DIRECT USE RESERVOIR MODELS
HOW WE THINK THEY WORK

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ABSTRACT

The resource base for low-to-moderate temperature direct use geothermal applications is large and wide spread throughout the western United States. The models for direct use resources likely to be utilized in EPA Region IX depict fluids percolating to significant depths, being heated and convecting to the surface or near surface. The most commonly utilized resource is the fault controlled lateral leakage type. Geothermal fluids within the shallow reservoir vary in temperature and chemistry depending on the distance from the upflow zone. Regulations governing injected water chemistry compared to receiving water chemistry should take variations of chemistry into account.

INTRODUCTION

Direct use of geothermal resources covers the range of from about 65°F to 270°F. If one excludes aquaculture, spas and pools which can utilize the lowest temperatures, actual uses range from 99°F used to heat a church in Idaho to 270°F utilized for vegetable dehydration in Nevada. Most of the current uses are for space and domestic water heating; but, the potential for increased industrial processes is fairly large if fossil fuel prices remain high.

Studies by the U.S. Geological Survey state that the resource base for geothermal is very large. Reed (1983) identified 1,324 low-to-moderate temperature resources in the U.S. Of these, 1,282 were hydrothermal convection dominated and 42 conduction dominated. It is estimated that there may be about an equal number undiscovered. In convection dominated systems upward circulation of water transports heat to shallow reservoirs or the surface. These systems commonly occur in areas of active tectonism and above normal heat flow, such as much of the western United States. In conduction dominated systems, deep aquifers are heated by near normal heat flow--conditions that occur beneath many deep sedimentary basins throughout the United States. The resource base in these systems is large because of the very large volumes of water. Convection systems are the type most often utilized since they bring thermal fluids to the surface or shallow reservoirs within economic drilling depths.

Simplified models of hydrothermal resources were presented by Sorey (1983) to explain the basic process. Only models thought to be important in EPA Region IX will be discussed here. In detail of course, each resource is unique and much more complicated than shown. Some people prefer that these be called cartoons rather than models because of the simplification. As more data on a given resource is obtained through drilling and testing, the model is continually refined.

One of the models (Figure 1) depicts water percolating to considerable depth, perhaps along fractures, moving laterally through permeable zones at depth, heated by normal or elevated heat flows and rising up fractures near a valley wall. Springs are often high in TDS due to solution of evaporites deposited in the early stages of the valleys evolution. There may be several resources of this type in California mostly along the western margin of the central valley. Utilization is difficult and not economically feasible under current conditions. Drilling to reach the larger volume resource near the valley basement is expensive, high TDS fluids are difficult to handle in surface equipment and disposal of spent fluids presents real problems. Surface temperatures and flows are rarely adequate for anything but the most modest use.

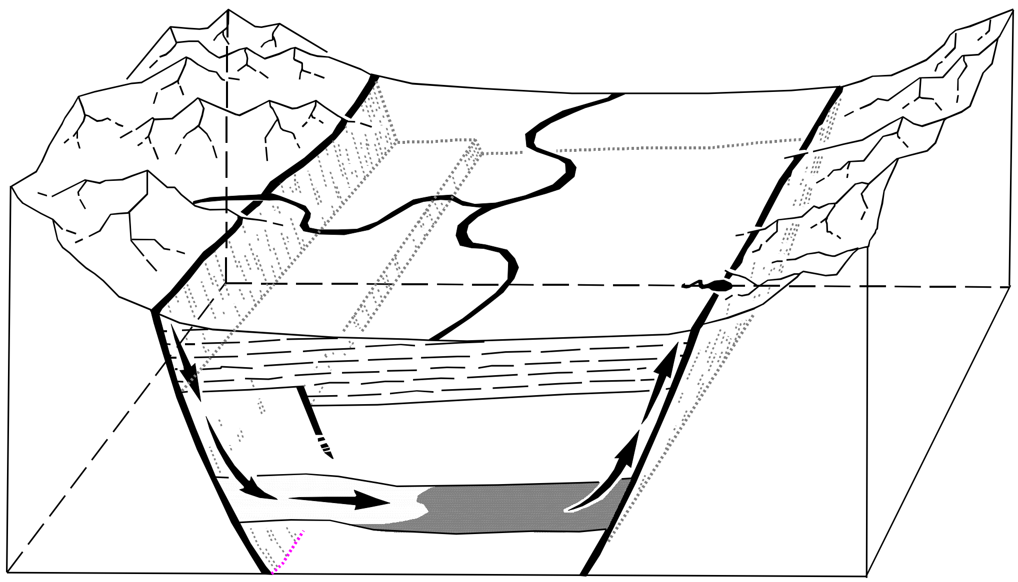

Figure 1. Deep reservoir hydrothermal-convection system.

