Geothermal Resources Council, SPECIAL REPORT NO. 13, May 1983

BASIN AND RANGE GEOTHERMAL HYDROLOGY: AN EMPIRICAL APPROACH

FRANK YEAMANS

Reno, Nevada

ABSTRACT

Basin and Range hydrothermal systems are dynamic flow systems rather than reservoir systems. The systems share underlying fundamental similarities such that they can be classified as a generic group. The systems are structurally controlled, occurring where the extensional tectonics of the province have created permeable flow paths. Possible recharge zones can be identified by stable isotope relationships and, if available, hydrologic and geologic information from deep wells. Where there are no cold meteoric waters to sample and few deep wells the location of recharge zones is speculative. Depths of circulation can be roughly estimated by use of predictive chemical geothermometers and measured temperature gradients but actual flow paths are unknown. Saturated thicknesses, porosity, lateral extent and boundaries all are either unknown or can be estimated only in the most favorable of circumstances. The discharge zone is the best understood part of the system. The discharge rate, including convective heat discharge, can be calculated with varying degrees of accuracy, depending upon the physical setting (surface, subsurface, or both) of the individual discharge zone.

Production zones are fracture or fault controlled and may be separated by significant blocks of impermeable rock. The effective porosity of production zones may be very low, perhaps less than 1-2% of the total thermal anomaly defined by drilling. The existence of deep reservoirs is problematical. Flow test data have been interpreted as indicating extremely large volumes of fluid in place yet deep drilling (>1000 meters) has been disappointing.

Empirical methods that do not require knowledge of the controlling hydrologic parameters can be used to evaluate the natural energy discharge and to predict production potential. Step-wise increases in the production rate allows development of empirical response curves that, with longer periods of record, will predict system response to increased production rates in the future.

INTRODUCTION

Previous work on Basin and Range hydrothermal systems has demonstrated a basic similarity in the geologic setting of these systems (Hose and Taylor, 1974; Olmsted et al,. 1975; Garside and Schilling, 1979). Studies of individual hydrothermal systems have viewed them as being within the overall framework of Basin and Range hydrothermal systems; Steamboat Springs (White et al., 1964), Roosevelt Hot Springs (Nielson et al., 1978), Long Valley (Sorey et al., 1978), Leach Hot Springs (Welch et al., 1981), Stillwater hydrothermal area (Morgan, 1982). Thus, just as it can be held that Basin and Range hydrothermal systems share sufficient common geologic characteristics to be classified as a generic group, it is thought the hydrologic regimen of the systems share an underlying fundamental similarity.

Continued research coupled with exploration efforts have increased the knowledge of these systems, particularly the intermediate and deeper levels. Basin and Range hydrothermal systems are liquid dominated dynamic flow systems transporting thermal energy from deeper levels to the shallow subsurface and to the surface. They are not, in the main, porous-medium reservoir or storage systems and thus are distinct in this respect from geothermal reservoirs in other provinces such as the Imperial Valley. Successful development of Basin and Range hydrothermal systems must be based on a clear understanding of the fundamental hydrologic regimen.

The first part of this paper reviews the common hydrologic components of Basin and Range hydrothermal systems. The systems discussed generally are the high temperature (>150°C) ones where exploration drilling and testing have led to an increased understanding of the deeper parts of the systems. The fundamental similarities of these systems should be applicable to low (<50°C) and moderate (50°-150°C) temperature systems in the Basin and Range province. The Steamboat Springs system frequently is used as an example as much research and exploration work has been done there.

The second part of this paper examines the geologic and hydrologic setting of some Basin and Range production wells. Many of the production wells have similar production zone characteristics and thus an understanding gained from one well is applicable to others. The geologic and hydrologic factors that control production from one Basin and Range hydrothermal system also operate, although perhaps in different proportions, to control production from other Basin and Range hydrothermal systems.

Lastly, a conceptual hydrologic model is presented. An empirical lumped parameter method is proposed as an appropriate approach for future geothermal exploration and development in the Basin and Range. An advantage of this approach is that it does not require detailed knowledge of such hydrologic characteristics as hydrologic boundaries, porosity, transmissivity, and storativity.

HYDROLOGIC CHARACTERISTICS

In a systems approach a Basin and Range hydrothermal system can be divided into several components that can be studied individually. Within a geologic setting the system is composed of:

1) recharge zone - where the recharge water enters the subsurface;

2) flow paths - the subsurface pathways the fluid follows;

3) depth of circulation - the depth of circulation required to obtain the maximum temperature, assumed to be the maximum depth of circulation;

4) discharge zone - channels and flow paths of upflow from the deepest depth of circulation, includes surface discharge as hot springs and subsurface discharge into thermal aquifers.

Geologic Setting

When discussing the geologic setting of a Basin and Range system it generally is the discharge zone that is placed within a geologic setting as it often is the only component that can be readily identified and studied. Discharge zones are associated with three structural settings.

The close spatial association of many Basin and Range hot springs with major range-bounding faults indicates the underlying portions of the discharge zones of the hydrothermal systems also are related to the faults. Production wells at Dixie Valley (Parchman and Knox, 1981) and Beowawe (Epperson, 1982) are thought to tap upflow zones along the faults. The Kemp thermal anomaly indicates thermal waters may circulate along the range-bounding faults even where there are no surface thermal manifestations (Flynn et al., 1982). Such flow probably is a common occurrence creating numerous small thermal anomalies along many of the range-bounding faults. At Long Valley many hot springs are located within the resurgent dome suggesting the volcanic feature is responsible for the location of the springs. However, within the resurgent dome many of the hot springs are found along the Hilton Creek fault, an active Sierra Nevada frontal fault bisecting the caldera's southern margin (Bailey et al., 1976). The association of the hot springs with the fault suggests the springs occur where there is permeability along the fault (Bailey et al., 1976).

A second geologic setting for the discharge z is within small, highly faulted, relatively low relief, horst blocks. Found here are Desert Pea (Benoit et al., 1982), Steamboat Springs (White al., 1964), and Coso Hot Springs (Duffield and Bacon, 1981). These are among the hottest known systems in the western part of the province. These horst blocks are not the main, high-relief ranges of the province.

