GEOTHERMAL DEVELOPMENT
in KLAMATH FALLS, OREGON

Prepared For The
Oregon Department of Energy
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ACKNOWLEDGEMENTS

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INTRODUCTION

Since the turn of the century, the geothermal resource in Klamath Falls, Oregon, has been used for domestic hot water, space heating and process heat. Today, more than 400 thermal wells supply heat to homes, schools and commercial establishments -- the largest geothermal application of its kind in the United States.

Geothermal resource development in Klamath Falls increased dramatically with completion of Phase I of the city geothermal heating system in 1982. Phase I can supply 14 government office buildings and 127 homes in two low-income residential areas with heat and hot water. However, Phase I has not been used because of a lack of historical data regarding long-term sustainability of the resource. This lack of technical knowledge has resulted in conflicts over how to use the resource. This report describes both the cumulative scientific knowledge and the conflicts and groups involved, and offers a comprehensive view of geothermal development in Klamath Falls.

RESOURCE UTILIZATION

Uses

In 1974, the first scientific estimate of total geothermal heat use in the Klamath Falls area was conducted. The results are shown in Table 1. Since the 1974 estimate, new geothermal applications have been initiated but energy estimates are unknown. The largest single application capable of serving the most people in the Klamath Basin is the inoperative city district heating system.

City District Heating System

In January 1977, formation of a city-wide geothermal heating district was proposed in a feasibility study by the consulting firm, LLC, (Paul Lienau, John Lund and Gene Culver, in cooperation with the Geo-Heat Center at Oregon Institute of Technology). Before seeking money for the project, the City of Klamath Falls surveyed public opinion. A newspaper and city household survey during development of the comprehensive land-use plan showed that a majority of respondents approved a central geothermal district heating system.

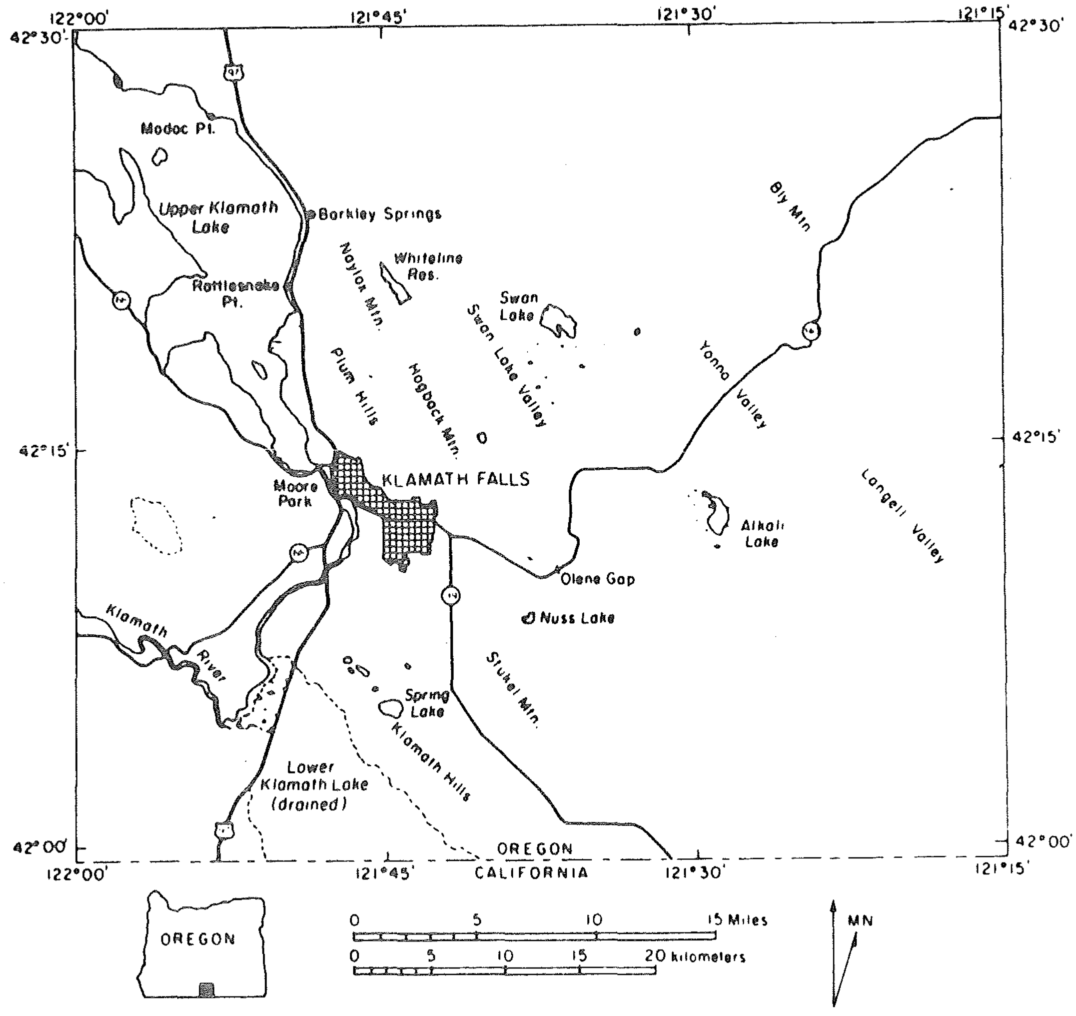


Figure 1 Klamath Falls area and major geographical features (O'Brien and Benson, 1980)

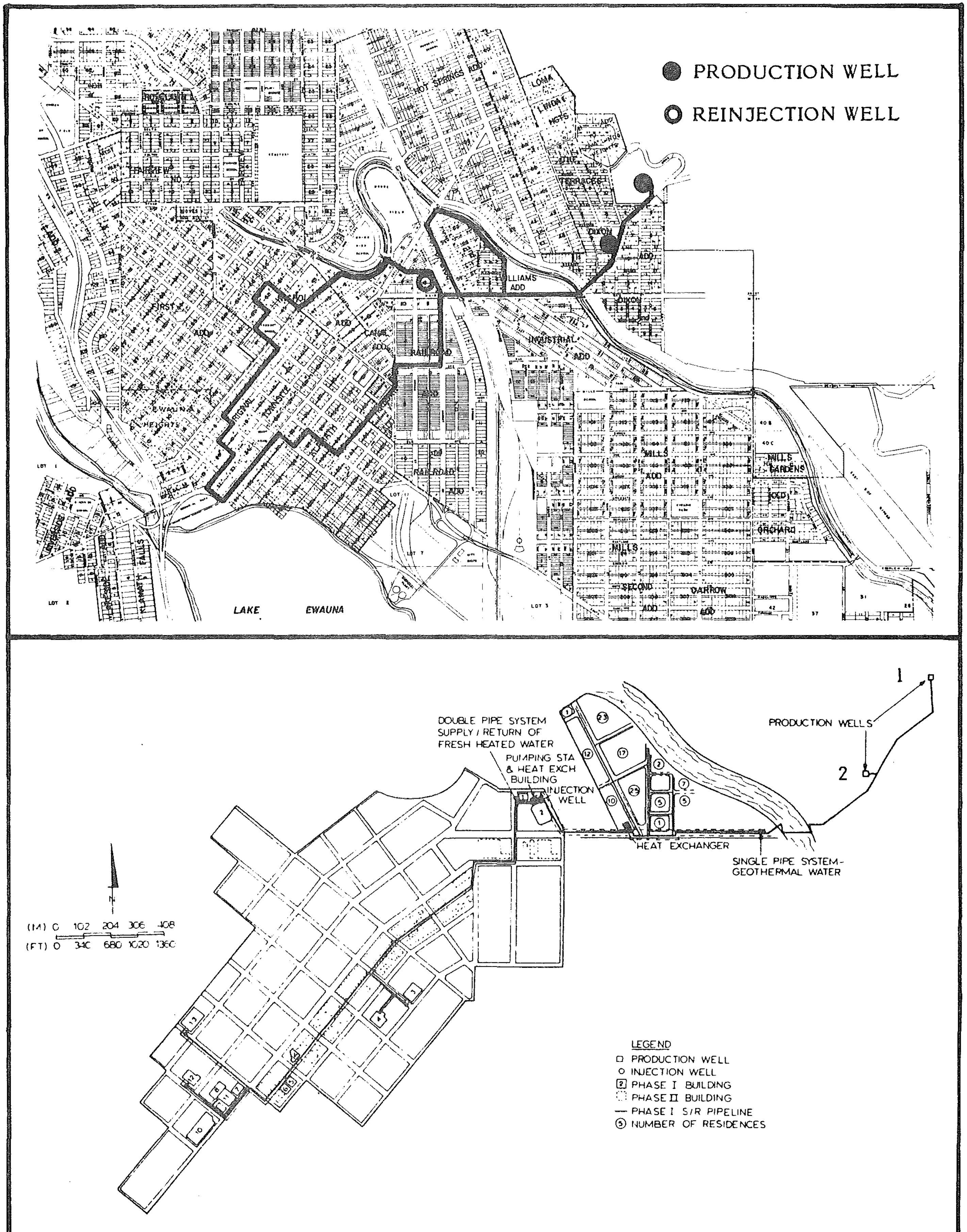


Figure 2 Proposed area to be heated by Phase I (Gunther, 1982)

Table 1 Klamath Falls geothermal heat utilization (Lund, et al., 1974)

468 residences at 1.75 Btu/year/each	=	819 x 10^8 Btu/year
11 apartments at 9 x 10^8 Btu/year/each	=	100 x 10^8 Btu/year
1 municipal swimming pool at 3 x 10^8 Btu/year	=	3 x 10^8 Btu/year
1 hospital at 65 x 10^8 Btu/year	=	65 x 10^8 Btu/year
3 churches at 12 x 10^8 Btu/year	=	37 x 10^8 Btu/year
8 commercial establishments	=	200 x 10^8 Btu/year
7 schools at 29 x 10^8 Btu/year/each	=	200 x 10^8 Btu/year
1 college (OIT) at 250 x 10^8 Btu/year	=	250 x 10^8 Btu/year
Total 500 locations using 400 wells	=	1,674 x 10^8 Btu/year

Funding for a district heating system was awarded by the U.S. Department of Energy in 1978. Construction of Phase I of the heating system began in 1979. Phase I, requiring 700 gpm of 104°C (220°F) geothermal fluid, is designed to supply space heating and hot water to 14 government office buildings in the downtown area and to 127 homes in two low-income residential areas. This phase was planned as the first of six phases that initially would supply heat to the central business district and later would expand to serve the entire urban area of approximately 20 square miles and 35,000 persons. Phase I, consisting of two production wells, one reinjection well and a distribution system, was completed in Fall 1982.