Another type of system is depicted in Figure 2. Here water percolates to depth along a fault, and after being heated, rises along the same or an associated fault at another location. This type of system is probably responsible for many of the isolated thermal springs in the Sierra Nevada and southern Cascades in California. Where the fault has considerable length, there may be several such convection cells along its length. There seems to be linears of springs with similar water chemistry along the San Andreas and its branches. In this type of system, springs range from warm to boiling at the surface, flows may be substantial though most are modest and TDS generally low. For the most part, they occur in isolated areas. Development is usually resort type with pools and some space heating utilizing the natural or improved surface flow. Where this is a true depiction of the system, temperature and flow might be increased by drilling to intersect the fault at depth. This is not as simple as it may seem since real life faults are rarely the simple plane depicted. Pumping of wells near springs likely will reduce or halt spring flow. Subsurface disposal probably will not be required since reduction of natural thermal flow would adversely affect the natural ecosystem.

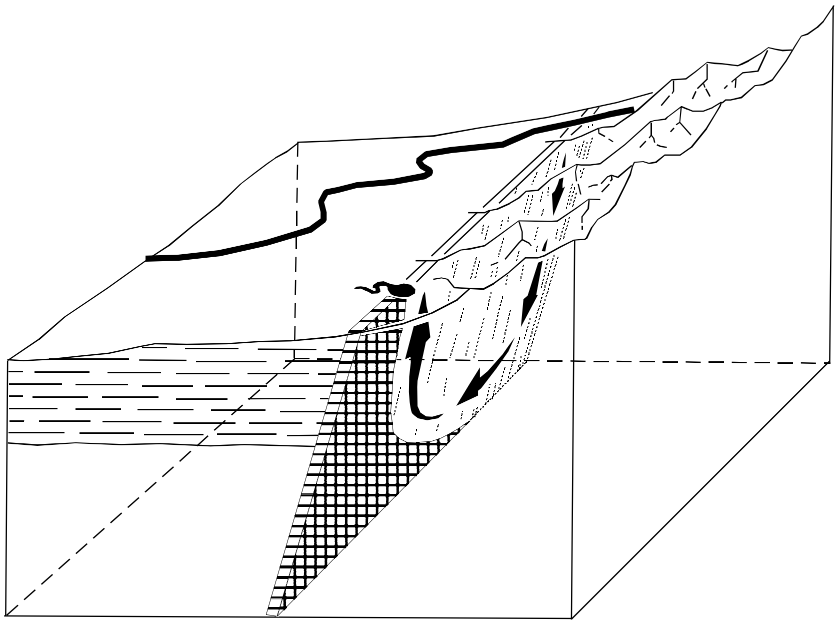

Figure 2. Faut plane hydrothermal-convection system.

There are at least two of this type of resource that have seen considerable development. Since the resources are limited to areas of 40 acres or less, they might be considered point sources as depicted in this model. One is Pagosa Springs, Colorado, but subsurface disposal is not practiced there. The other is Vale, Oregon, where subsurface disposal has been practiced with less than desirable results. The Vale resource and problems are discussed in a case history elsewhere in this volume.

The most often exploited direct use resource is the fault controlled-lateral leakage type. This type of resource is utilized at Susanville, San Bernardino, Desert Hot Springs, Calistoga, Paso Robles and others in California as well as Reno, Elko and Carson City, Nevada. Boise, Idaho and Klamath Falls, Oregon, are additional examples of these resources. There are many others that have seen minimal or no development.

In this resource type, geothermal fluids rise along fault zones to intercept a subsurface permeable layer where fluids spread laterally down hydraulic gradient. One variation of this model is depicted in Figure 3 which shows a valley border fault typical of a horst and grabben structure in the Basin and Range Province. There may or may not be surface discharge of thermal fluid.

There are several important features of this type of resource.

1. The shallow exploited resource is of limited thickness bounded above and below by less permeable rocks which contain cooler water. Rocks within the shallow geothermal aquifer are heated by the flow of geothermal water through them.

2. Geothermal fluids cool by conduction and some mixing as they flow away from the fault chemically equilibrating to the lower temperature. Cooling and equilibration depend on residence time which in turn is governed by transmissivity of the aquifer. There can be large differences in transmissivity among different resources and between different areas of the same resource. The fluids retain some of their geothermal chemical signature after considerable cooling but ultimately become part of the regional groundwater.

