test holes were to be used to site a slim-hole production well. The results from the intermediate-depth holes, including 36-32, were not sufficient to confidently site the slim hole. The well was to be jointly funded through the DOE cost share program in order to show the feasibility of discovering and proving geothermal reservoirs by drilling slim-hole production wells. After evaluating all of the results the decision was made to not proceed with additional drilling.

While drilling 36-32 warm artesian water flowed into the well bore from a depth of 62 meters. The character of the water and the qualitative geothermal imprint on the water confirm that a thermal system has been active within the area. The character of the water is similar to the 168°C resource at Stillwater and the 188°C resource at Soda Lake. The chemical character of the water and the 191°C measured at 2119 meters in OH-3 suggest a resource around 190°C can be expected, likely, at a shallower depth.

### REGIONAL GEOLOGIC SETTING

The Carson Lake project is located near the southeastern corner of the Carson Sink, the largest basin in northwestern Nevada (Figure 1). Within and along the margin of the Carson Sink geothermal reservoirs are currently being produced at Soda Lake (14 MW), Stillwater (11 MW), Desert Peak (10 MW), and Brady's (16 MW). Just northeast of the Carson Sink the Dixie Valley geothermal plant currently produces 56 MW. Two other promising geothermal areas, both located along the southeast margin of the Carson Sink, are Lee Hot Springs and Salt Wells Basin.

The existing fields produce from a wide range of rock types. Desert Peak and Dixie Valley produce primarily from Mesozoic metamorphic rocks with lesser production from siliceous and mafic Tertiary volcanic rocks. Brady's produces from mafic Tertiary volcanic rocks. Soda Lake produces from Tertiary siliceous volcanic rocks and from Quaternary sediments. Stillwater produces from Quaternary sediments and Tertiary basalts. Production from the Navy's OH-3 hole appears to be from Tertiary siliceous volcanoclastic rocks.

The stratigraphy in the Carson Lake region is described as five to six main units (Figure 3). The deepest unit is a crystalline basement of Mesozoic or Tertiary granitic rocks which was encountered in the Navy's OH-3 and in Anadarko's Salt Wells Basin well 14-36. The crystalline basement was not encountered in the shallower holes, 36-32, 72-7, OH-1 and OH-2. Above basement in OH-3 is a 46 meter thick Triassic (?) phyllite that is not encountered in the shallower holes. The next main unit in OH-3 is a sequence described as Tertiary siliceous volcanic rocks. A likely equivalent unit was described as Miocene rhyolite in 36-32 and a possible equivalent unit was described in 72-7.

Overlying the siliceous unit is a sequence consisting mainly of mafic to intermediate composition volcanic flows that are described as Tertiary basalts in 36-32. This sequence of rocks was encountered in all of the intermediatedepth holes except OH-1 which reportedly was completed in alluvial deposits.

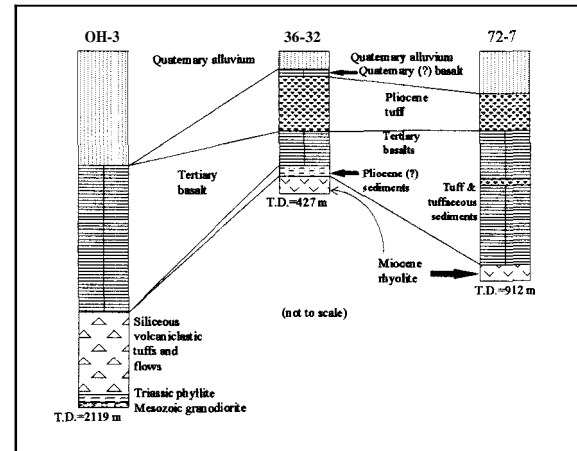


Figure 3. Stratigraphic comparison.