Low Temperature Geothermal Resource Management

Though management of ground water appropriation is predominantly the responsibility of the Oregon Water Resources Department (WRD), the City of Klamath Falls was concerned that the small staff at WRD could not give local reservoir assessment and management the attention it warrants. With Oregon Department of Energy funding in 1980, the city contracted with Eliot Allen and Associates to author the "Preliminary Model Ordinance for Municipal Geothermal District Heating and Reservoir Management". In addition to presenting a comprehensive administrative scheme, the ordinance presents a case for joint management of the geothermal resource between WRD and the local municipality. Currently, no such authority for joint management has been granted Klamath Falls nor any other city by WRD. The ordinance has been studied by the University of Oregon Bureau of Government Research, the Earl Warren Legal Institute of Berkeley, California, the U.S. Conference of Mayors in Washington, D.C. and the National Conference of State Legislatures and is considered a prototype for planning in states that have geothermal resources.

The City devised a preliminary administrative system for the proposed heating district using authority from ORS Chapter 523 "Geothermal Heating Districts". These statutes allow cities, counties or private corporations to operate a geothermal heat distribution system for consumers much as a municipal water district supplies water. Under ORS 523, an incorporated city is empowered to provide geothermal heating district service by a home rule charter or by a vote of the people if the city has no home rule charter.

Because it has a home rule charter, the City did not need a charter amendment to authorize formation of the geothermal heating district. However, to reinforce district formation, the City offered a charter amendment to voters. During a special election in March 1982, voters, apparently worried about negative impacts to the aquifer, rejected the charter amendment.

Three months later, an initiative filed by Citizens for Responsible Geothermal Development (CRGD) was approved by voters. The measure prevents use of the completed geothermal heating system by prohibiting withdrawal of geothermal waters unless returned undiminished in volume to the *same* well.

Most of the concern came from homeowners in a residential area where about 500 homes use the resource for space and water heating. Most of these homes are heated with downhole heat exchangers in individual private wells. In Klamath Falls a typical downhole heat exchanger works by circulating city water through a "U"-shaped pipe (locally called a "coil") in a thermal well. No withdrawal of water from the well is necessary. The citizens feared that the City's heating system would jeopardize their heating wells by withdrawing both water and heat.

The reasons for the electorate's reaction to the city heating plan are complex. It appears a major factor may have been lack of sufficient citizen participation in the planning process (Gunther, 1982 and Gardner, et al., 1981). The City Planning Commission had regular monthly briefings with citizens before completion of Phase I. However, these meetings ceased in late 1979. Consequently, citizen involvement was minimal during detailed design stages. The Citizen's Committee, CRGD, was concerned at the distance between the production and reinjection wells and with effects of pumping if reinjection was not near the point of withdrawal (Gunther, 1982).

The citizen initiative was challenged by WRD in the Klamath County District Court. Because the initiative virtually precludes use of the geothermal resource except through downhole heat exchange (where there is no withdrawal of water), WRD claimed that the initiative, in effect, regulates the appropriation of ground water resources. WRD contended that such local regulation is an infringment of WRD's exclusive statutory authority to manage ground water. However, the initiative was upheld in Circuit Court. The court ruled that the State has not preempted local governments from adopting regulations and that the local ordinance did not conflict with any state regulations for ground water resources. WRD has taken the case before the Oregon Court of Appeals. A judgment is expected in late 1984.

Current Status

In the meantime, positive steps have been taken to resolve the conflict by independent citizens, City Council and the Citizen's Committee. The Klamath County Chamber of Commerce serves as mediator and, in January 1983, enlisted the help of U.S. Geological Survey (USGS) hydrologist, Edward Sammel.

Sammel has studied the Klamath Basin extensively and has long stressed the need for a sustained aquifer test of the production and reinjection system. He concluded that without long-term data there was no way to accurately determine how Phase I would affect the geothermal reservoir. Supported by the Chamber and the City, Sammel organized all groups for a long-term data-gathering and well-monitoring program that began in March 1983. Funding from the U.S. Department of Energy launched tracer tests and an intensive eight-week aquifer test that began in May 1983. The tests are to determine the extent and sustainability of the geothermal resource so citizens can decide how to use it most effectively. Test procedures and preliminary results are described in later sections of this report. Final results are published in USGS Open-File Report 84-146.

RESOURCE CHARACTERIZATION

The following scientific knowledge of the Klamath Falls geothermal system is from published and unpublished works of many scientific investigators who have studied the area.

Generalized Klamath Basin Geology

* Klamath Falls is within a complex NW-trending graben immediately east of the Cascade Mountains in south-central Oregon. Structurally, the area is typical of the Basin and Range Province. There is an abundance of nearly vertical normal faults. The major fault system trends N25-35°W, although there are also N-S and NNE-SSW trending faults. The geothermal resource is concentrated on the east side of the city along the scarp of the fault or faults forming the eastern boundary of the graben.

* There are two important bed rock units in the Klamath Falls area. The uppermost is a thick sequence of lacustrine and fluvial tuffaceous siltstone, sandstone, diatomite, basaltic tuff and breccia, with rarer intercalated thin basalt flows (Peterson and McIntyre, 1970). This unit is often referred to as the Yonna Formation. Although its

thickness beneath the basin floor largely is unknown, in adjacent ridges it ranges from a few feet to at least 850 feet thick. Individual beds and flows within the Yonna Formation vary considerably in thickness and distribution. Correlation between rock units is difficult even over short distances.

* The Yonna Formation unconformably overlies a thick sequence of Pliocene basalt flows. Although not exposed in Klamath Falls, these basalts are noted in drillers' logs and are exposed south and east of the area. They are thought to be correlative with extensive basaltic lavas forming the Modoc Volcanic Plateau in Northern California. Figure 3 shows the regional geology and structure.

Conceptual Model of the Hydrothermal System

* The Klamath Falls geothermal reservoir is a shallow, liquid-dominated, fault-charged hydrothermal system.

* Though an abundance of data have been collected in the area, there is argument over details pertaining to the basic conceptual model. The stratigraphy and faulting of the Yonna Formation and Pliocene basalts are complex. Additionally, hydrologic interpretation has been difficult because of a lack of accurate lithologic logs, meaningful temperature profiles and, until recently, isotopic analyses and long-term aquifer testing.

* Edward Sammel postulates a system whereby deeply-circulated thermal water of the Pliocene basalts moves upward along the principal hot water bearing faults discharging thermal water laterally into permeable strata of the Yonna Formation. The upward movement primarily is a function of the system's artesian nature and the relatively low density of the warm water. The thermal water cools as it moves away from the fault. It mixes with non-thermal ground water of recent meteoric origin found in the upper rock units (Sammel, 1980, 1983).

* The Yonna Formation and underlying basalts appear hydraulically connected through fractures. Because of the fractures, the two bedrock units probably are one hydrologic continuum (Sammel, 1983).