3. In the few direct use reservoirs that have been more thoroughly studied, chemical and isotopic geothermometers indicate temperatures higher than those actually encountered in the shallow aquifer. This implies a mixing zone somewhere below the depths currently tested by drilling. Age dating indicates the geothermal fluids are at least 10,000 years old, but the cooler component is younger (Sammel, 1984; Flynn, 1983).

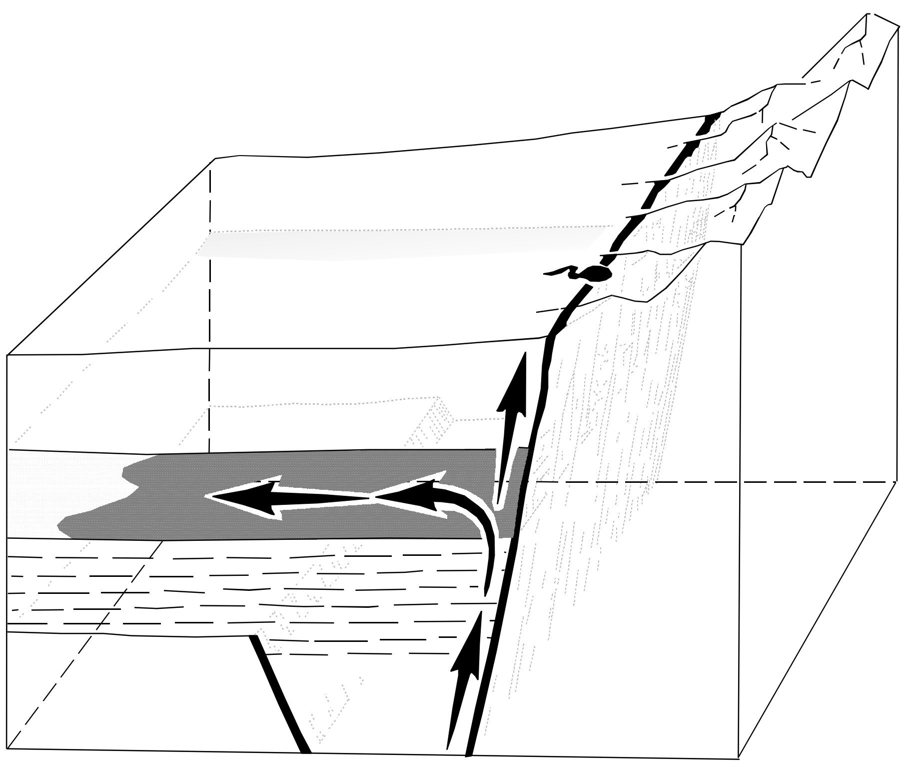

Figure 3. Lateral leakage hydrothermal-convection system.

Figure 3 showed the fluids rising along a fault typical of the Basin and Range. Similar situations occur in other geologic provinces. Figure 4 shows a schematic diagram of a cross section across the upper Napa Valley at Calistoga, California (Youngs, et al., 1980). Here geothermal fluids rise along a valley central axis fault and flow laterally in both directions towards the valley sides. Wells 6 and 9 were drilled through the shallow geothermal aquifer into the impermeable zone below and had temperature reversals. Similar situations occur in San Bernardino and Desert Hot Springs.