Overlying the Tertiary basalt in 36-32 is a sequence consisting mostly of tuff with some inter-layered basalt flows. An equivalent unit was described in 72-7. The tuff sequence generally has been included in the sedimentary sequence mapped by Willden and Speed (1974). Hence, it is not apparent from the lithologic descriptions of OH-1, OH-2 and OH-3 if an equivalent unit is present. The uppermost unit is unconsolidated Quaternary sediments that generally thicken towards the center of the basin, i.e. west and northwest of the Carson Lake area (Figures 1 and 2). The ground surface consists mainly of Quaternary alluvial deposits and Tertiary volcanic rocks, and except for the crystalline basement and the Triassic (?) phyllite, all of the above units crop out in the Lahontan Mountains just north and east of the immediate area.

The dominant structures in the Carson Sink area are north-south to northeast-southwest trending normal faults. Extensional faulting in the region is ongoing as demonstrated by the 1954 north-south to north-northeast trending surface ruptures on the east side of Rainbow Mountains about 10 km east of the Carson Lake anomaly.

Several north-northeast trending Quaternary **scarps** are present in Wyemaha Valley, which separates the Eetz, Seho, Salt Wells and Rainbow Mountains. The Wyemaha Valley and the above four mountains (Figure 2) form the Lahontan Mountains as shown on Figure 1.

**An** impressive north-northeast trending lineament as defined **by** a steep, narrow, valley splitting Eetz Mountain is approximately on strike with the thermal anomaly. This feature also was noted **by** Trexler, et al., (1981). While apparently not recent in age, this feature is the most conspicuous surface feature within the area of the Carson Lake thermal anomaly. Three intersecting lineaments at the southeast corner of NASF were reported **by** Geothermex, 1983. Of these three lineaments, the northeast-southwest trending one closely coincides with a subsurface normal fault delineated **by** seismic data (Monastero, Personal Communication, 1995).

Drilling to date suggests that "major" range-front faults do not occur at the base of the ranges such as Eetz or the Bunejug Mountains. However, the Navy ran seismic lines in the area and several normal faults are depicted in the area of NASF and Carson Lake (Monastero, Personal Communication, 1996). The apparent lack of recent **scarps** indicate they are not currently active. Some of these faults display the regional northeast-southwest trend and are generally down-dropped to the northwest (Figure 2).

#### STRATIGRAPHIC COMPARISON OF DEEPER HOLES

Most of the surface in the area of the thermal anomaly consists of Quaternary eolian and playa deposits with the immediately surrounding ranges dominated **by** various volcanic units. Prior to the drilling of 36-32 all of Oxbow's drilling had been to depths of 150 meters or less. Quaternary sedimentary deposits and volcanic sequences similar to the upper portion of 36-32 were encountered in the shallow temperature-gradient holes. The most striking geological aspect of 36-32 is the shallow depth to the harder more-consolidated volcanic rocks relative to the other deep holes in the area (Figure 3).

Five intermediate-depth holes have been drilled within or on the **flanks** of the anomaly. The lithologies in 36-32 and two other holes, OH-3 and 72-7, are compared in Figure 3.

Hole 36-32 was drilled through a 2 meter thick sequence of Quaternary dune sand and silt. Beneath this thin veneer is a 53 meter thick sequence, consisting mostly of gray clay, believed to be Quaternary Lake Lahontan deposits. The Quaternary alluvial sequence is thinnest in 36-32 (**55** meters), intermediate in thickness in Unocal's 72-7 (171 meters), and thickest in the Navy's OH-3 (687 meters).

Underlying the lacustrine deposit in 36-32 is a 21 meter thick dark-gray basalt sequence. The basalt has a similar appearance to Quaternary basalt cropping out in the Fallon area, some 18 km to the northwest, therefore, is considered to be of Quaternary age. The basalt in 36-32 is a minor unit that may or may not have an equivalent in 72-7 or OH-3. It is not apparent from the lithologic descriptions of the two other holes if an equivalent unit is present.