A third setting is within the basins at consi erable distances from the ranges and with few su indications of structural control. Examples inc the Hyder Hot Springs that emerge in the middle Dixie Valley and the Soda Lake hydrothermal syst that is at least 18 km. from any major mountain There is evidence, however, that structural feat are controlling the location of these thermal sy tems. The homogeneous water chemistry of the Hy Hot Springs suggests a fault-controlled flow sys separated from the cold water aquifers in the al luvium (Denton et al., 1980). The Soda Lake hyd thermal system is associated with a buried struc feature defined by the phreatic explosion crater Soda Lake and the volcanic Upsal Hogback to the east (Olmsted et al., 1975; Hill et al., 1979).

Thus Basin and Range hydrothermal systems are structurally controlled. They are not confined the main range-bounding faults, however, but may occur within other structural settings where the extensional tectonics of the province have creat permeable flow paths. There is no geologic evid of stratigraphic or lithologic control of latera extensive hydrothermal systems at drilled depths

Recharge

The oxygen-deuterium stable isotope relations has been used to identify possible recharge zone for hydrothermal systems. Meteoric waters, part cularily cold springs, with the same deuterium v as the oxygen-shifted thermal water can be consi to be located within a possible recharge area fo hydrothermal system (Craig et al., 1956). Basin Range recharge studies include Coso Hot Springs (Fournier and Thompson, 1980), Steamboat Springs (Nehring, 1980), Roosevelt Hot Springs (Rohrs an Bowman, 1980), and Long Valley (Sorey et al., 19

Nehring (1980) concluded the major recharge z for the Steamboat Springs hydrothermal system is the Carson Range some 16 km. to the west of the springs. Similar deuterium values for cold spri and thermal waters suggests the recharge zone is an average elevation of 2100 meters and limited an area between Galena Creek and Evans Creek (Fi 1). Nehring (1980) concluded recharge along majo faults within the Carson Range moves deep enough to be heated by regional conduction or by a poss magma chamber beneath the Steamboat Hills (Fig.

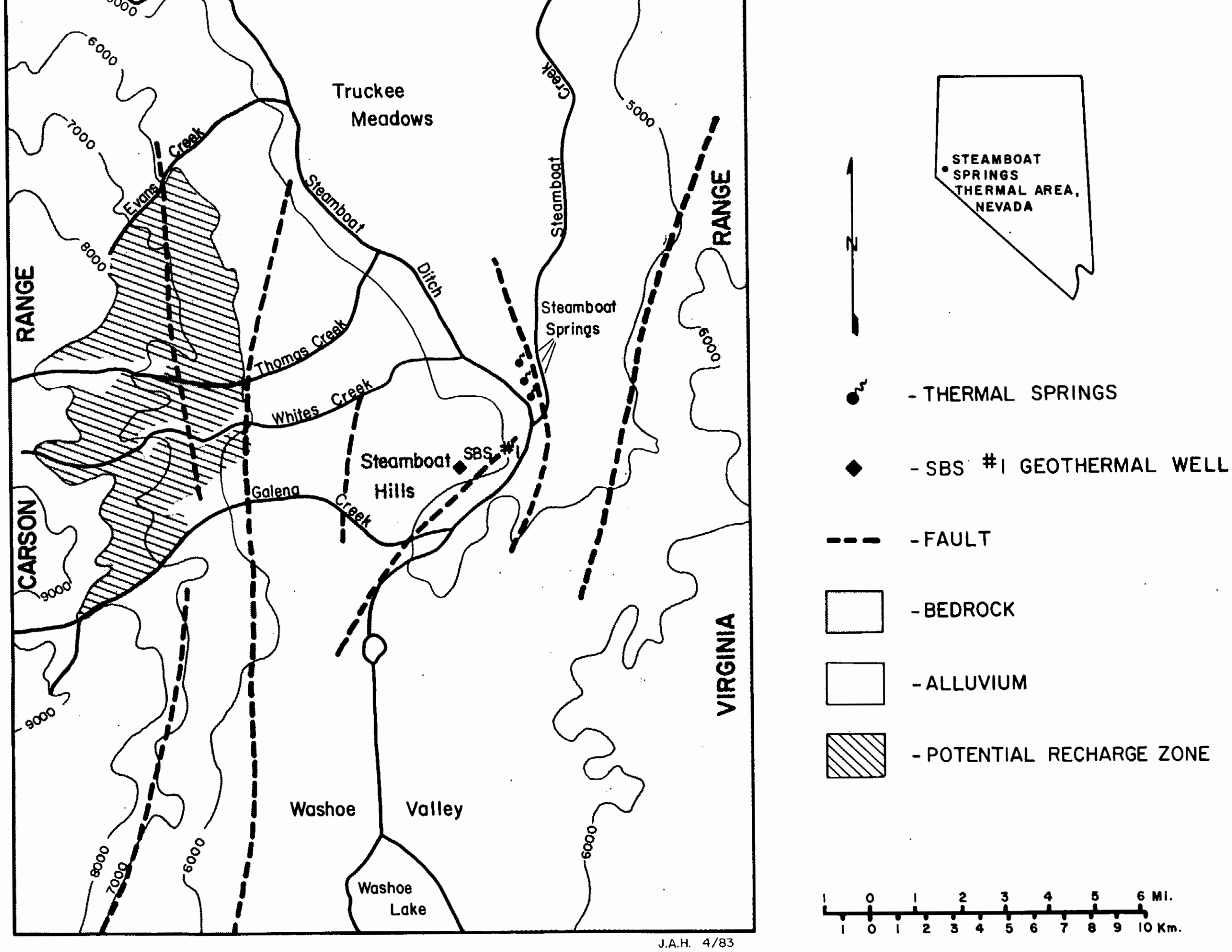

FIGURE 1. Potential recharge zone to the Steamboat Springs hydrothermal system (modified from Nehring, 1980).

There also is hydrologic data to support this isotope recharge model. Skau (in preparation), using data from numerous drainage basins on the east front of the Sierra Nevada, defined an inverse relationship between streamflow and total linear length of mapped faults within a drainage basin. Skau's data indicates the Galena, Whites, and Thomas Creek drainages have extensive faulting within the mountain block and less than expected streamflow where the streams debouche onto the alluvial fan.