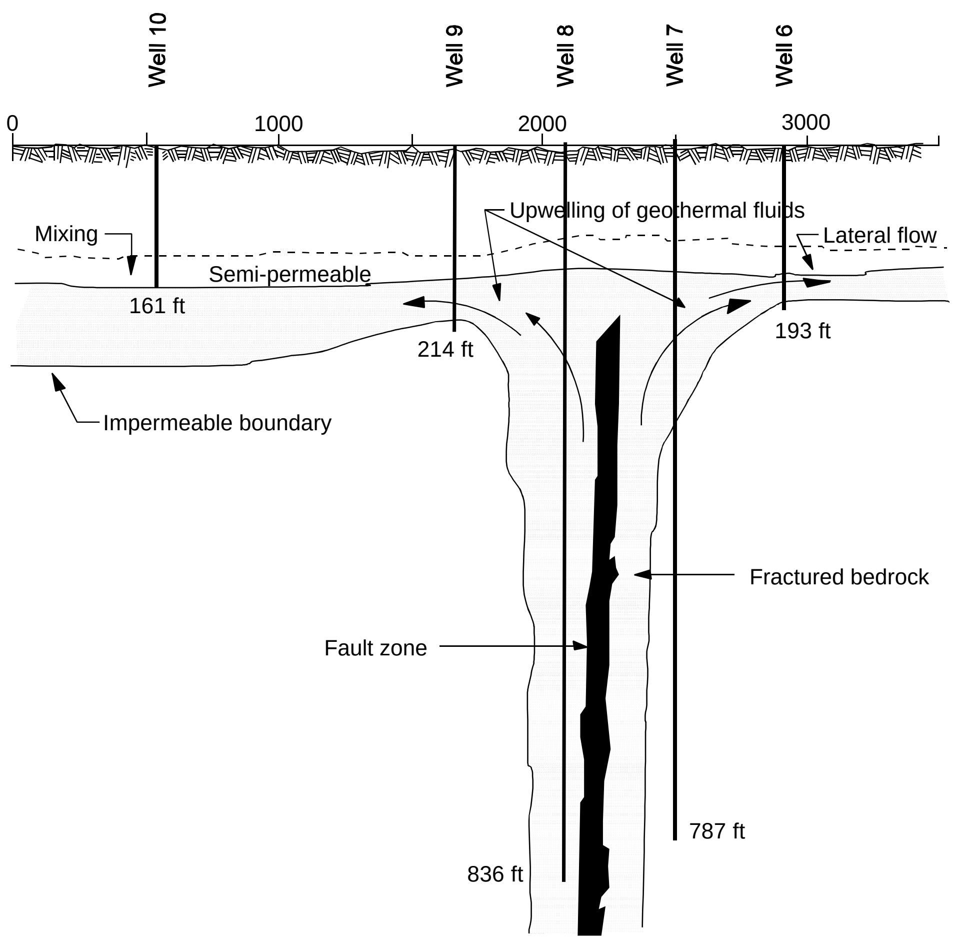

Figure 4. Schematic diagram of the fault-charged hydrothermal system at Calistoga (Youngs, et al., 1980).

A number of test holes in Calistoga were drilled using the dual-tube air-rotary method which allows very accurate lithology and chemical sampling as the well progresses. In a well drilled through the shallow aquifer, water quality gradually decreased to 120 feet, remained relatively constant to 664 feet, then increased to the bottom hole depth of 885 feet (Murray, 1986).

Murray (1986) obtained water samples from a large number of wells in the Calistoga area. Temperature contours (Figure 5) and isochloride concentrations (Figure 6) indicate upwelling along the valley axis and cooling with increasing water quality as the fluids move away from the upwelling zone. A similar situation occurs at Desert Hot Springs where measured temperatures were compared with geothermometry temperatures (Figure 7). The higher geothermometry temperatures indicate higher chemical concentrations (Corbaley, 1986).

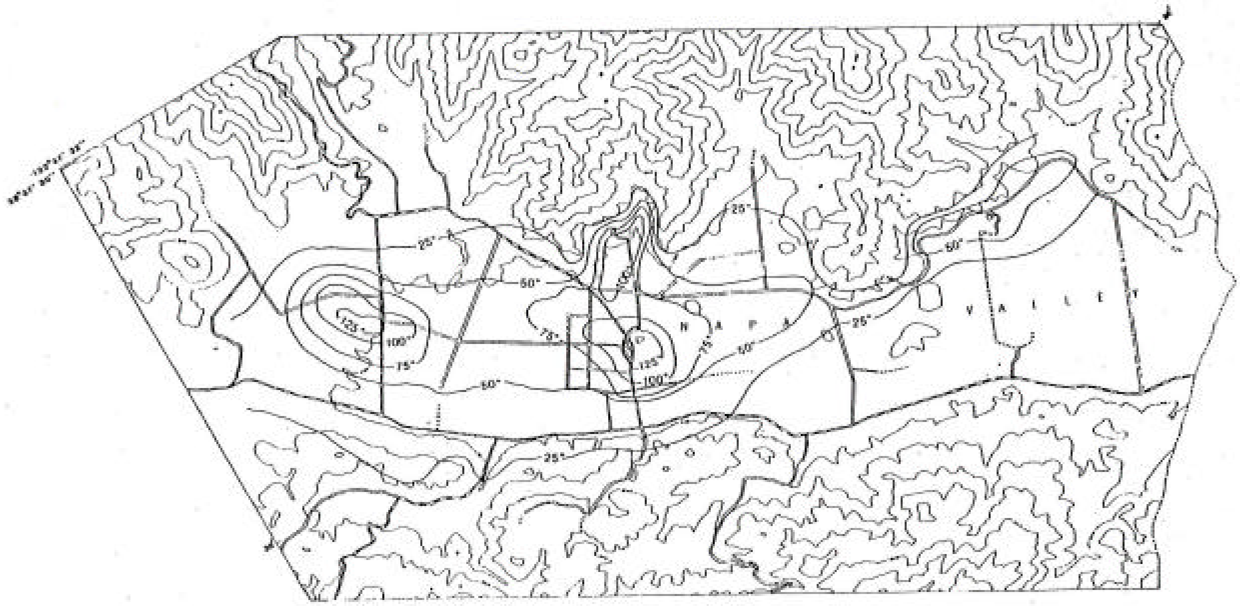

Figure 5. Isothermal map of water temperatures from wells 200 to 300 feet deep.