Underlying the Quaternary basalt in 36-32 is a sequence consisting of brown to reddish-brown **tuff** with some inter-layered basalt flows. This sequence of rocks crops out just north and east of the immediate area and generally has been included in the sedimentary sequence of Pliocene age mapped by Willden and **Speed** (1974). The Pliocene sequence is 165 meters thick in 36-32, the equivalent unit is 146 meters thick in 72-7 and apparently absent from OH-3.

Underlying the **tuff** unit in 36-32 is a sequence consisting mainly of basalt flows with some inter-layered **tuff**. In OH-3 and 72-7 the unit consists mostly of intermediate to mafic volcanic flows and tuffs, and in the case of 72-7 some more felsic intervals. The Tertiary unit is 103 meters thick in 36-32, 530 meters thick in 72-7, and 862 meters thick in OH-3.

Below the Tertiary basalt, in 36-32, a sedimentary sequence consisting mainly of volcanic-origin gravel and sand with some clay was encountered. The 31 meter thick sedimentary sequence is assumed to be of Pliocene age because of its' association with the overlying volcanic sequence. The Pliocene sedimentary deposit in 36-32 is a minor **unit** that may or may not have an equivalent in 72-7 or OH-3. It is not apparent from the lithologic descriptions of the two other holes if there is an equivalent unit.

At a depth of 375 meters a light to medium-gray rhyolite was encountered in 36-32. A similar rhyolite crops out just to the north and has been identified as Miocene age by Willden and Speed (1974). The rhyolite encountered in 36-32 continues to total depth, therefore, has a minimum thickness of 52 meters. An equivalent rhyolite continues to total depth in 72-7 with a minimum thickness of 65 meters. A Possible equivalent unit in OH-3 described as undifferentiated Tertiary siliceous volcanoclastic tuffs and flows is 493 meters thick.

In OH-3 a 46 meter thick Triassic (?) phyllite underlies the siliceous volcanic rocks. OH-3 was completed in Mesozoic (?) granitic rocks. The phyllite and granitic rocks were not encountered by any of the shallower holes.

The surface trace for several subsurface normal faults bounding the area of the thermal anomaly and Eetz Mountain are shown on Figure 2. The faults partially delineate a rhomboid-horst block in the area of the thermal anomaly and Eetz Mountain. As described above, the stratigraphic units in 36-32 were encountered at shallower depths relative to the units in the deep holes OH-3 and 72-7. A cross section, A-A', depicting the above observations was constructed through the intermediatedepth drill holes (Figures 2 and 4).

#### TEMPERATURE COMPARISON OF DEEPER HOLES

The temperature profiles of selected holes are shown on Figure 5. The lower portion of OH-2 has a conductive temperature gradient of  $75^{\circ}\text{C}/\text{km}$ , and a maximum temperature of  $154^{\circ}\text{C}$  at the bottom hole depth of 1367 meters. While temperature data for OH-3 was not available to this author, the profile reportedly is similar to that of OH-2 over the depth interval shown.

OH-1 has a conductive near-surface gradient, a minor temperature reversal at the depth interval of 327-366 meters, a lower hole temperature gradient of  $92^{\circ}\text{C}/\text{km}$ , and a maximum temperature of  $97^{\circ}\text{C}$  at the bottom hole depth of 616 meters (Figure 5). The temperature profile of OH-1 apparently reflects hot water flow in the 327-366 meter interval, suggesting the well bore is near a hot aquifer or a fault intersection (Figures 4 and 5).

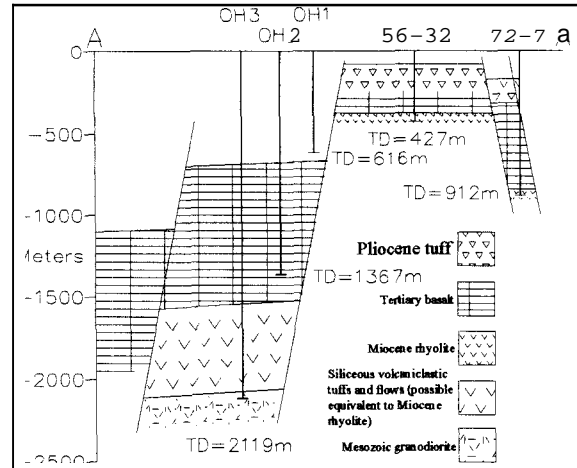


Figure 4. Geologic cross section A-A'.