Identification of one potential recharge area does not preclude the possibility of other recharge areas or more than one flow path for the recharge water. At Long Valley the large areal variability in the isotopic composition of the thermal waters indicates the involvement of meteoric waters from at least two different sources (Sorey et al., 1978).

Some Basin and Range hydrothermal systems have very subtle recharge systems. Welch and others (1981) suggested discharge at the Leach Hot Springs either is from modern-day precipitation at an elevation higher than that in the immediate vicinity of the hot springs or it was recharged during an earlier, colder, climatic period. This conclusion is based on the fact deuterium values of the thermal waters are more negative than that of the surrounding cold waters. Elevation zones where precipitation can be expected to have the same deuterium values as that of the thermal waters are so far away (160 km.) that under a ground water flow rate of 10 meters/yr. the infiltration event could have occurred up to 16,000 years ago and thus the recharge water still would be considered "paleowater" (Welch et al., 1981). Young and Lewis (1980) suggested present-day discharge from the Bruneau-Grand View hydrothermal system in Idaho was recharged during late Pleistocene glacial advances when the climate averaged 3-5C° colder than at present.

The Desert Peak hydrothermal system is located in the arid Hot Springs Mountains where the small amount of precipitation is consumed by evapotranspiration and there is little or no ground water recharge except from rare, high-intensity storms that occur years or decades apart. No springs exist in the mountains nor are there a significant

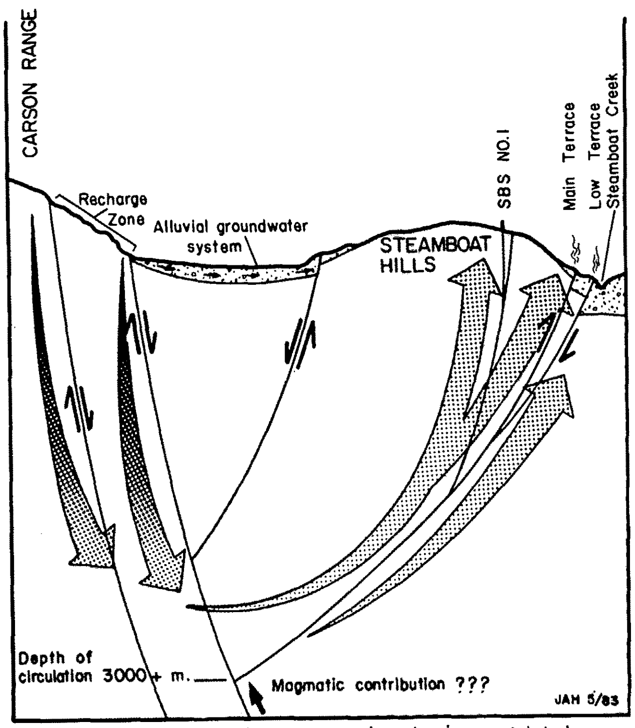

FIGURE 2. Diagrammatic cross-section showing postulated recharge to the Steamboat Springs hydrothermal system.

number of cold water wells that can be sampled for isotope values. In this instance another approach must be used to identify the recharge zone. A recharge mechanism is discussed later in the section on hydraulic gradients.

Delineation of recharge zones by isotope studies alone is circumstanial in those areas where there are meteoric waters to be sampled. Only in rare instances are there a sufficient number of deep wells from which hydrologic and geologic data can be collected to substantiate conclusions based on isotope data. In areas where there is no correlation with nearby meteoric waters the recharge mechanism of the hydrothermal system remains speculative. If recharge occurred at an earlier time under different climatic conditions is it still occurring and at what rate? If recharge is occurring at great distances from the discharge zone where is the recharge zone and what is the nature of the aquifer system that allows such a long flow path in the structurally discontinuous Basin and Range province?

Depth of Circulation and Flow Paths

The minimum depth of circulation required for conductively heated hydrothermal systems under steady-state conditions can be estimated from the following equation. Note that with flow paths of finite length greater depths of circulation would be required to attain the observed or estimated temperature. (Welsh, et al., 1981).

$$D = (T_s - T_r)/g$$

where D = depth of circulation;
T_s = maximum temperature in system, predicted from geothermometers;
T_r = surface temperature of recharge water, generally taken as the average annual temperature;
g = temperature gradient.

A conductive temperature gradient of 76.4C°/km was measured in the fine-grained sediments of the Carson Sink (Olmsted et al., 1975). Using this gradient and assuming a 10°C temperature for the recharging water, the depth of circulation for th 204°C Desert Peak hydrothermal system would be at least 2.5 km. This estimate assumes the temperat gradient is constant with depth. If more thermal conductive rock is present above the 2.5 km. dept there would be a lower temperature gradient and thus greater depths of circulation would be requi to obtain the same maximum temperature. For Leac Hot Springs Welch and others (1981) estimated a depth of circulation on the order of 3 km. to obt temperatures of 180°C. Sammel and Craig (1981) calculated a circulation depth of at least 4 km. to obtain a temperature of 170°C for the Warner Valley hydrothermal system. Morgan (1982) calculated that for a maximum temperature of 160°C depth of circulation would be at least 2.5 km. fo the Stillwater hydrothermal system.

The deepest production well in Dixie Valley is 2.8 km.(Benoit and Butler, 1983), within the ran of the minimum depth of circulation required for conductive heating to what is thought to be a maximum temperature of over 200°C for the system. An earthquake swarm in Warner Valley produced seismic focal points along the western boundary fault at depths between 2 and 13 km. (Schaff, 1976 in Sammel and Craig, 1981). This indicates fault planes exist to depths of 13 km. in Warner Valley and such faults could be conduits for circ lation within the hydrothermal system. Thus it appears permeable conduits exist at the depths required for conductive heating.

Fluids at or near the maximum predicted temper atures have been found at depths much shallower t the depth required for conductive heating; 204°C 915 meters at Desert Peak (Benoit et al., 1982); 227°C at 760 meters at Steamboat Springs (Desormi 1983). These high temperatures in the shallow su surface are maintained by relatively high upflow rates that overcome conductive heat loss to the w rock (Sorey, 1975).