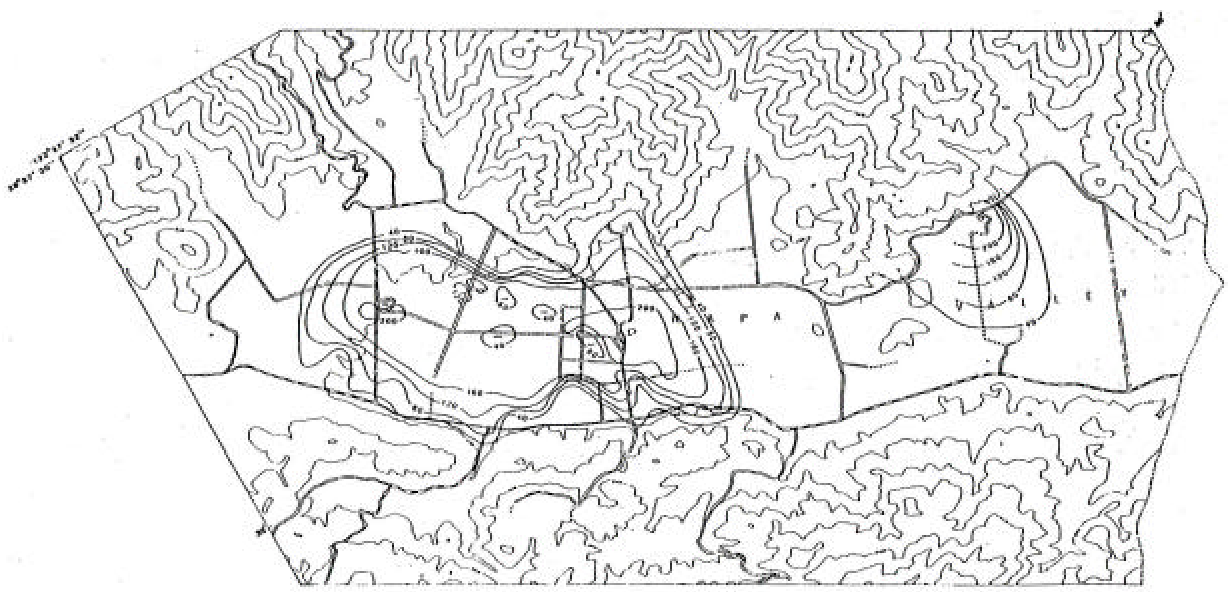

Figure 6. Isochloride concentrations map.