Above a depth of 305 meters the temperature gradient of 72-7 is  $256^{\circ}\text{C}/\text{km}$ . Between 305 and 366 meters the gradient is intermediate (Figure 5) and below 366 meters the temperature gradient is nearly isothermal at  $0.5^{\circ}\text{C}/\text{km}$ . The bottom hole temperature of 72-7 is  $131^{\circ}\text{C}$ . The temperature profile for the lower portion of 72-7 possibly is a bore hole effect, e.g., bore hole flow between aquifers or bore hole convection. The 305-366 meter interval in 72-7 is at a similar depth to the suspected aquifer in OH-1. The 305-366 meter zone suggests the 72-7 well bore is also near a hot aquifer or a fault intersection (Figure 4).

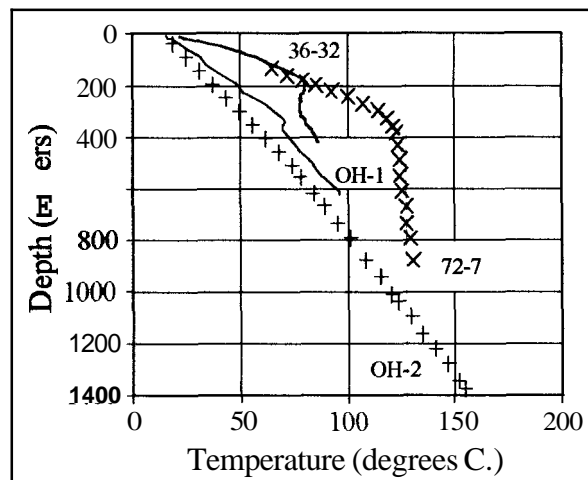


Figure 5. Temperature profiles of selected holes.

The 36-32 temperature profile shows a high temperature gradient for the upper portion of the hole, followed by a temperature reversal at a depth of 191-252 meters, and lastly a recovery to a near-normal temperature-gradient of  $55^{\circ}\text{C}/\text{km}$ , attaining a maximum bottom hole temperature of  $88^{\circ}\text{C}$  (Figure 5). The reversal in 36-32 occurs at a higher temperature ( $81^{\circ}\text{C}$ ), than the reversal in OH-1 ( $71^{\circ}\text{C}$ ) and at a lower temperature than the suspected aquifer in 72-7 ( $117\text{-}122^{\circ}\text{C}$ ). Another difference between the reversal in 36-32 is that it occurs at a shallower depth (191-252 meters), than the disturbed zones (about 305-366 meters) in OH-1 and 72-7.

## DISCUSSION

The shallow depths of the 36-32 lithologic units relative to the units in holes OH-3 and 72-7 suggests that 36-32 was drilled into a horst block (Figure 4). The normal faults bounding the area of the thermal anomaly and Eetz Mountain partially delineate the rhomboid-horst block (Figure 6). The self-potential map presented by Ross, et al., 1996 generally shows high SP values in the horst block area and low SP values north and southeast of the horst block. In the southeast area of the SP map (Figure 7 in Ross, et al., 1996) the change from high to low values is well defined and closely corresponds in location and trend to the northeast-southwest horst bounding fault as delineated by seismic data and shown on Figures 6 and 7.

A closer examination of Figure 6 suggests the horst block is more complex than indicated by the above described bounding faults. The northern lobe of the 150 meter isothermal map is elongated in a direction parallel to the Eetz Mountain front and transverse to the normal faults shown on Figure 6. The shape for this part of the thermal anomaly may reflect hot water upwelling within a transverse fault. The transverse fault likely is related to the Eetz Mountain uplift relative to the immediate area of 36-32. In the area of the transverse fault there is a more subtle but definite change from high to low SP values (Figure 7 in Ross, et al., 1996). The trend of this SP change is more or less parallel to the Eetz Mountain front and to the suspected transverse fault.