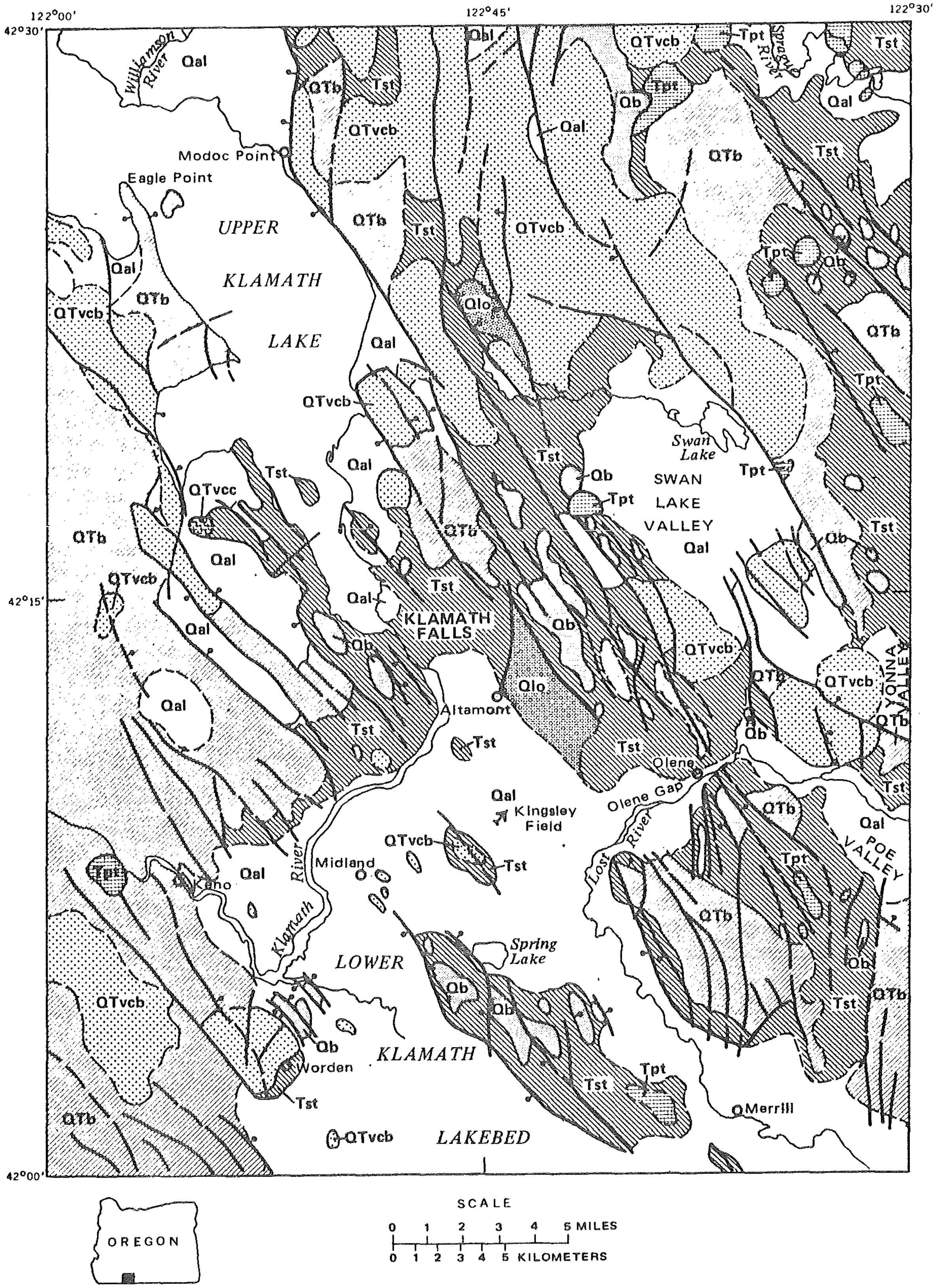
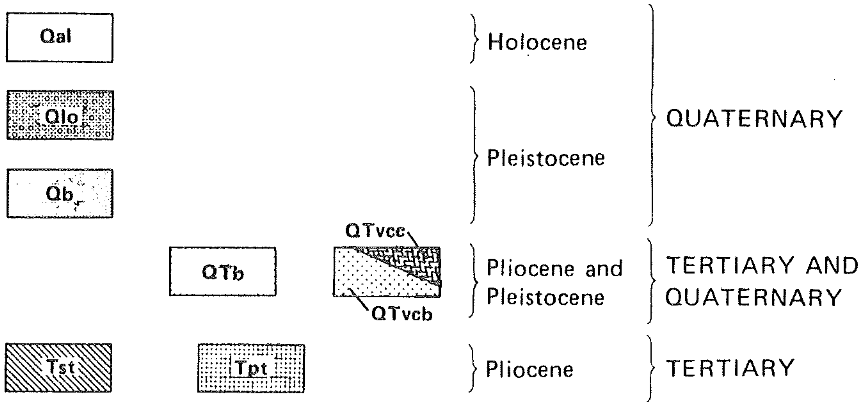


Figure 3 Geology of the Klamath Falls area (Sammel, 1980, modified from Peterson and McIntyre, 1970)

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Qal	Alluvial deposits including diatomite and peat
Qlo	Fluvial terrace and lacustrine deposits
Qb	Basalt flows
QTb	Basalt flows, pyroclastic breccia, and agglomerate, of uncertain stratigraphic relationships. May in part be contemporary with Tst and Qb
QTvcb	Basaltic eruptive centers
QTvcc	Basaltic cinder cones
Tst	Lacustrine and fluviatile tuffaceous siltstone, sandstone, ashy diatomite, basaltic tuff and breccia, few thin basalt flows (=Yonna Formation)
Tpt	Maar and tuff-ring deposits

——— - - - - Contact – Dashed where approximate

———•——— - - - - Fault – Dashed where approximate. Ball on downthrown side

Figure 3, continued

Ground Water and Heat Flow

* Generally, ground water temperatures are highest in a narrow belt on the east side of the city along the scarp of the normal fault or faults forming the eastern boundary of the Klamath Falls graben. This is known as the hot well or hillside area.

* The potentiometric surface of the reservoir primarily slopes to the southwest. The surface probably represents the composite head of the fracture-related, hydraulically connected Yonna and basalt aquifers.

* Generally, temperature profiles obtained from wells in the Klamath Falls hillside area indicate upward-flowing thermal water in the well bore and lateral flow in adjacent formations (Sammel, 1980). Figure 4 shows a profile of the Klamath Falls City Well 2. The profile indicates conductive heat transfer in the top 200 feet, typical convective heat transfer from 200-250 feet and downhole heat flow below 250 feet (O'Brien and Benson, 1980). The profile has been explained as fault recharge to an aquifer from 200-250 feet with subsequent lateral transport of the hot water into the aquifer and conductive heat loss to overlying and underlying strata (Bodvarsson, et al., 1981).

* In general, temperature profiles in Klamath Falls do not offer meaningful data regarding size, shape or depth to the heat source. Most wells have minimal casing or the casing is perforated allowing water to commingle among permeable strata via the borehole. Commingling makes differentiation between fluid flow within the borehole and fluid flow within the formation difficult.

* The heat source for the thermal fluids is thought by some researchers to be a function of deep circulation of water in a region of relatively normal geothermal gradient. Though deep circulation alone could account for the observed thermal anomalies, the possibility of contribution from an igneous source cannot be discounted.

* The supply of heat to the reservoir appears constant. Fluctuations in fluid temperatures most likely are due to heat extraction, seasonal water level changes, reinjection, and mixing of water from different strata induced by well construction.

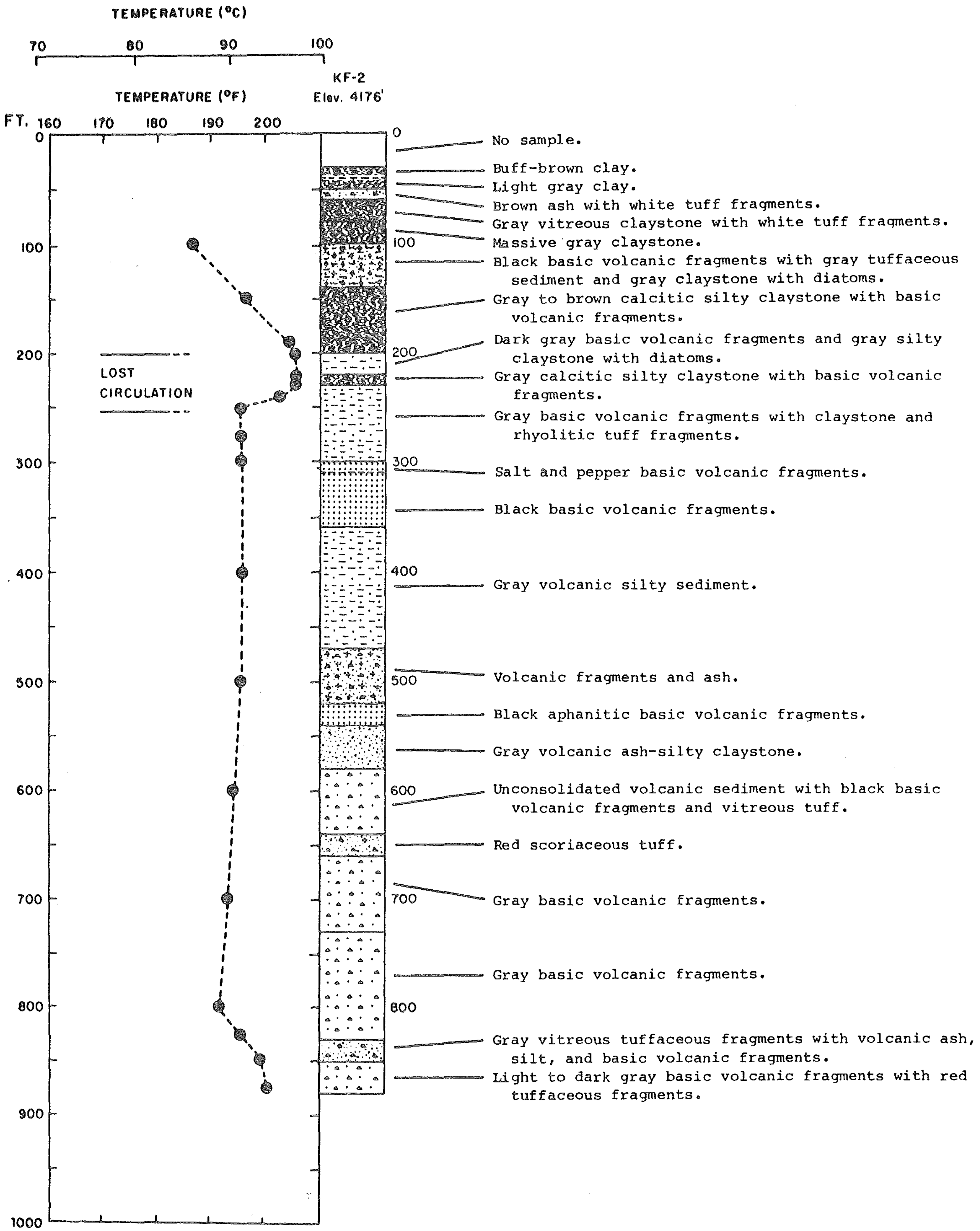


Figure 4 Temperature profile and lithology of Klamath Falls City Well 2 (O'Brien and Benson, 1980)

- Density of water increases as heat is extracted. Extraction of heat and water is responsible for seasonal water level fluctuations of as much as 11 feet (Benson, 1984).