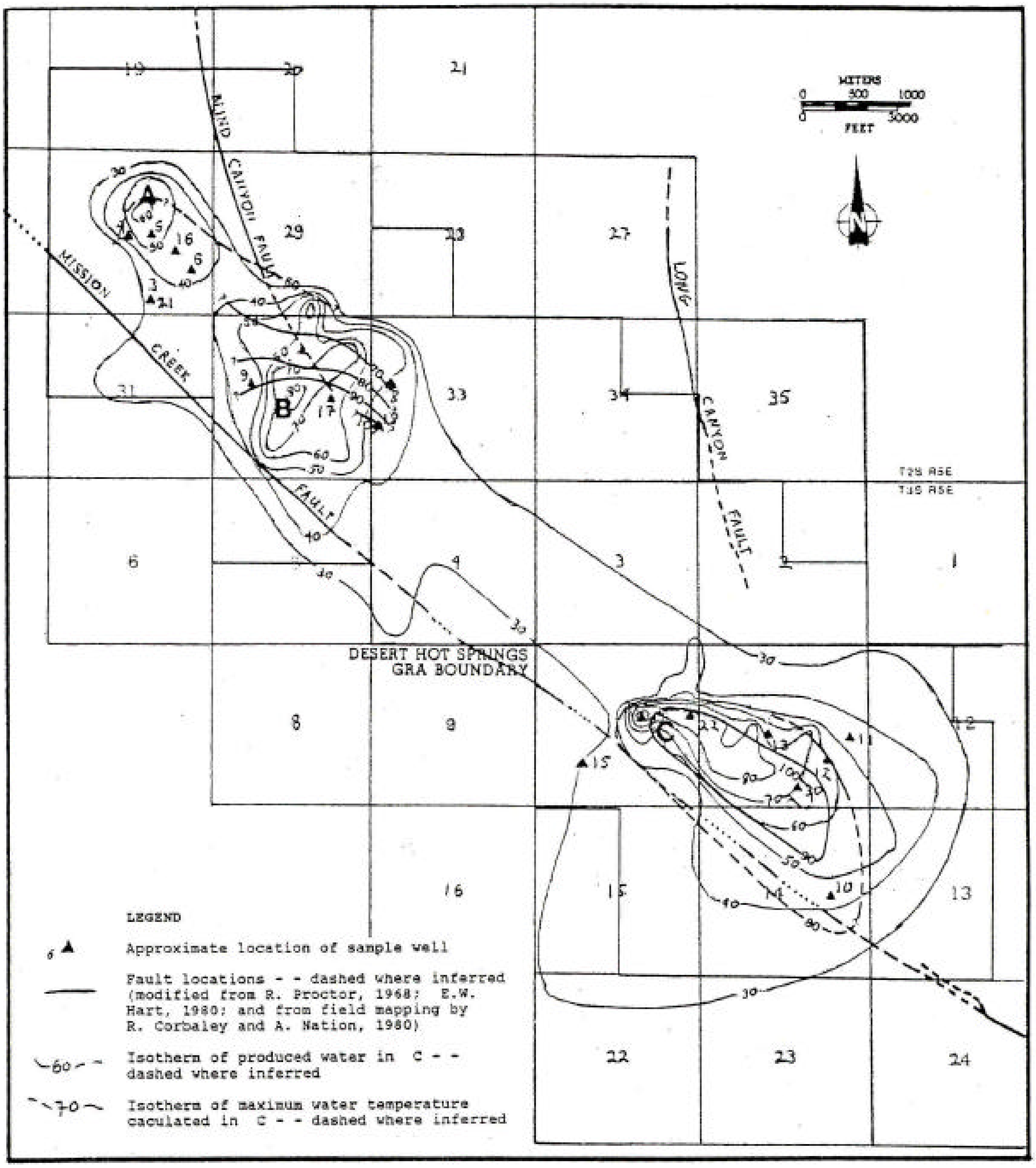

Figure 7. Map of Desert Hot Springs Area in California, showing locations of sampled wells, traces of major faults, isotherms of produced-water temperatures, and isotherms of maximum water temperatures. Maximum water temperatures were calculated by averaging two chemical geothermometer equations for SiO_2 and Na-K-Ca.

Figure 8 shows the temperature gradient for one of the Klamath Falls district heating system production wells. This is a classic example of a temperature reversal after drilling through the shallow geothermal aquifer. Note that it appears that there may be another geothermal aquifer, at about the same temperature, just below where drilling stopped. This second aquifer, if it really exists, has never been encountered in any wells in Klamath Falls--but there are very few wells this deep and none nearby.

This well was originally cased to 360 feet and during the first pump test produced 60 gal/min of 190°F water with a drawdown of 170 feet = .35 gpm/ft. After perforating between 195 and 240 feet, the well produced 720 gpm of 212°F water with a drawdown of 7.2 feet = 100 gpm/ft. This isolated example may not be typical but simple logic tells us the difference in transmissivity between the geothermal aquifer and zones above and below must be significant else those zones would be part of the geothermal aquifer.

What happens to the geothermal water? Obviously where there are surface thermal springs, the water mixes with and becomes part of the surface water.

Only a small part of the fluids in most lateral leakage reservoirs reaches the surface. As the water moves away from the fault, the upflow zone spreads filling a continuously enlarging volume. In a homogenous reservoir of uniform thickness, the volume will increase as the square of the radius ($V = \pi r^2 h$). A constant flow entering an ever increasing volume means flow rates at the perimeter of the volume continuously decrease. Thus, the water cools and equilibrates more rapidly at the perimeter and we see isothermal and isochemical contours at closer and closer spacing--as we saw in Figures 5, 6 and 7. The shape of the contours is determined by hydraulic gradients and permeabilities.

As the geothermal fluids move away from the upwelling zone, they also mix with cool ground and meteoric waters. Flynn (1983) found geothermal fluids at Moana decreased in average age and in-creased in tritium content as sampling traversed from west to east away from the fault area assumed to be the source of geothermal fluids. Concentration of bicarbonate and magnesium increased and boron, sulfate, silica and calcium decreased moving west to east.