The minor temperature reversal in OH-1 (Figure 5) reflects hot water flow in the 327-366 meter zone

suggesting the well bore is near an aquifer or a fault intersection. The hot water apparently rises along the western horst bounding fault and flows down the hydraulic gradient towards the west and likely towards Carson Lake in the south (Figure 7). The flow must be minor because it is not apparent in hole OH-2 located just to the northwest of OH-1. It is unlikely that such minor flow could cause the large Carson Lake thermal anomaly.

The unusually low temperature gradient of  $0.5^{\circ}\text{C}/\text{km}$  for the lower portion of 72-7 is likely due to flow between bore hole and fault intersections one of which is depicted in Figures 4 and 6. The 305-366 meter zone in 72-7 also suggests the well bore may be near an aquifer. The character of the temperature disturbance in this zone (Figure 5) only allows minor flow. Hot water apparently rises along a fault east of the horst block (near 72-7) and flows down the hydraulic gradient towards the southeast and possibly southwest (Figure 7). Again, it is unlikely that such minor flow could cause the large Carson Lake thermal anomaly.

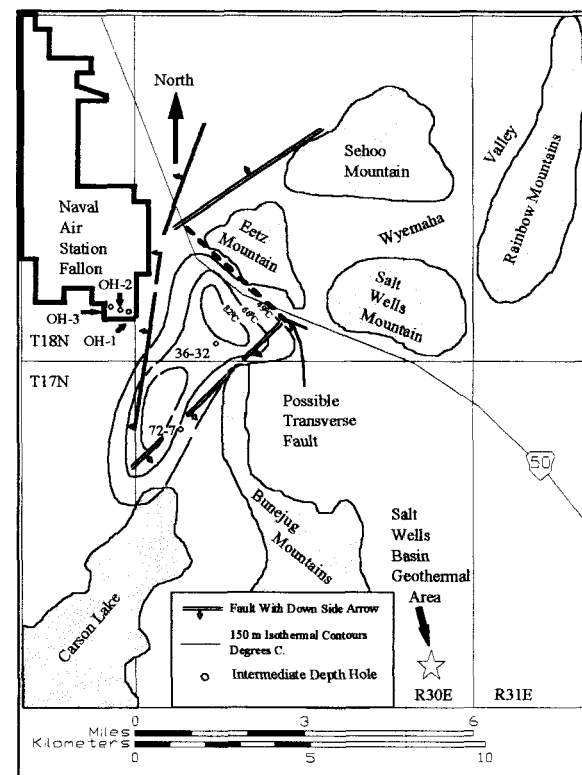


Figure 6. 150 meter depth isothermal map and surface fault traces.

temperatures in 36-32 are higher at shallow depths (<191 meters) than the other intermediate-depth holes (Figure 5). The temperature reversal in 36-32 is of a greater magnitude and occurs at a higher temperature (81°C) than the reversal in OH-1 (71°C). These observations suggest that 36-32 is either closer to a hotter-larger source of near-surface water than holes OH-1, OH-2 and OH-3, or possibly located in an area of higher permeability and higher aquifer flows (Figure 7).