- The heat content of the hot well area of Klamath Falls is estimated to be 2.7 x 10^{17} calories or 1.1 x 10^{18} Joules. This assumes the reservoir temperature is 150°C (302°F), the reservoir is 1 Km thick above a depth of 4 Km, the specific heat of the reservoir rocks is 0.6 cal/cm^3°C, and that the reservoir area is 1.25 miles wide and 6.5 miles long (Sammel, 1980, 1983).

Recharge

- The source of recharge to the system is thought to be through deep circulation of meteoric water that percolates into the porous, lava-covered upland areas surrounding the Klamath Falls graben complex. Though discharge of thermal fluids appears to take place along specific channels associated with the major faults, recharge is thought to occur as slow diffuse seepage throughout the faulted and fractured graben complex (Sammel, 1980).

- There are three areas of hot water discharge in the Klamath Falls Basin: 1) the hot well area in Klamath Falls, 2) a hot spring area to the southeast at Olene Gap and 3) a hot well area to the south near Klamath Hills. Assuming a radius of 25 miles from the center of the triangle formed by these three hot well areas, Sammel (1980) calculates that average annual precipitation is 2.4 x 10^6 acre-feet. From this amount, 2.1 x 10^6 acre-feet per year is estimated to be lost through evapotranspiration. This leaves 0.3 x 10^6 acre-feet per year available for runoff, soil moisture and recharge (Sammel, 1980).

- Ground water flow into the lower Klamath Lake Basin from upper basins may be as much as 170,000 acre-feet per year. A deep regional flow system may also be present bringing unquantified amounts of additional ground water into the area from the High Cascades (Sammel, 1980).

- In the absence of long-term water level data, it is unclear how quickly the hydraulic system responds to precipitation.

Chemistry

* Hot water discharge in Klamath Falls ranges from 61 to 120°C (141 to 248°F) and is mildly alkaline. Hot waters are high in sodium, silica, sulfate and chloride and low in magnesium and bicarbonate relative to cooler waters of the area. Total dissolved solids are generally no more than 1000 milligrams per liter (Sammel, 1980). Figure 5 shows the average chemical quality for hot and cold waters in the Klamath Basin.

* The chemistry of water from the three hot well areas in the Klamath Basin indicates the hot water has equilibrated in nearly identical rocks at similar depths and temperatures. Though chemistries are similar, evidence suggests these three reservoirs are distinct. Additionally, oxygen and deuterium isotope ratios and the sulfate-oxygen isotope geothermometer imply separate sources of recharge water for the three areas (Sammel, 1980).

* Estimated reservoir temperatures, calculated for silica and Na-K-Ca geothermometers and for silica mixing models, range from 65 to 184°C (149 to 363°F). Isotopic data were collected during the 1983 long-term aquifer test by the USGS. Preliminary interpretations suggest that at depth, the reservoir is probably 175°C (350°F) or hotter (Truesdell, 1984). Final interpretations are expected in the 1984 test report.

Well/Resource Interaction

* Most heat extraction in the hot well (hillside) area of Klamath Falls is obtained by circulating city water through downhole heat exchangers in thermal wells. No withdrawal of water is required. Single wells frequently supply two or more residences. In the Klamath Falls artesian (urban) area, west of the hillside area, most heat extraction involves diverting hot water from the well through an above-ground heat exchanger. The effluent is then eliminated by disposal to the storm sewer or reinjection to a suitable aquifer.

* Most residential wells used for domestic heating and hot water range from 90 to 900 feet deep, with 200 to 300 feet being most common. Commercial uses, requiring greater heat output, may need well depths in the range of 1000 to 1300 feet (Culver, et al., 1981). However, deeper wells are not necessarily more productive (Sammel, 1983).

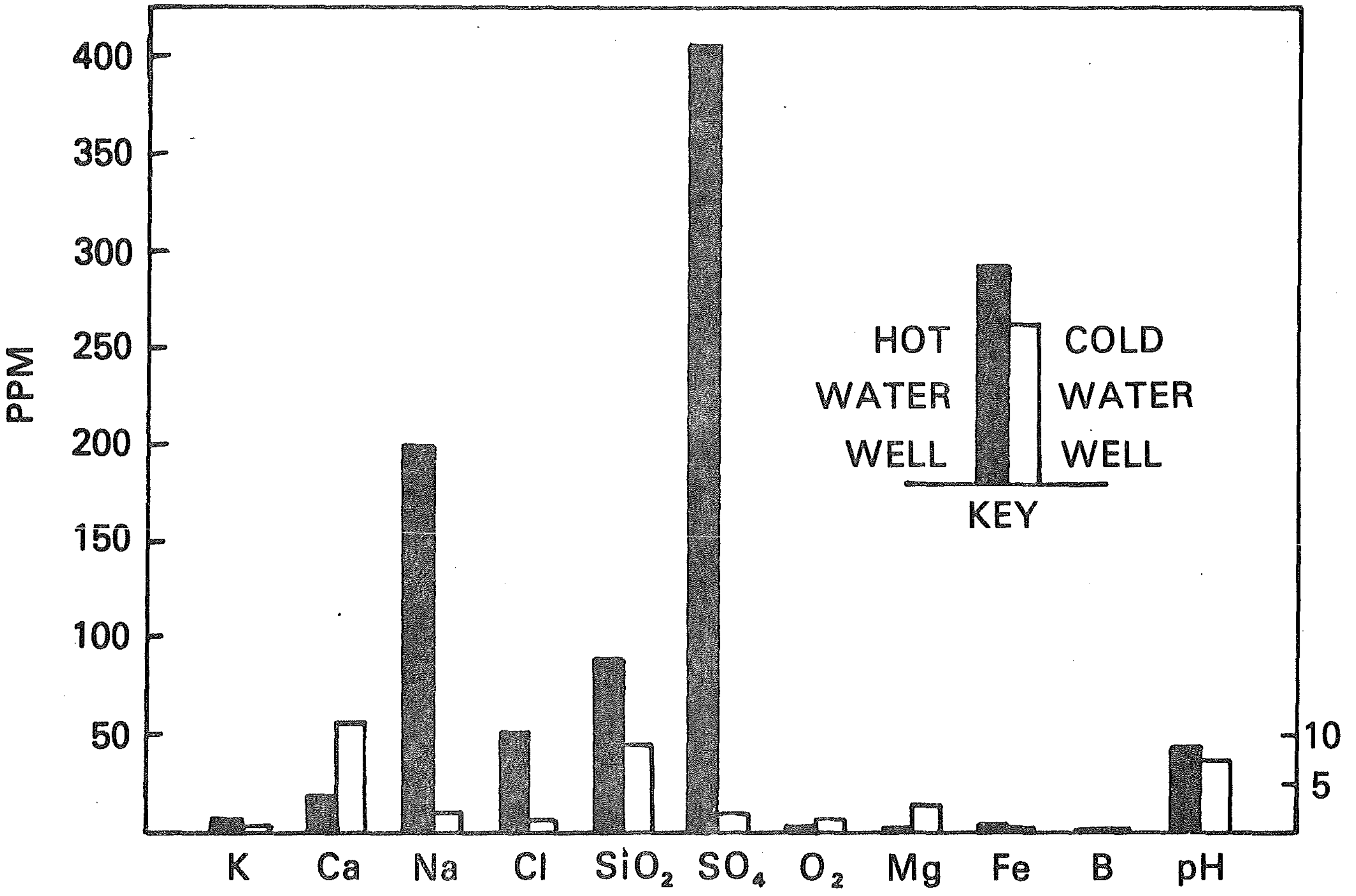


Figure 5 Klamath Basin chemical composition of cold and hot ground water (Lund, 1978)

- Most residential wells in the hot well area are constructed to allow convection of water within the well bore from one water-bearing zone to another. Older wells often have only enough casing to seal off cool aquifers found near land surface. Because of caving problems, newer wells are often drilled two or four inches greater in diameter than the casing diameter. Following drilling, the casing is lowered into the hole and is sealed into the first confining unit or to a confining unit below a cool aquifer. Packers are also used to seal off cool aquifers. The casing is then perforated opposite permeable hot aquifers regardless of rock type and potentiometric head. Through subsequent commingling of water from these different permeable zones, a convection cell is established in the borehole. This convection cell enhances efficiency of the downhole heat exchanger. See Figure 6.

- A typical failure of hot wells is the corroding or scaling of heating equipment. The iron downhole heat exchanger pipes commonly corrode at the air/water interface or at places where the pipe inadvertantly touches the casing. However, for their temperature, the geothermal waters in Klamath Falls are relatively non-corrosive. To reduce corrosion, many well owners pour parafin or motor oil into the well to reduce evolved gases and provide a protective coating on the pipe surface. It is hoped that a substitute can be found for this locally acceptable practice that is considered unsafe according to WRD and DEQ standards.

- Static water levels vary from flowing artesian to 350 feet below land surface with most being from 50-100 feet below land surface (Culver, et al., 1974). Seasonal fluctuations in water level trend toward a lower water level in the winter when heat and fluid withdrawal from the thermal reservoir is greatest. Temperatures in most wells reportedly rise during the heating season when water levels are lowered. However, some wells may cool due to local recharge of surface water.