The Boise Capital Mall district heating system wells are down hydraulic gradient from the Boise City system wells. In Table 1 we see that in the Capital Mall system temperature, TDS, silica and sodium are lower, and pH and carbonate are higher than in the City system--as would be expected for cooling equilibrating waters. The anomalously higher sulfate in the Mall's system is perhaps due to sampling procedure. The City system has a small amount of hydrogen sulfide. If the Mall system also has H_2S, improper sampling and handling would allow the H_2S to oxidize to SO_4.

Table 1 provides major chemical species for most of the larger direct applications of geothermal energy in the west. All applications listed are district heating systems; but, the chemistry is typical of many other resources. Geothermal water is used for culinary use and bathing at Boise,

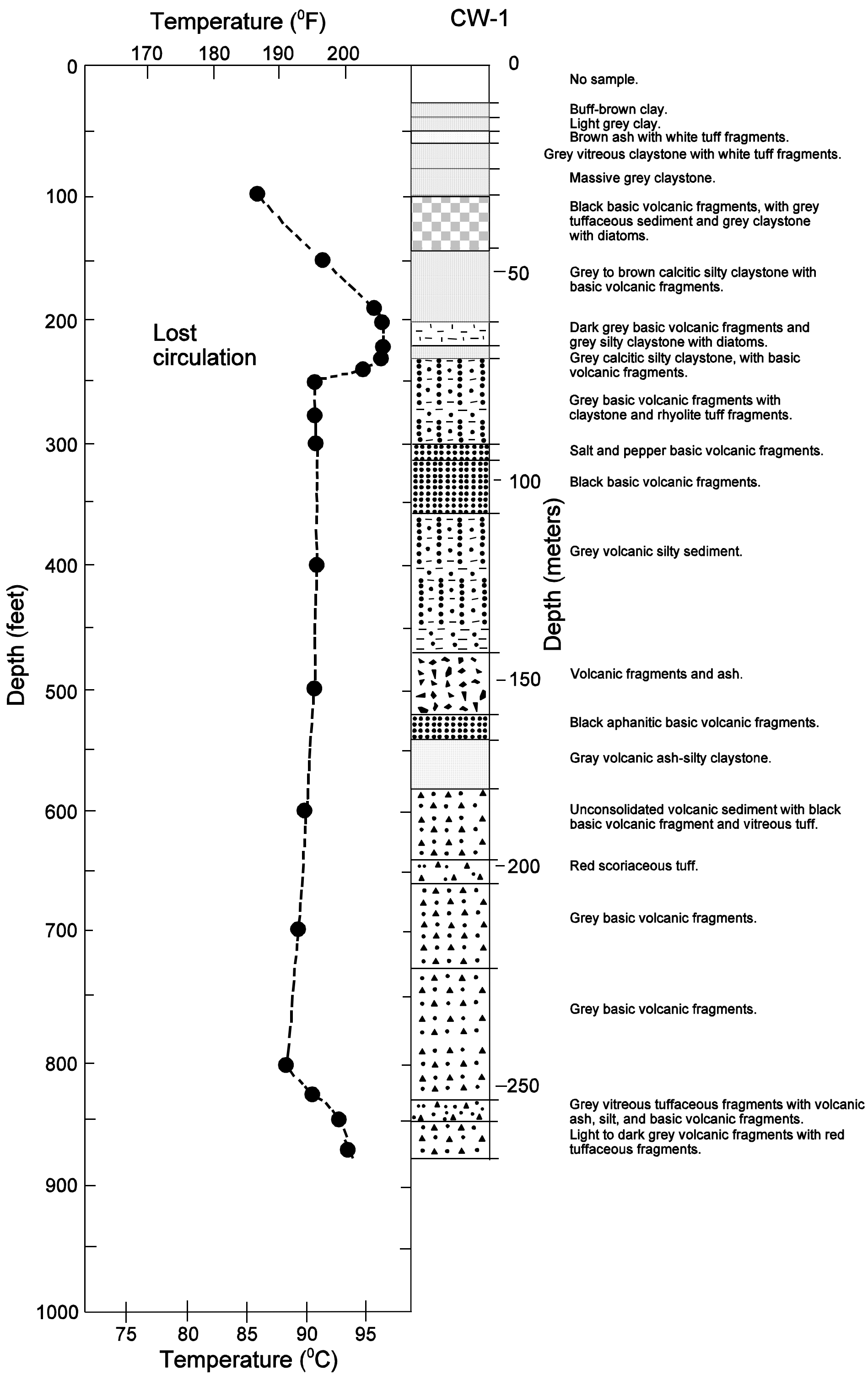

Figure 8. Lithologic log and temperature profile for Well CW-1.