It has been hypothesized that a magma chamber is present beneath the Steamboat Hills and serves as the heat source for the Steamboat Springs hydr thermal system (White, 1968). Depths of circulat could be much less than that required by regional conductive heating if the magma chamber were at a relatively shallow depth. However, if the alkali chlorides found in the thermal waters at Steamboa Springs are being transferred from the magma cham a hydrostatic pressure of at least 305 kg./cm.^{2} (3000 meters) is required for the existence of a dense high-pressure steam to transport the chlorides (White, 1968). Therefore, circulation may be to depths of a few kilometers even in the presence of a shallow, localized magmatic heat source.

Thus the extensional tectonics of the Basin and Range have created permeable flow paths at the necessary depths for conductive heating to the predicted and measured temperatures. Maximum depths of circulation remain unknown. It is interesting to note the maximum temperatures of the high temperature systems associated with conductive heat flow (Beowawe, Desert Peak, Dixie Valley, Humboldt House, and Soda Lake) generally are grouped together between 200°C and 225°C. This suggests they all may have a common maximum depth of circulation on the order of 2.5 to 3.0 km. There is no evidence that if a shallow localized heat source is present the depth of circulation is less than that for a regional conductive heat source. In any case fluids at or near the maximum predicted temperatures are found at relatively shallow depths due to rapid upflow along permeable conduits.

Hydraulic Gradients

Fluid flow in hydrothermal systems results from mechanical energy (potential differences) and thermal energy (density differences). Potential differences occur where recharge zones are higher than discharge zones. For hydrothermal systems in areas of high topographic relief recharge could occur in the mountain ranges and descend deeper than recharge to the shallow cold water aquifers. Flow direction, however, generally would be in the same direction (see Fig. 2).

Input of thermal energy creates a density difference when cold recharge water is heated. Depending on temperature differences, density differences can be a significant part of the overall hydraulic gradient. White (1968) calculated density differences could account for as much as 275 meters of the hydraulic head at Steamboat Springs. Recharge at an elevation of 2100 meters in the Carson Range would have an elevation advantage of 675 meters over the hot springs discharge zone.

At Desert Peak there is no evidence of a potential gradient from a recharge zone located at a higher elevation. It is possible fluid flow is solely the result of density differences. The Carson Sink to the east of and the Fernley Sink to the southwest of Desert Peak are sites of major shallow ground water discharge by evapotranspiration. Yet the sinks also may serve as recharge zones to the hydrothermal system. In a cross-section from the Carson Sink on the east through the well field at Desert Peak to the Fernley Sink on the southwest, the computed static water levels for the well field, referenced back to a column of water at 15.6°C, are lower than those of the surrounding sinks (Fig. 3). Although there is the possibility of a potential gradient from the Fernley Sink to the Carson Sink of 43 meters it also is reasonable to visualize recharge to the hydrothermal system coming from one or both of the sinks with the energy gradient required for flow being density differences created by the thermal energy of the heat source. Such a flow system requires a diversion of the discharge from the hydrothermal system (see Fig. 3). Part of the hydrothermal discharge flows down gradient to discharge in the sinks and part moves downward under the density gradient to become recharge to the hydrothermal system.

It is difficult to separate the potential and density differences of the total gradient. Both potential and density differences have both horizontal and vertical components (Olmsted et al., 1975). Determination of the vertical component requires at least two observation wells at different depths at a single location in the hydrothermal system. Determination of the density differences requires data on the entire depth and temperature distribution of the discharge zone. This generally is unknown but reasonable estimates can be made using the predicted maximum temperature and depth of circulation of the system.

Determination of the static pressure of an individual production zone also is difficult. Deep exploration-production wells generally are completed with several hundred meters of uncased open hole. If separate production zones with different static pressures are intersected the borehole pressure will be intermediate between the highest and lowest pressured zones intersected.

Discharge

The discharge zone is the best understood part of a Basin and Range hydrothermal system. Hot springs are the easiest place to collect data on heat and mass transfer and to predict maximum subsurface temperatures by using chemical geothermometers. Hot springs represent discharge from the deeper parts of the system and as such are an intergal component in exploration.

The total convective heat flow of a system provides a first approximation of the minimum rate at which energy can be withdrawn (Benseman, 1959, and Bodvarsson, 1964 in White, 1968). Thus understanding the discharge zone may be the key to evaluating the production potential of the hydrothermal system. Olmsted and others (1975) proposed two discharge systems, a leaky system where thermal discharge is into shallow ground water aquifers and a non-leaky system where the upflow conduits are sealed off from the shallow aquifers and all fluid discharge is via hot springs. All systems studied apparently have some subsurface discharge. For systems that have both surface and subsurface fluid discharge the ratio between the two can vary widely. White (1968) calculated hot spring discharge at Steamboat Springs constitutes only 6% of the total thermal fluid discharge of 71.2 liters/sec., the rest being discharged into the shallow ground water system and eventually into Steamboat Creek.