- There is a lack of compatible, quantitative data regarding long-term developmental impact to the thermal reservoir. Under Oregon Department of Energy sponsorship, WRD established a network of 24 hot wells in the hillside area of Klamath Falls in 1982 to monitor long-term fluctuations in water level. See Figure 7. Currently water level data are gathered in winter and summer. These well network data are available from WRD. Methods of data acquisition are suggested so data gathered by different individuals are compatible, allowing long-term trends to be noted with accuracy.

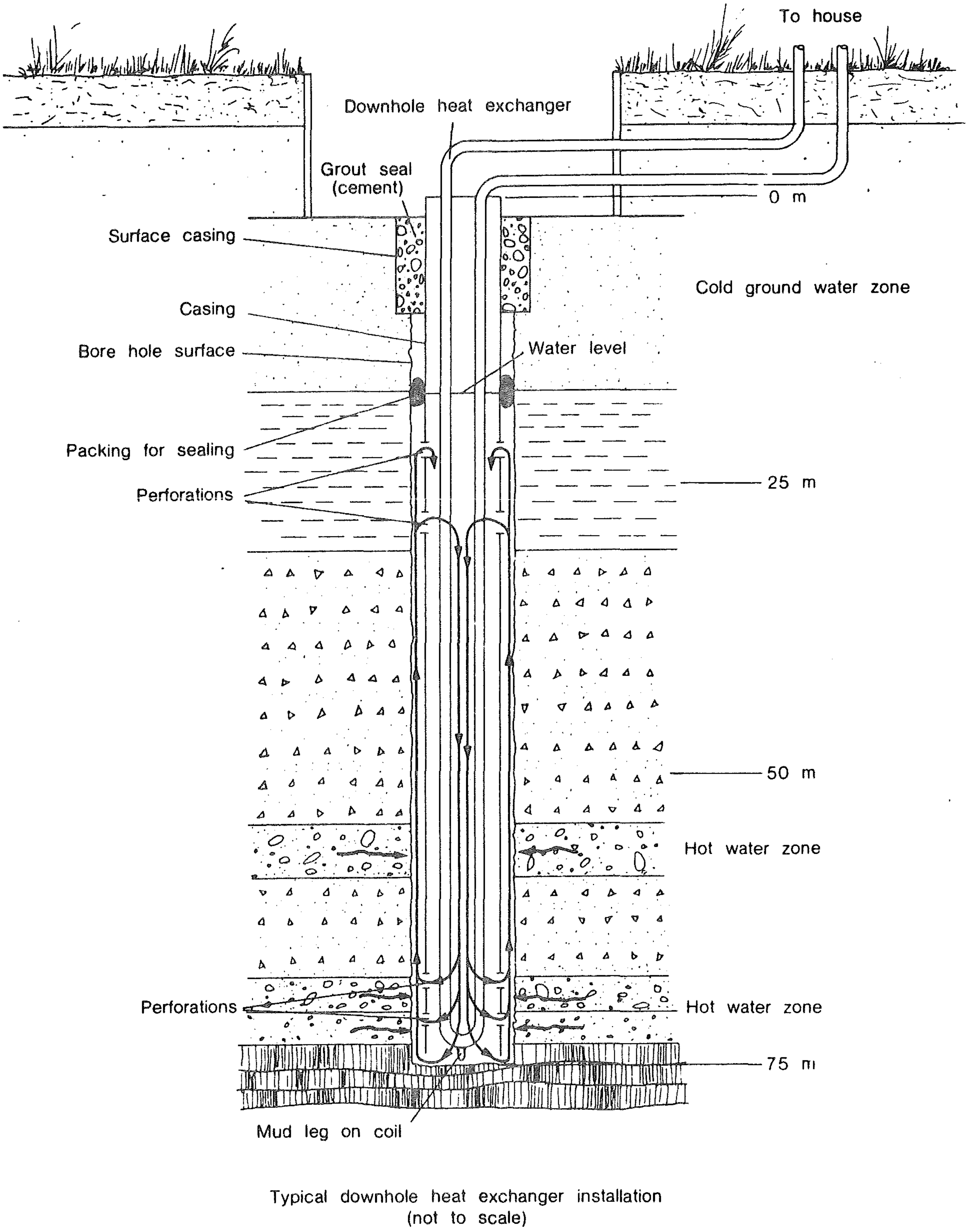


Figure 6 Typical Klamath Falls well with downhole heat exchanger (Justus, et al., 1980)

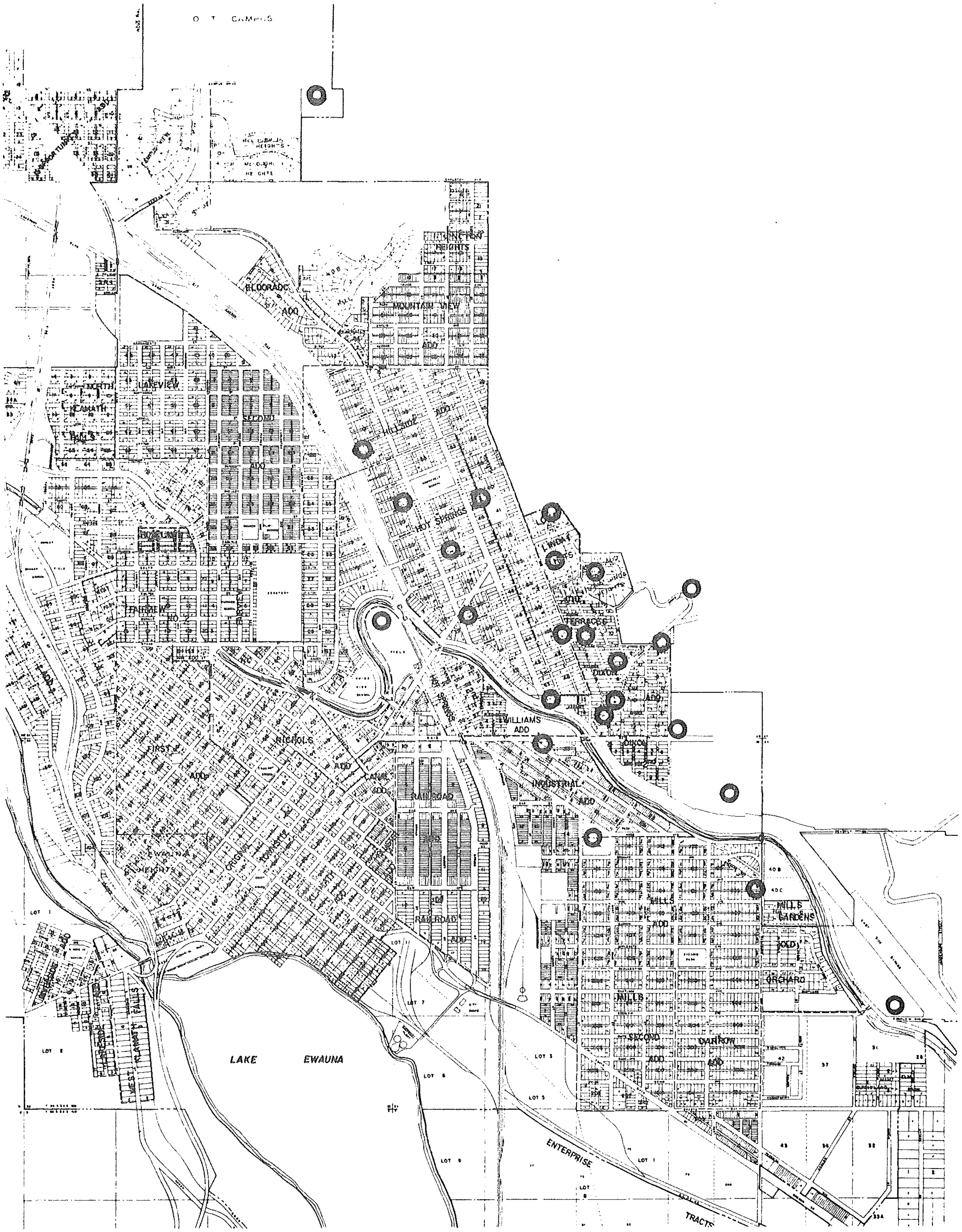


Figure 7   Water Resources Department long-term observation wells

- Diminished hot spring activity in the hillside area and reduced artesian head in some flowing wells have been documented (Culver, et al., 1974).

RESOURCE TESTING

Historical Aquifer Testing

Over the years, several aquifer tests have been conducted in Klamath Falls. These "stress tests" have analyzed both hot and cold aquifers. In 1956, Robinson and Roberts, Groundwater Geologists of Tacoma, Washington, ran a test on the Weyerhauser Well 4 in Township 39 South, Range 9 East, Section 8. This well is open to the Pliocene basalt aquifer from 276 to 545 feet below land surface. Analysis of test data by Sammel (1980) indicates a transmissivity of 11,000 feet^2/day.

In 1974, the USGS and OIT performed an aquifer test using the OIT thermal wells. OIT Well 5 was pumped and OIT Well 6 and the Presbyterian Hospital Well were observed. Analysis showed hydraulic connection between the three wells. Apparent transmissivity was calculated to be 22,000 feet^2/day at prevailing temperatures (Sammel, 1980). However, when converted to standard values for comparison with nonthermal aquifers of 16°C (60°F), transmissivity was estimated at 7,000 feet^2/day (Sammel, 1980).