Table 1.

	Boise Capital Mall	Boise City	San Bernardino	Susanville	Warren Estate (Reno)	Pagosa Springs	Elko School	Klamath Falls
Temp. ^oF	169	176	136	174	196	140	190	210
TDS mg/l	283	290	290	810	1097	2160	645	765
pH	8.9	8.2	8.6	8.1	8.2	6.7	7.7	8.6
SiO_2 mg/l	88	160		116	61.4	77.8	48	
Ca	2	2	9	32	26	240	68.9	26
Na	83	100	116	205	285	640	114	205
K	1.7	1.6			10	87	38.5	4.3
SO_4	32	23	32	294	505	1520	71	330
Cl	10	10	82	120	56	160	18	51
F	18	18			5.2		1.86	1.5
CO_3	25	4	12	1		0	0.01	15
HCO_3	70	70	88	37	6	810	500	20
NO_3	1	1	49					4.9
B	0.14	0.14	2.2	2.5	2.4	>5		
H_2S		Trace		0.5			0.6	1.5

Reno, Klamath Falls and many spas and resorts, and for laundry at Elko, San Bernardino, Klamath Falls, and again at many spas and resorts. The water is quite benign and often meets potable water standards.

Most geothermal direct use applications surface discharge. This is quite natural since most of the developments use or are very near natural thermal springs and to do otherwise would change the ecosystem. However, in some areas development and pumping from wells has halted natural spring flow and significantly lowered aquifer pressure/water levels. A few areas were "blind" resources, there was no surface discharge, i.e., Susanville, CA and Newcastle, UT. Injection is desirable in order to maintain aquifer pressures and sustain continued utilization. This brings up the question of where to inject.

From the explanation of how we think the systems work, it is obvious that siting production wells very near the fault providing the upflow will provide the hottest fluids. This minimizes capital and operating costs since we can extract more heat from a given volume of fluid. It follows that injection wells should be located far enough from production wells to minimize temperature break-through, yet within aquifer boundaries in order to maintain pressures.

If injection is at another location along the fault, there is danger of thermal breakthrough. Along the fault permeability is high and fracture controlled. Fluid velocity between wells within the fractured area is not dependent on the square of the distance as in a homogenous aquifer, but directly on the distance. Tracer studies have shown fluid velocities in the low-temperature resource at Klamath Falls can be as much as 50 ft/per hour (Gudmundsson, 1984) and velocities of 80 ft/per hour have been noted in high-temperature fracture controlled resources (Pruess, 1983).

Injection into the permeable outflow zone provides several advantages--provided there are no hydrologic boundaries between injection and production.

1. The outflow zone is more likely to behave hydrologically like a homogeneous aquifer.

2. The natural hydraulic gradient tends to oppose the impressed hydraulic gradient caused by pumping and injecting.

3. Fluids in the aquifer are cooler here and injection of fluids cooled by the surface utilization will have less impact on any nearby wells.

This kind of injection scheme short circuits the natural system. Fluids that are destined to arrive at or near the injection site at some future time simply arrive sooner.

However, there are some factors that have created a dilemma. Fluids moving naturally through the system may take years, tens of years or even more to travel the distance from production well to injection well. As they travel, they cool, chemically equilibrate to the lower temperature and mix with some meteoric water. Pumped water on the other hand may arrive at the injection well in minutes. Since the equilibration process is slow and the pumped water has no opportunity to react with rocks or mix with meteoric water, it arrives at the injection well essentially chemically the same as when it was pumped, even though it may be the same temperature as the aquifer surrounding the injection well. Therein lies the dilemma.

Some regulating agencies have taken the stand that injection must be into an aquifer of equal or lesser quality water even though the fluids may be chemically similar. This is an admirable goal and understandable when dealing with classical cold and relatively static groundwater systems. But, it places severe restrictions on utilization of many direct use geothermal resources and will prohibit use of many.

It is true that there will be a plume of lesser quality fluids down gradient from the injection well. The extent of the plume and its impact depends on the aquifer characteristics and the location and type of down gradient uses.

Geothermal resources can provide economical and clean energy sources. There are no greenhouse gases, particulates or noxious gas emissions. Regulation of injection should recognize the natural processes within the reservoir and be broad enough to take into account current and future beneficial use of both the water and the heat it contains.

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