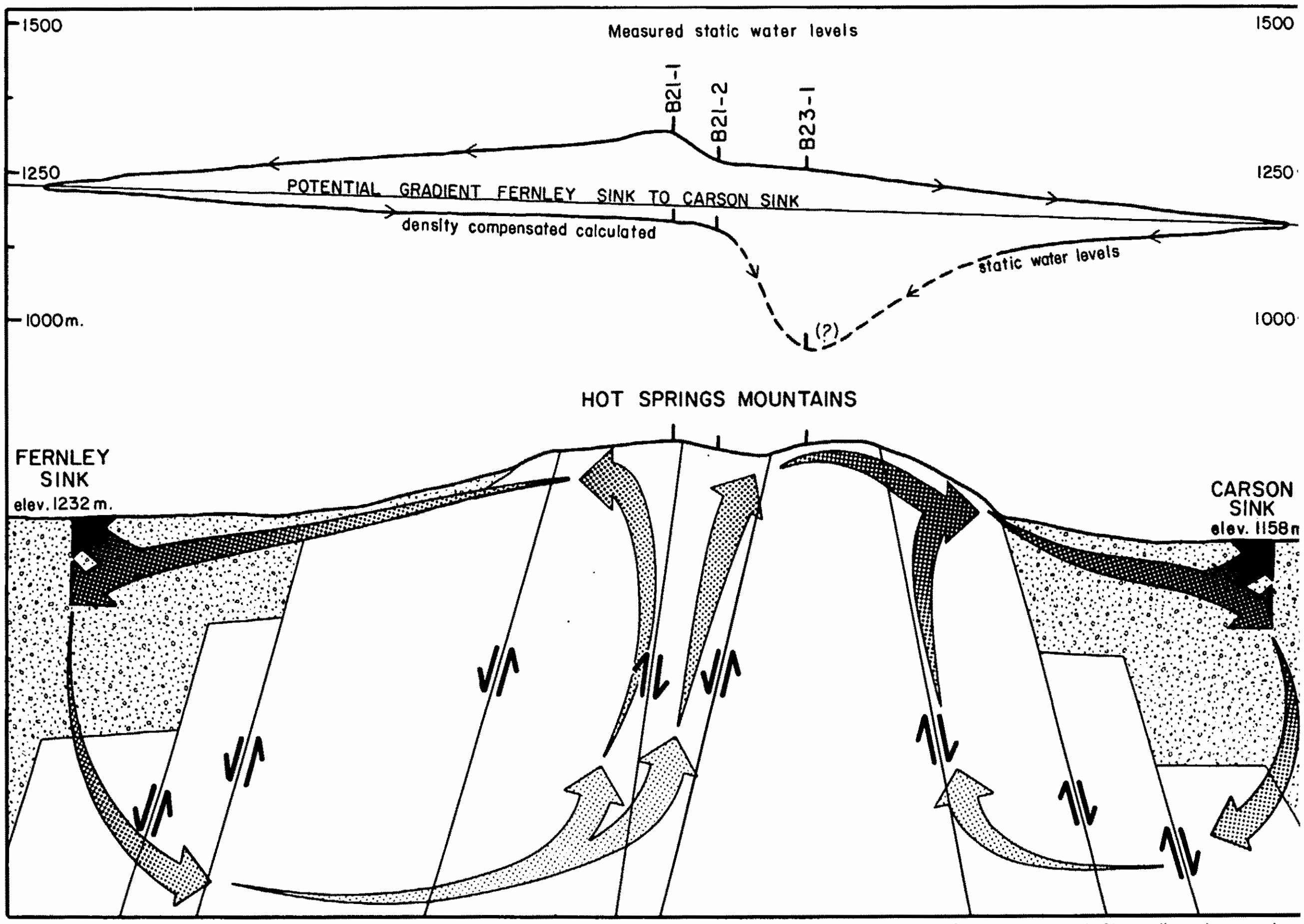

FIGURE 3. Diagrammatic cross-section through the Desert Peak hydrothermal system showing postulated flow direction and measured and calculated static water levels.

At Long Valley 80% of the total thermal fluid discharge of 248 liters/ sec. occurs as hot spring discharge within Hot Creek Gorge (Sorey et al.,1976). Some systems are totally leaky with all discharge into the subsurface. Roosevelt Hot Springs and Humboldt House are examples where spring flow has ceased and all discharge now is into the shallow subsurface.

Where there is no surface discharge and little or no other surface evidence of a hydrothermal system such as fossil hot spring deposits or altered and bleached rocks, the system is referred to as being "blind" (Blackwell and Czang, 1973). These systems can be identified by the thermal "halo" created by leakage into shallow thermal aquifers (Benoit et al., 1982). The shallow thermal aquifers have anomalously high temperature gradients above them (often >300C°/km.) and generally have a temperature reversal below the aquifer.

Calculation of total heat and mass discharge can be based on predicted maximum temperature by geothermometers and the measurement of conservative chemical constituents of the thermal fluid as found in nearby surface waters into which the thermal waters drain (White, 1968; Sorey et al., 1978). If there are no surface waters that collect the thermal discharge then calculations can be made of the amount of heat convected into the shallow thermal aquifers (Olmsted et al., 1975; Benoit et al., 1982).

A brief summary of the knowledge concerning the hydrologic setting of Basin and Range hydrotherma systems is as follows.

1) recharge zone - Where cold meteoric waters are available for sampling, possible recha zones and elevations can be identified. W there are no cold meteoric waters to sampl location of the recharge zone is speculati

2) depth of circulation - Can be roughly esti by use of predictive chemical geothermomet and measured temperature gradients; actua flow paths are unknown.

3) aquifer geometry - Thickness, porosity, la extent, boundaries, all are either unknown or can be only roughly estimated in the mo favorable of circumstances.

4) discharge zone - Discharge rate, including convective heat discharge, can be calculat with varying degrees of accuracy depending on the physical setting (surface, subsurfa or both) of the individual discharge zone.

Production Zones

Deep drilling in the Basin and Range province has intersected the higher temperature parts of hydrothermal systems in fractures in a "hardrock" environment. Commonly an isothermal zone in a static equilibrated temperature profile is interpreted as the production thickness. In a porous, liquid dominated sedimentary hydrothermal reservoir an isothermal zone may accurately reflect thermal convection within the production zone. This interpretation, however, often is not correct for Basin and Range wells. One interpretation is that by Urban and Diment (1982) who suggested the over 1480-meter thick isothermal section measured in well B23-1 at Desert Peak might result from hot water from a shallow, higher pressure thermal zone flowing down hole to exit in deeper, lower-pressure permeable zones. This flow would mask the undisturbed thermal regimen of the lower portion of the hole and would suggest an exaggerated thickness to the pay zone.

At both Steamboat Springs and Beowawe measured wellhead temperatures and pressures did not agree with predicted values from computer simulations of test conditions (Baza, 1981; Epperson, 1982). At Beowawe later geologic data indicated the well was producing from two intervals with the deeper interval having a lower production temperature (Epperson, 1982). At Steamboat Springs the ambiguity between predicted and measured values was resolved when a temperature survey was run while injecting cold water. The injection temperature survey identified a second production zone at the predicted temperature located below the maximum temperature isothermal zone (see Fig. 4).