In 1976, the Geo-Heat Center at OIT conducted a 28-hour test of the artesian Museum Well in the urban area of Klamath Falls. The Museum Well penetrates Yonna Formation and lower basalt to a depth of 1234 feet below land surface. Twelve nearby wells were monitored during this test. Those monitored wells for which data could be analyzed were less than 500 feet deep and penetrated only Yonna Formation. Temperatures in the monitor wells ranged from 56° to 85°C (132 to 185°F). Sammel's analysis indicates hydraulic continuity between all the wells. Transmissivity was calculated at approximately 20,000 feet^2/day at prevailing temperatures. Following conversion to a standard non-thermal reservoir temperature of 16°C (60°F), transmissivity was estimated at 10,000 feet^2/day. Storage coefficient was in the range of 0.001 to 0.01 (Sammel, 1980).

Aquifer Tests of City Heating System Wells

More recent aquifer tests have been performed by Lawrence Berkeley Laboratory (LBL) on the heating district's two supply wells and reinjection well (Museum Well). City Wells 1 and 2 are near the south end of the hot well area. The Museum Well is west of the hot well area in the urban or artesian well area. Sites were chosen based on proximity to the most active thermal region, availability and accessibility of land, and distance to private thermal wells (Benson, et al., 1979).

City Well 1 is 360 feet deep and has 300 feet of sealed casing. From 300 to 367 feet the well is uncased. The well penetrates 253 feet of lacustrine and volcanic sediments of the Yonna Formation and then enters the Pliocene basalts. Figure 8 shows well construction and lithology.

City Well 2, initially drilled to 900 feet, is now 880 feet deep and has 334 feet of casing sealed to 60 feet. The casing is perforated from 190 to 245 feet opposite the main production zone. Figure 9 shows well construction and lithology.

The Museum Well was drilled to a depth of 1234 feet. However, based on a temperature profile done in August 1983, the well has caved in to approximately 1155 feet below land surface (Swanson and Benson, 1983). The well is cased to 450 feet and sealed to 132 feet below land surface. Figure 10 shows well construction and lithology.

In test analyses, LBL uses conventional units designed for single phase, liquid dominated geothermal studies to define aquifer parameters. Transmissivity is defined in units of millidarcies X feet/centipoise [md(ft/cp)] and storativity is defined in units of ft/psi. Using these units it is possible to describe aquifer properties independent of fluid viscosity.

1979 Test of City Well 1

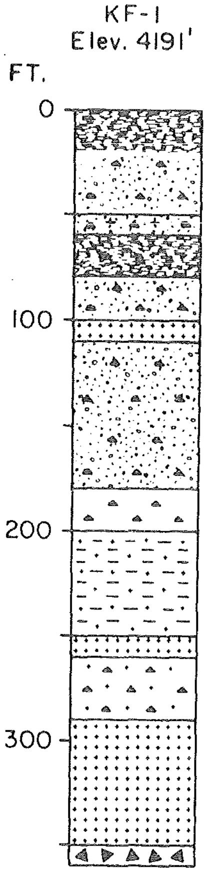
City Well 1 was pump tested in August 1979, for 15.5 hours. During the test, a maximum pumping rate of 680 gpm was held constant for 7.5 hours; 77 feet of drawdown were recorded. Discharge temperatures varied from 102 to 104°C (217° to 219°F). The test was designed to determine production potential of the shallow aquifer and to assist in constructing a comprehensive hydrogeologic model of the reservoir to aid resource management (Benson, et al., 1979).

CONSTRUCTION*:

Depth: 367 feet
Drilling Method: Rotary
Casing: 12-inch; 0 to 300 feet
Perforations: None

Annular Seal: 0 to 300 feet
Driller: Carl Enloe
Completion: November 6, 1979
Static Water Level at Completion: -76 feet

* From driller's log



Light gray cherty claystone, white siliceous claystone (reworked ash?).

White siliceous tuff, very fine grained, poorly indurated, trace lithic grains.

Lithic micro-graywacke with cherty claystone fragments.

Gray siltstone and silty claystone.
Buff to gray tuffaceous sediment, increasing volcanic fragments in lower portion.
Basic volcanic fragments, aphanitic, vugs, pyrite.

Buff to brown tuffaceous sediment, vitreous luster, poorly indurated, trace volcanic fragments, black glassy phenocrysts (150-160').

White tuff, with black glassy shards, tuff welded in lower portion.

Basic volcanic sediments, fine grained, vitreous luster, rounded grains in siliceous matrix.

Dark gray basic volcanic fragments, aphanitic, moderately hard.
Volcanic graywacke, dark gray angular to subrounded inclusions, some pyrite, vein filling matrix light gray, vitreous luster, chalcopyrite/marcasite (280').

Gray basic volcanic fragments, aphanitic, massive, hard, trace amounts of veination (300-320'), few euhedral pyrite (320-340').

Red basic volcanic breccia, scoriaceous, subangular, 1-3 mm aphanitic basaltic inclusions, red aphanitic matrix, vitreous luster, many vugs sometimes filled with silica, zeolites, calcite and/or pyrite.

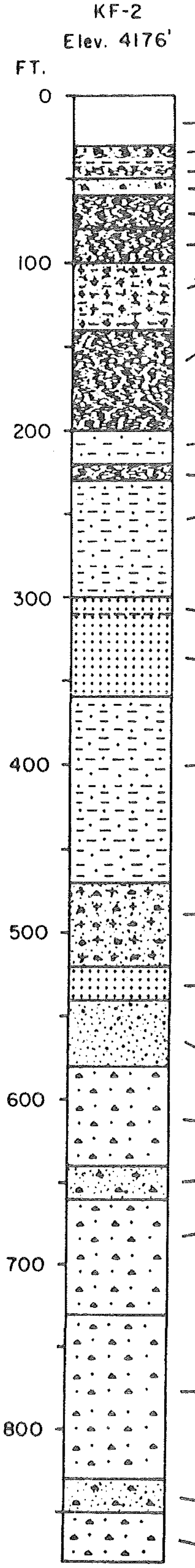
Figure 8 Construction and lithology-City of Klamath Falls Well 1 (O'Brien and Benson, 1980)

CONSTRUCTION*:

Depth: 900 feet
Drilling Method: Rotary
Casing: 12-inch; 0 to 334 feet
Perforations: 190 to 245 feet

Annular Seal: 0 to 60 feet
Driller: Carl Enloe
Completion: March 24, 1980
Static Water Level at Completion: -60 feet

* From diller's log



No sample.

Buff-brown clay with few glassy-pumice fragments, unconsolidated.

Light gray clay, vitreous, glassy, lithic frag. moderate consolidation.

Brown ash with white tuff fragments.

Gray vitreous claystone, poorly indurated, with white tuff fragments.

Massive gray claystone, moderate to well indurated, conchoidal fracture.

Black basic volcanic fragments, with gray tuffaceous sediment and gray claystone with diatoms, Stephanodiscus sp. 100-110, 120-130 ft.

Gray to brown calcitic silty claystone with basic volcanic fragments. Claystone is poor to moderately well indurated, vitreous, effervescent, with few glassy fragments.
- 180-190' trace amount volcanic lapilli
- 190-200' first occurrence pyrite, euhedral, 2 mm, vein filling.

Dark gray basic volcanic fragments and gray silty calcitic claystone with trace amounts of white tuff fragments, diatoms.

Gray calcitic silty claystone, with basic volcanic fragments, tuff, pyrite.

Gray basic volcanic fragments with calcitic claystone and pyrite, silica and pyrite veination, trace rhyolitic tuff and porcelain fragments.
- 252' gray siliceous tuff
- 250-260' red volcanic fragments with black glassy inclusions
- 270-280' possible baked contact.

Salt and pepper basic volcanic fragments with clear, white and black microphenocrysts.

Black basic volcanic fragments, angular, massive, vitreous luster.

Gray volcanic silty sediment, unconsolidated to poorly consolidated, with calcitic matrix, few volcanic fragments with inclusions, few white tuff fragments.
- 450-460' first occurrence marcasite/chalcopyrite (?)

Volcanic fragments and ash in siliceous and calcitic matrix, a "micro-graywacke."
- 480-490' first occurrence of green mineral
- 510-520' pyrite and chalcopyrite (?) phenocrysts, 2.0 mm.

Black aphanitic basic volcanic frag., vitreous, white glassy "powder" on surface, some glassy shards.
- 520-530' euhedral pyrite crystals, 2-4.0 mm
- 530-540' subhedral calcite, 1-2 mm; euhedral pyrite 1-3 mm; red cinders, 1-2 mm.

Gray volcanic ash-silty claystone, first occurrence zeolite 540-550'
- 570-580' first occurrence Fe oxide, illite (?)

Unconsolidated volcanic sediment with black basic volcanic fragments and vitreous tuff with inclusions.

Red scoriaceous tuff with glassy inclusions and basic volcanic fragments; 650-660' zeolite, euhedral.

Gray basic volcanic fragments, vitric, aphanitic, massive, with white glassy "powder" on surface.
- 660-670' zeolite, 0.25-0.75 mm
- 670-680' black glassy fragments, obsidian (?)
- 680-690' white milky to green mineral; first occurrence
- 700-710' red tuffaceous frag., vitreous; white and black glassy inclusions
- 720-730' pyrite associated with volcanic fragments.

Gray basic volcanic fragments with varied texture: aphanitic and massive to vesicular, micro-phenocrysts, white aphanitic to opaline vug filling, pyrite.
- 760-770' white tuffaceous and red tuffaceous fragments
- 780-790' subrounded volcanic fragments old surface (?)
- 820-820' Fe oxide vein filling, illite (?).

Gray vitreous tuffaceous fragments with vitreous black and white inclusions with volcanic ash and silt, basic volcanic fragments and white tuffaceous fragments.

Light to dark gray basic volcanic fragments, vitreous, aphanitic, massive, subangular to subrounded, often with vitreous inclusions, red tuffaceous fragments, moderate effervescence.