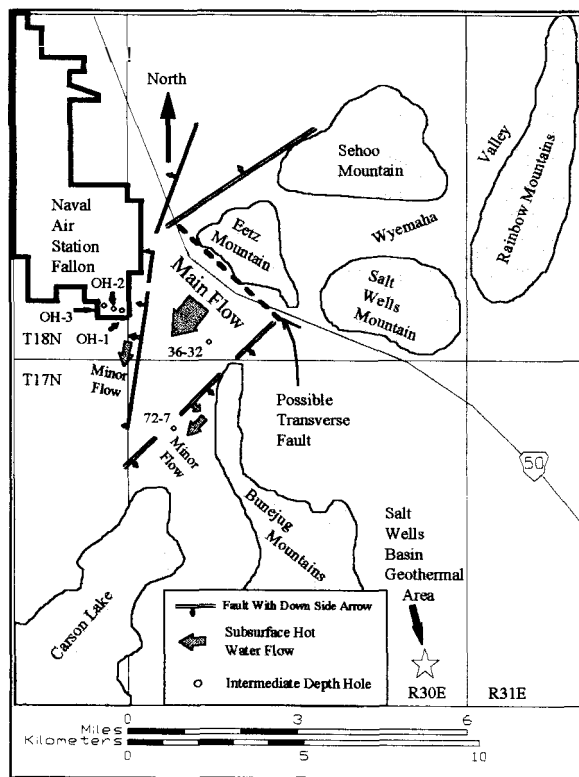


Figure 7. Subsurface hot water flow directions, possible transverse fault and horst block delineated by normal faults.

The shape of the thermal anomaly and high temperature gradients of shallow holes (not shown) suggest the hotter-larger flow source likely is from the north and may even be from a fault transverse to the horst bounding faults (Figure 7). The 150 meter isothermal map supports this concept (Figure 6), and also shows a separate, but related, heat source in the south near the western and eastern horst bounding faults in the vicinity of hole 72-7. The northern heat source combined with the southern heat source likely causes the large Carson Lake thermal anomaly.

## SUMMARY AND CONCLUSIONS

Unexpected hard drilling and other drilling problems contributed to only completing one test hole at Carson Lake rather than the two to three holes originally planned. The shallow depth to the harder, more-consolidated volcanic rocks relative to the other intermediate depth holes in the area and other structural data indicate that 36-32 was drilled into a complex horst block. Several subsurface normal faults bounding the area of the thermal anomaly and Eetz Mountain are seen on reflection seismic surveys conducted by the U.S. Navy.

Additional evidence for the existence of these horst-bounding normal faults are seen in the Bouguer gravity, the aeromagnetic, and the self potential maps (Ross, et al., 1996). Several of these surveys partially define the rhomboid outline of the horst block and provide evidence for the existence of a transverse fault in the area southwest of Eetz Mountain. The shallow temperature data reflect the horst-bounding normal faults and the transverse structure.

Minor amounts of hot water apparently rise along the western horst bounding fault and flow down the hydraulic gradient towards the west and likely toward the south. Minor amounts of hot water also rise along a fault east of the horst block and flow down the hydraulic gradient toward the southeast and possibly southwest. It is unlikely that such minor flows could cause the large Carson Lake thermal anomaly.

The artesian-flowing drill hole reported by Bruce, 1980 and the artesian flow into hole 36-32 are evidence for hot water flow in the area. The character of the water is very similar to the resources at Stillwater and Soda Lake. The chemical character of the water and the 191°C measured at 2119 meters in OH-3 suggest a resource around 190°C can be expected, likely, at a shallower depth.

Temperatures in 36-32 are greater at shallow depths than other intermediate depth holes, the temperature reversal is of a greater magnitude and occurs at a higher temperature than the reversal in OH-1. These observations suggest that 36-32 is closer to a hotter, possibly larger source of near-surface water than holes OH-1, OH-2 and OH-3. The shape of the thermal anomaly and high temperature gradients of shallow holes suggest a flow source from the north, i.e. from the suspected transverse fault.

The 150 meter isothermal map supports this concept and also shows a separate, but related heat source in the south. The southern heat source is near the western and eastern horst bounding faults in the vicinity of hole 72-7. The northern heat source combined with the southern heat source forms the large Carson Lake thermal anomaly.

The disappointing results of over twenty years of exploration are that a commercial reservoir has yet to be discovered. The data suggest that a significant resource can be encountered at modest depth in the area of the Carson Lake project. The leases will be maintained until the market becomes more favorable for geothermal energy. During 1997, the Navy plans to run electrical logs in OH-3 and 36-32 to gain a better understanding of the geology, structure and geothermal resource. As the market improves a power sales agreement may be pursued.

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