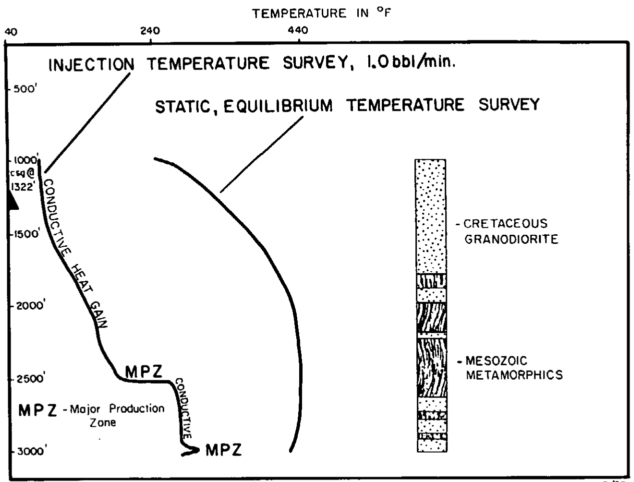

FIGURE 4. Static and injection temperature survey, S.B.S. no. 1, Steamboat Springs, Nevada.

The average depth of all successful high-temperature geothermal wildcat wells in the northern Basin and Range province from 1974 through 1981 was a relatively shallow 1030 meters (Edmiston, 1982). This depth is far less than the depths of circulation estimated by use of chemical geothermometers and background temperature gradients. The relatively shallow depths of production support the earlier statement that the existence of high temperature fluids at relatively shallow depths results from rapid upflow within permeable channels. Figure 5 is a generalized geologic map of the Humboldt

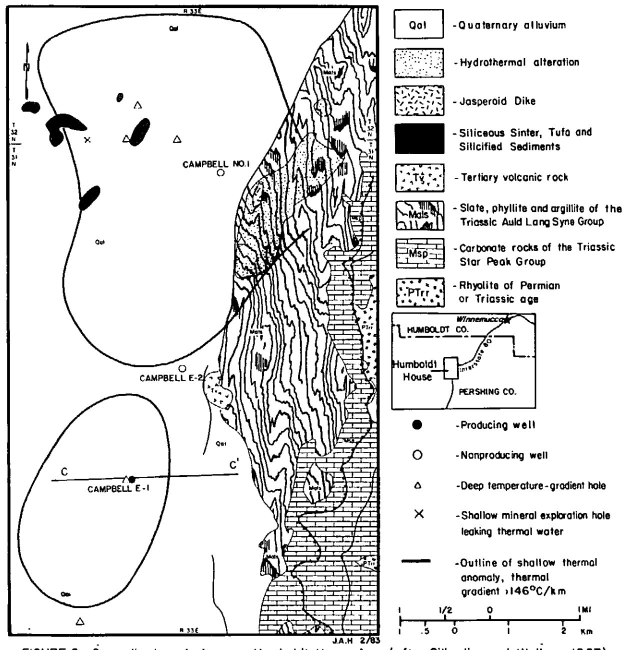

FIGURE 5. Generalized geologic map, Humboldt House Area (after Silberling and Wallace, 1967).

House prospect. It is of the main range-bounding fault type. Data from two deep wells, Campbell No. 1 and Campbell E-2, were used to construct the idealized geologic cross-section for the Campbell E-1, the only producing well in the prospect (Fig. 6).

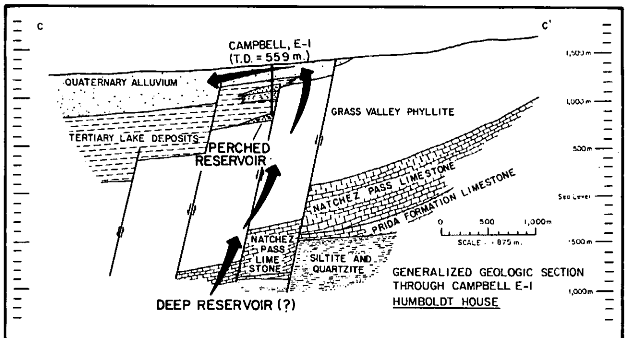

FIGURE 6. Generalized geologic cross-section through Campbell E-1, Humboldt House.

The well produces from a Tertiary limestone "boulder" deposit (Desormier, 1979) that can be considered a perched reservoir of limited volume. It is thought to be recharged from a deeper zone via a main range-bounding fault that is an upflow conduit. The recharge rate to the perched reservoir and thus the sustained or long-term production rate of the system is controlled by the least transmissive section of the upflow conduit (Welch et al. 1981).

At Desert Peak a temperature cross-section through the well field indicates the permeable upflow channels are nearly vertical and are separated by significant blocks of impermeable rock (Fig. 7). The elevated temperature contours in the vicinity of wells B21-2 and B23-1 result from upflow along