Figure 9 Construction and lithology-City of Klamath Falls Well 2 (O'Brien and Benson, 1980)

CONSTRUCTION*:

Depth: 1235 feet (caved to 1177 feet**)
Drilling Method: Rotary
Casing: 16-inch; 0 to 132 feet
16.75 inch; -1 to 450 feet
Perforations: None

Annular Seal: 0 to 132 feet
Driller: David Storey
Completion: May 30, 1975
Static Water Level at Completion: +4.5 feet

LITHOLOGY*:

0 to 2 feet	fine gravel
2 to 5 feet	black clay
5 to 9 feet	green clay
9 to 56 feet	yellow shale with streaks cemented gravel
56 to 75 feet	yellow shale
75 to 127 feet	gray shale
127 to 222 feet	hard gray chalk rock
222 to 402 feet	black basalt
402 to 477 feet	black basalt with streaks gray clay
477 to 525 feet	black basalt with streaks black clay
525 to 541 feet	brown shale
541 to 544 feet	black basalt
544 to 560 feet	broken gray basalt
560 to 635 feet	gray shale
635 to 698 feet	hard gray pink shale
698 to 738 feet	black basalt
738 to 794 feet	hard gray shale with pink layers
794 to 819 feet	black basalt with streaks gray pink shale
819 to 847 feet	gray pink shale (hard)
847 to 850 feet	black basalt with streaks gray clay
850 to 884 feet	gray shale
884 to 912 feet	black basalt broken
912 to 938 feet	broken gray shale
938 to 945 feet	black basalt
945 to 994 feet	hard broken gray basalt
994 to 1060 feet	black basalt with streaks gray shale
1060 to 1070 feet	broken black basalt
1070 to 1175 feet	black basalt crevices with streaks gray shale
1175 to 1206 feet	black basalt with streaks gray shale
1206 to 1216 feet	brown shale
1216 to 1235 feet	black basalt with streaks gray shale

* From driller's log
** Benson, 1983

Figure 10 Construction and Lithology - City Of Klamath Falls Museum Well

To monitor interference effects three nearby wells were observed. Rapid water level declines took place in all three wells. The closest monitor well, 150 feet away, responded in less than 10 seconds; after 7.5 hours of pumping at 680 gpm, a maximum drawdown of 1.2 feet was noted. Transmissivity values ranged from 1.4 x 10^7 to 1.5 x 10^7 md(ft/cp), storativity values from 2.4 x 10^{-3} to 7.8 x 10^{-3} ft/psi, and a high permeability of 100 darcies was noted (Benson, et al., 1979). Late drawdown data suggested a hydraulic boundary was encountered. This test indicated a high degree of hydraulic continuity between City Well 1 and the observation wells. The continuity appeared to involve fracture-related vertical movement of fluid.

LBL concluded that the pump test offered promising potential for reservoir sustainability, but a longer-term test would be necessary to predict effects of continued withdrawal.

1981 Test of City Wells 1 and 2, Museum Well

On September 29, 1981, LBL conducted a 16-hour pump test of City Wells 1 and 2 and the City Museum Well. This test was designed to check the heating system for flaws and to determine reservoir response to withdrawal and reinjection. Nine monitor wells were selected: five in the reinjection area and four in the production area.

During this test, the production wells were pumped at several different rates for varying amounts of time. Each of the monitor wells in the production area behaved differently both before and during the test period. Analysis of a short segment of data from the Parks Well (while City Well 2 was being pumped), suggested a transmissivity of 3.4 x 10^7 md(ft/cp). However, due to the fluctuations in pumping rate it was difficult to determine reservoir properties with accuracy.

In total, 5.4 x 10^5 gallons of 96°C (205°F) fluid were reinjected into the Museum Well. Data analysis in the reinjection area indicates reservoir transmissivity in the range of 1 x 10^6 to 10 x 10^6 md(ft/cp). These results were in reasonable agreement with results of the 1976 drawdown test of the Museum Well. Most wells in the reinjection area produce water between 65 and 82°C (150° and 180°F). Since this is cooler than the production area, the only thermal change expected from the reinjection process would be one of increasing temperature. Thermal breakthrough, however, was not observed in any monitor wells. Two of the five monitor wells showed an increase in head due to reinjection. At the time, it was unknown which strata in the reinjection well were accepting fluid.

Because the test was short, neither the degree of hydraulic communication between the production and reinjection areas nor the effects of withdrawal and reinjection on nearby wells were accurately assessed (Benson, 1981).

1982 Test of City Well 2, Museum Well

From February 8 through 12, 1982, LBL conducted a 97-hour withdrawal/reinjection test involving City Well 2 and the Museum Well. City Well 2 was pumped at approximately 540 gpm and experienced a maximum drawdown of 4.5 feet. Four wells near City Well 2 were monitored with continuous recording equipment and the maximum drawdown measured was 8 inches. Data from the monitor wells indicate a reservoir transmissivity of 2.0×10^7 md(ft/cp).

Water levels were also measured in monitor wells near the reinjection site. Partial pressure support from the reinjection process was thought responsible for maintaining water levels in the production area.

Data from all the wells confirmed a high reservoir permeability and indicated hydraulic continuity between the hot well (hillside) and the artesian (urban) areas. The test was too short to determine location of the conduit or fracture system that supplies the reservoir with hot water. It was unknown what strata in the deep Museum Well were accepting reinjected effluent. As such, it was impossible to predict the partial pressure support the reinjection process could provide to maintain water levels in shallower wells in the production area. Additionally, boundaries that have the potential to be encountered during a long-term test were not identified. This made extrapolation of future impact to the reservoir impossible (Benson, 1982).

1983 Long-Term Test of City Well 2, Museum Well

Data from previous tests were not adequate to predict long-term consequences of the proposed withdrawal and reinjection. The tests were too short to determine if the geothermal reservoir could sustain the stress necessary for Phase I without unacceptable changes in water levels, temperatures or aquifer properties. After lengthy preparation, an eight-week aquifer test of the supply and reinjection system began in July 1983 with pumping from the 900-foot deep City Well 2. The salient features of the test are described below. An open file report (Benson, et al., 1984) is available showing complete data gathered during this test.

Organization: In January 1983, the Klamath County Chamber of Commerce began organizing for a long-term test of the city heating system. Under a $150,000 grant from the U.S. Department of Energy, several scientific research groups were funded. Primary investigator and coordinator for the long-term test was Edward Sammel of the USGS. Playing the key role in aquifer test analysis was Sally Benson of LBL. Also as part of the testing program, Alfred Truesdell of the USGS, sampled waters for chemical and isotopic analyses; Dr. Jon Gudmundsson of Stanford University, directed tracer studies to help indicate ground water flow paths and velocities; Paul Lienau and Gene Culver of the Geo-Heat Center at OIT, provided logistical support. Local coordinators of monitoring and data collection were Susan Swanson and Dennis Long of D.C. Long Energyman, Inc. Amongst other efforts, Long and Swanson have developed a historical data base for all hot wells in the city.

Procedures and Monitoring: Pre-test data gathering began in March 1983. Monitoring included collection of water level, temperature and chemical data from wells. After careful planning, the aquifer test began July 5. City Well 2 was pumped at a constant rate of 720 gpm. For approximately three weeks, from July 5 to 27, the effluent was discharged into the Klamath Falls "A" Canal. The effluent was then reinjected into the Museum Well for nearly one month, until pump shutoff on August 24. From August 24 to September 6, recovery was monitored. Some monitoring continues indefinitely.

During the test, 9 wells were equipped with quartz pressure transducers that provided water level data as a function of pressure. Thirteen wells were equipped with Stevens Type F continuous water level recorders. Twenty-five wells were hand-measured for water level on a daily or weekly basis by the scientific crew, and 13 wells were hand-measured for water level by volunteer well owners. The volunteer effort was coordinated by I.H. "Bud" and Deborah Hart of CRGD. All monitor wells were within a radius of 6400 feet from the production and reinjection wells.

At City Well 2, discharge was monitored using a Dynasonic doppler flow meter. A constant discharge of 720 gpm was monitored during the first stage of the test. When reinjection into the Museum Well began, the discharge rate fluctuated between 720 and 680 gpm. Water level in City Well 2 was measured using an airline and bourdon tube. Discharge temperature was recorded regularly and was stable at approximately 100°C (212.3°F) throughout the test. During the reinjection phase, the Museum Well was monitored using a quartz pressure transducer placed at 900 feet and a well head pressure gauge.

Several wells were sampled for chemical and isotopic analysis. Major-ion analyses were performed by LBL; these and oxygen^{18}, carbon^{14}, sulfate (O^{18}), deuterium and tritium analyses will be interpreted by Truesdell of the USGS. The tritium analyses will be useful in estimating flow rates, mixing of hot and cool aquifers and amount of recharge.

A tracer was added to the Museum Well during reinjection and was detected in a well approximately 50 feet away. The tracer was not observed in any of the regularly monitored wells. The plume of reinjected effluent may have migrated away from the monitor wells along the hydraulic gradient. However, it is possible that the tracer was adsorbed onto Yonna Formation clay particles within a short radius of the Museum Well. A final report on the tracer studies will be published by Stanford University.

Observations: In response to pumping, City Well 2 had a drawdown that varied between 8 and 10 feet. The nearest observation well, the Parks Steamer Well, 120 feet away, had 4.66 feet of drawdown. This was measured at the end of the non-reinjection phase of pumping (Benson, et al., 1984).