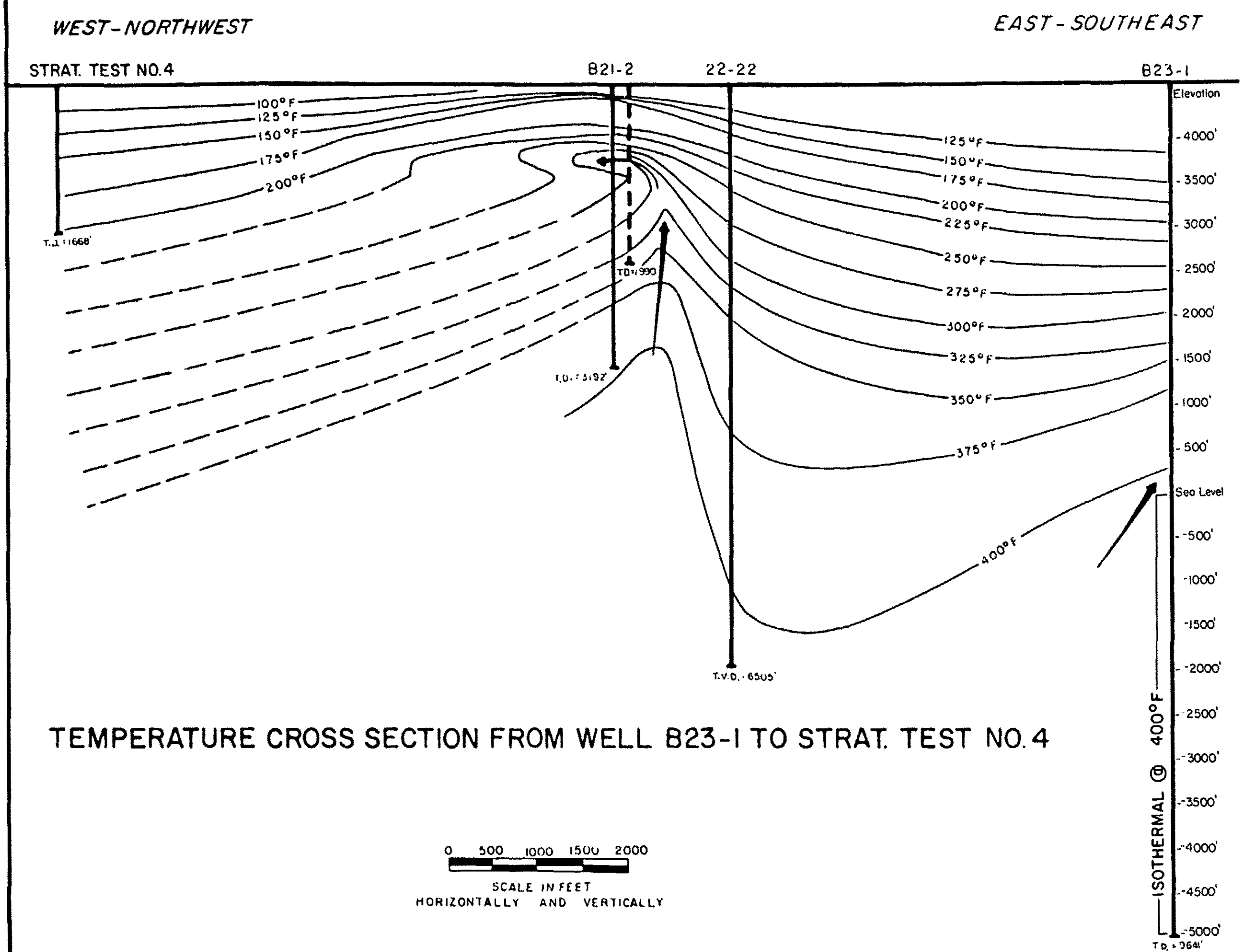

FIGURE 7.

the discharge zones that are the production zones. Well 22-22, not tested at this time, is at some distance from a discharge zone and is within a zone of low permeability as indicated by the relatively depressed temperature contours.

Thus it seems reasonable to assume Basin and Range production zones, if not directly in discrete and singular faults and/or fractures (Desert Peak), are the result of upflow of thermal waters along such zones (Humboldt House). Fracture density is not thought great enough to consider the production zone to be a fractured rock matrix with any significant (>10 meters) saturated thickness and the effective porosity of the production zone may be very low, perhaps less than 1-2% of the total thermal anomaly defined by drilling.

Flow Testing and Analysis

Benson (1982) described a flow test of a 120°C Basin and Range geothermal well, the results of which should not go unnoticed. The well, WEN-1, is located on the eastern side of the Honey Lake Valley, California, near Wendel and Amedee hot springs. From a depth of 1545 meters to the TD of 1780 meters the well is completed open hole in granitic basement rock. From pre-test temperature and spinner surv it was determined 80% of the flow comes from one major fracture zone. The production zone is unde confined conditions and the well was tested by single phase artesian flow at four flow rates.

During testing the productivity index, dischar drawdown, decreased with increased flow rates, go from 0.45 liters/sec. per kN/m^2 at 13.9 liters/se to 0.20 liters/sec. per kN/m^2 at 42.9 liters/sec. In a 100% efficient well with laminar (Darcian) flow in the formation the productivity index is a constant, independent of flow rate. In reality well bore damage or enhancement from drilling results in a skin value. For this test an increa in the flow rate resulted in a proportionate incr in the calculated apparent skin value. Under the conventional definition of skin effects the skin value of a well should not be a function of the flow rate. Using a formulation (Ramey, 1965) tha included non-Darcian flow in the production zone, Benson calculated a true skin value near zero for the well. It was concluded non-Darcian flow in the fracture contributed significantly to the drawdown, resulting in the varying productivity index. Benson then developed an empirical relationship between the flow rate and drawdown for the well tested. It is possible this non-Darcian flow is a common occurrence in high temperature, high discharge-rate Basin and Range geothermal wells producing from narrow fracture zones. The calculated transmissivity of the production zone will vary inversely with the flow rate.

Responses in observation wells can be simultaneously quick and at distances greater than 2500 meters. At the Beowawe field responses within one hour of start of flow were observed at distances up to 2000 meters from the production well (Epperson, 1982). Responses also indicate the anisotropic nature of the hydrothermal system. At Steamboat Springs one observation well 2573 meters from the SBS # 1 production well responded to testing within 48 hours after kick-off and had a 0.8 meter drawdown after 15 days of flow. A second well at a distance of 2598 meters did not show a response to testing. At Desert Peak the observation wells for the testing of well 86-21 were three deep wells that intersected the hydrothermal system at roughly the same depth. Responses in these wells indicate the production zone not only is anisotropic but also is heterogeneous (Goyal, personal communication). Thus at a given point in the system hydraulic parameters of the system (permeability, transmissivity) are directionally dependent (anisotropic) and the values of the hydraulic parameters vary from point to point within the system (heterogeneous).

Limited testing of Basin and Range geothermal systems commonly results in the calculation of large volumes of fluid being affected by the testing. At Beowawe it was calculated a fluid volume of 1.59×10^{13} liters was affected by a 27-day flow test at a rate of 463,050 kg./hr. (Epperson, 1982). Other flow test data at Beowawe "indicate fluid volumes in excess of 10^{12} barrels (1.59×10^{15} liters); in other words, a volume larger than the Prudhoe Bay Oil Field" (Epperson, 1982). It is thought the major part of the system at Beowawe is in lower Paleozoic carbonates at depths approaching 6100 to 9100 meters but none of the wells drilled to date have reached the deep carbonates (Epperson, 1982). Such a proposed reservoir model must be examined to see if it is realistic. Using the calculated fluid volume of 1.59×10^{15} liters, a reservoir with 10% porosity would have a total rock and fluid volume of 15,900 km^3. One must ask if this is a realistic model, especially in light of the disappointing results from deep drilling in the Basin and Range (Edminston, 1982). Thus, although flow test data have been interpreted to suggest deep, large-volume hydrothermal reservoirs, their existence still is problematical.