After reinjection began, water levels began to recover. In the urban area, the maximum rise occurred in the Medo-Bel observation well, 640 feet from the reinjection well. Water level rose 6.8 feet and began flowing. In the hillside area, the maximum water level rise was 4.45 feet at the Rogers observation well, 2660 feet from the reinjection well. In general, water levels rose during the first two weeks of reinjection and then appeared to stabilize as the withdrawal and reinjection process equilibrated. Reinjection pressures incresed from 39 to 43 psi during the injection phase (Benson, et al., 1984).

Water was reinjected into the Museum Well at a temperature of 99°C (210.5°F). Before reinjection, a temperature profile was conducted. The temperature ranged from 65 to 92.9° C (149 to 199° F). The maximum temperature was measured at a depth of 1000 feet (Benson, et al., 1984). Most wells in the reinjection area produce water between 65° and 82°C (150° and 180°F). Thus, in the area of reinjection, the only resulting thermal change will be one of increasing temperature.

A spinner survey was performed during reinjection to help indicate what units in the Museum Well were receiving the effluent. It was determined that approximately 50 percent of the effluent enters the rock formation from 470 to 520 feet. The remaining effluent appears to be received below 1017 feet (Benson, et al., 1984).

The production zone in City Well 2 is from 195 to 240 feet below land surface. This appears to be the same aquifer shared by most wells in the hillside area. Data amongst the wells observed during the test were in good agreement. Transmissivity was high, approximating 5.2×10^6 md (ft/cp). Storativity approximated 2×10^{-3} ft/psi indicating semi-confined conditions. No hydraulic boundaries were encountered during the test (Benson, 1984).

According to Benson (1984), the hydraulic system responded quickly over long distances to pumping and reinjection. The test data fit a double porosity type curve. This indicates that two types of hydraulic flow systems were encountered. One type is of high transmissivity and low storage coefficient, the other of low transmissivity and high storage coefficient. Hydrogeologically, this is explained by the presence of both interstitial flow and fracture flow within the aquifer. The fractures appear to hydraulically connect the entire rock mass. During pumping, the fractures are quickly drained resulting in rapid response in water levels over long distances. This acute response is followed by less rapid interstitial fluid flow as units of the Yonna Formation and underlying basalt yield water more slowly toward the well.

CONCLUSIONS

Sammel and Benson consider the 1983 test data accurate, comprehensive and useful for making predictions of aquifer response to various district heating pumping regimes. The geothermal aquifer is highly permeable and extensive. Preliminary analysis indicates that with suitable reinjection, the reservoir may be capable of sustained yields at greater pumping rates than tested. However, wells near the pumping well may be adversely affected (Sammel, 1983). The maximum drawdown in the closest monitor well after three weeks of continuous pumping (without reinjection) was 4.66 feet. Reinjection into the Museum Well served to stabilize water levels throughout the monitored area. Seasonal fluctuation in the aquifer, before use of the city wells, amounts to a maximum of 11 feet. The final interpretation of the data will attempt to predict long-term consequences of additional development.

According to Sammel (1983), the expected outcomes of the investigation are as follows:

- * Values for transmissivity, storativity, and hydraulic boundary conditions in the shallow (less than 2500 feet deep) geothermal reservoir. Emphasis will be placed on that part of the aquifer system potentially affected by the proposed district heating system.
- * Predicted values of water level declines, buildups and recoveries in the aquifer under pumping and reinjection regimes proposed for the district heating system.
- * Estimates of chemical and physical effects that may occur in existing heat supply wells as a result of reservoir development.
- * Estimates of natural flow rates and the interaction of recharge and discharge in the reservoir, together with the aquifer hydraulic constants, will lead to estimates of the fluid mass and thermal energy available for development. The degree of anisotropy and the applicability of a double porosity model will also be estimated.

Final results from the 1983 testing program will provide long-awaited information to the people of Klamath Falls. Data from the tests will allow long-term effects of withdrawal and reinjection to be predicted. This scientific information will help guide Klamath Falls residents in evaluating options for the future of the geothermal resource and Phase 1 of the geothermal heating system.

The 24 observation wells established by WRD through ODOE funding in 1982, will be monitored every winter and summer. Additionally, the Chamber of Commerce will continue long-term monitoring of five unused wells with continuous water level recorders. Continuous data from these ventures will keep a finger on the pulse of developmental impacts to the aquifer.

A community advisory group is planned through the Chamber of Commerce. The primary function of the advisory group will be to represent each of the diverse user groups in the area so that a positive exchange of ideas will continue. It is important that all concerns and fears be aired in an unbiased, supportive setting so that an equitable consensus regarding use of the geothermal resource can be reached. The path of future geothermal resource development in Klamath Falls depends heavily on the final results of the 1983 aquifer test, the outcome of the WRD appeal of the Citizen Initiative, and the attitudes and cooperation of independent citizens, business groups, CRGD, the City, OIT, WRD and the Legislature.

The ground water hydrogeology of Klamath Falls is among the more complex of ground water regimes in the state. This semi-confined, highly permeable, dual porosity hydraulic system produces both hot and cold waters. Not only is the Klamath Falls ground water system called upon to provide the domestic, stock, fire protection, irrigation, commercial and industrial needs most commonly associated with water, but it is also asked to provide heat. Space heating and cooling, hot water heating, greenhouse horticulture, aquaculture and other commercial/industrial uses of the hot water are common. Responsible development of renewable resources is vital to a sustainable energy future. The economic stability of our society falters under increasing dependency on disappearing or imported energy resources. The history of geothermal development in Klamath Falls has illuminated the importance of fully understanding the extent and limits of a local geothermal resource so that efficient planning and resource sustainability may be attained. The cooperation by diverse groups in Klamath Falls during the 1983 testing program is an unprecedented recognition of the importance of community action in local energy planning.

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REFERENCES

Allen, Eliot, "Preliminary Model Ordinance for Municipal Geothermal District Heating and Reservoir Management", Salem, OR, October 1980.

Benson, S.M., Goranson, C.B. and Shroeder, R.C., "Evaluation of City Well 1, Klamath Falls, Oregon", Lawrence Berkeley Laboratory, Berkeley, CA, 1979.

Benson, S.M., Janik, C.J., Long, D.C., Solbau, R.D., Lienau, P.J., Culver, G.G., Sammel, E.A., Swanson, S.R., Hart, D.N., Yee, A., White, A.F., Stallard, M.L., Brown, A.P., Wheeler, M.C., Winnett, T.L., Fong, G. and Eakin, G.B., "Data from Pumping and Injection Tests and Chemical Sampling in the Geothermal Aquifer at Klamath Falls, Oregon", U.S. Geological Survey Open File Report 84-146, April 1984.

Benson, Sally, "Klamath Falls (WP-1 and WP-2) System Check, September 29 through September 30, 1981", Lawrence Berkeley Laboratory, Berkeley, CA, 1981.

Benson, Sally, "Klamath Falls (WP-1, Supply and Distribution Network, Museum Well) System Check", Lawrence Berkeley Laboratory, Berkeley, CA, February 1982.

Benson, S.M., Personal Communication, 1984.

Bodvarsson, G.S., Miller, C.W. and Benson, S.M., "A Simple Model for Fault-Charged Hydrothermal Systems", Lawrence Berkeley Laboratory, Berkeley, CA, August 1981.

Culver, G.G., Lund, J.W. and Svanevik, L.S., "Klamath Falls Hot Water Well Study", Lawrence Livermore Laboratory, University of California, UCRL-13614, Livermore, CA, October 1974.

Gardner, T.C., Bressler, S.E. and King D., "Existing Institutional Arrangements for Geothermal District Heating Systems: Their Value as Models and Their Lessons for Future Planning", Geothermal Energy Project, Earl Warren Legal Institute, Berkeley, CA, January 1981.

Gunther, John J., Executive Director, "Groundwater and Geothermal: Urban District Heating Applications", U.S. Conference of Mayors, Washington, D.C., 1982.

Justus, D.J., Basescu, N., Bloomquist, R.G., Higbee, C. and Simpson, S., "Oregon: A Guide to Geothermal Energy Development", OIT Geo-Heat Utilization Center in cooperation with Oregon Department of Energy, June 1980.

Klamath Falls, City of, "Klamath Falls District Heating", for U.S. Department of Energy, January 1979.

Lund, J.W., Culver, G.G., Lienau, P.J. and Svanevik, L.S., "Geothermal Hydrology and Geochemistry of Klamath Falls, Oregon, Urban Area", Oregon Institute of Technology, Klamath Falls, OR, July 1978.

Lund, J.W., Culver, G.G. and Svanevik, L.S., "Utilization of Geothermal Energy in Klamath Falls", Oregon Institute of Technology, Klamath Falls, OR, 1974.

National Conference of State Legislatures, "Geothermal Guidebook, Prepared for the Oregon Legislature, 1980 Geothermal Policy Review", National Conference of State Legislatures Energy Program - Geothermal Project, Denver, CO, May 1980.

O'Brien, M.T. and Benson, S.M., "Reservoir Evaluation of Klamath Falls, Oregon", Lawrence Berkeley Laboratory Annual Report, Berkeley, CA, 1980.

Peterson, N.V. and McIntyre, J.B., "The Reconnaissance Geology and Mineral Resources of Eastern Klamath County and Western Lake County, Oregon", Oregon Department of Geology and Mineral Industries Bulletin 66, 1970.

Sammel, Edward A., "Hydrologic Appraisal of the Klamath Falls Geothermal Area, Oregon", U.S. Geological Survey Professional Paper 1044-G, 1980.

Sammel, Edward A., Personal Communication, 1983.

Swanson, S.R. and Benson, S.M., Personal Communication, 1983.

Truesdell, Alfred, Personal Communication, 1984.

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