CONCEPTUAL MODELS

Reservoir Model

Traditional models for ground water and petroleum resources have treated these systems as static volumes. Development of a ground water or petroleum reservoir is based on obtaining knowledge of the physical and hydraulic parameters that control the

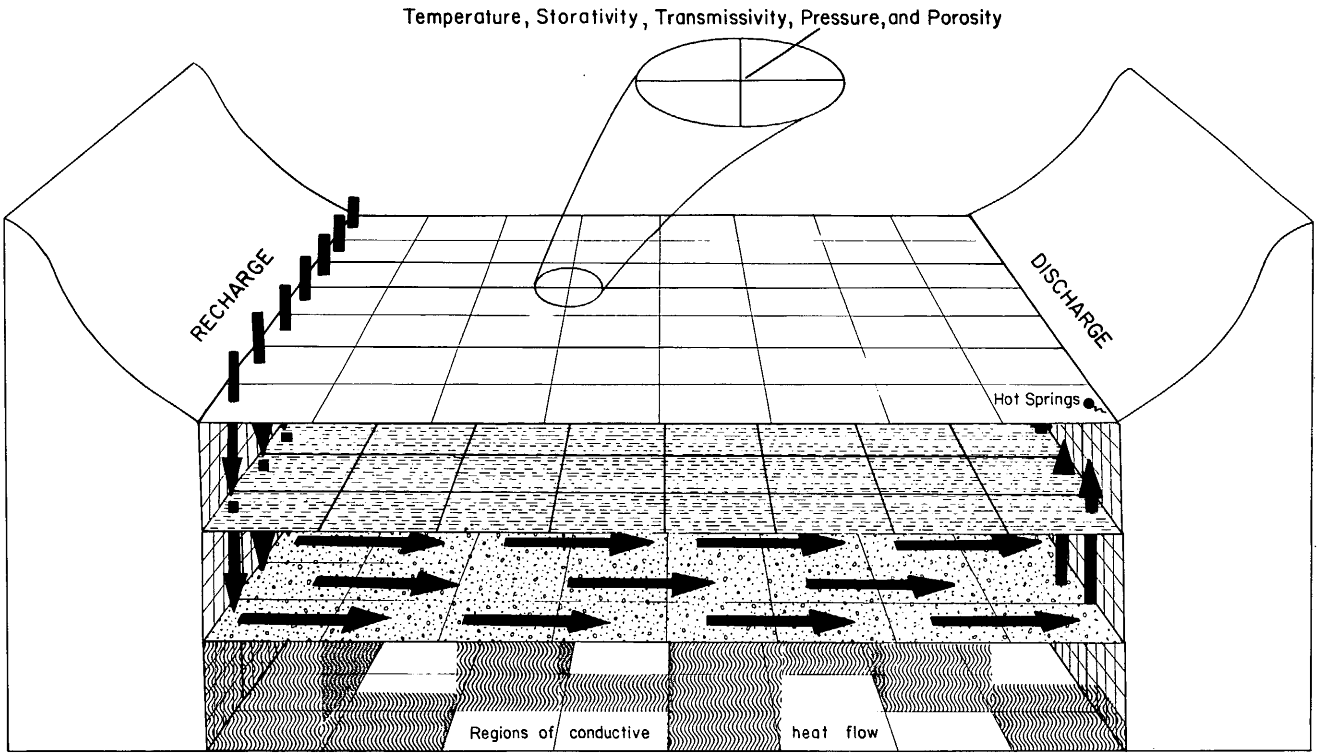

FIGURE 8. Idealized cross-section for a laterally continuous hydrothermal reservoir with overlay of grid required for a distributed parameter model (modified from Welch et. al., 1981).

production rate from the reservoir; transmissivity, storativity, viscosity, porosity and saturated thicknesses. Assuming a geologic setting (formation, lithology, and/or structure) that contains within it the hydraulic continuum of the reservoir, drilling and testing are performed to determine the physical and hydraulic parameters of the reservoir and to develop an analytical solution to predict future reservoir production potential. Figure 8 is an idealized hydrothermal system of the reservoir type that might be found in the Imperial Valley or at Cerro Prieto. A distributed parameter grid is overlain showing the reservoir parameters that would be defined for each node in the grid. However, drilling results to date have shown Basin and Range hydrothermal systems to be much more complex than the simplified model presented here.

In one respect development of a petroleum reservoir is different from that of a ground water system even though the underlying hydraulic principles are the same. Production from an oil or gas reservoir is an extraction process to remove as completely as possible the oil or gas that exists within a closed system (no "recharge" of oil or gas). Ground water development, however, involves taking water from storage at a faster rate than natural recharge. If pumping stops, over a long enough time recharge will replace the water removed.

Development of a Basin and Range hydrothermal system is closer to that for a ground water resource than that for the development of a petroleum reservoir. Using the Beowawe system as an example, it is uneconomical and impractical to drill wells to depths of 6100 to 9100 meters in order to "mine" the projected 10^{15} liters of fluid and contained energy in the hypothesized deep reservoir. Fluid produced from existing shallow production wells in the Malpais Fault discharge zone comes from the elastic compression of the reservoir as the pressure declines and from the expansion of the fluid (Domenico, 1972). As long as production is from the discharge zone the deeper portions of the systems will never be "mined" or dewatered. Productivity of the system will be governed by its storativity and transmissivity. In this situation "reservoir volumes" calculated from flow test data are an inappropriate measure of the production potential of the system.

Two Basin and Range hydrothermal systems have been modeled using numerical methods for assumed reservoir systems. The Long Valley system was modeled by Sorey and others (1978). The model was a three-dimensional distributed parameter numerical model that attempted to represent what were considered to be the actual physical parameters of the system. A later numerical model by Welch and others (1981) for the Leach Hot Springs was a generalized model that examined the constraints on the age, depth and lateral extent of the system without the formulation of a detailed physical model of the system.

Dynamic Flow Model

Hot spring and shallow subsurface discharge imply a dynamic flow system with recharge. If discharge zones and the associated upflow conduits are discrete zones separated by large volumes of impermeable rock with low or nonexistent porosity, then produced fluids cannot be coming from storage in the shallow part of the discharge zone. What occurs is that production, with its subsequent pressure decline, increases the flow rate up the upflow conduit in order to reach a new equilibrium with the new discharge rate, the natural discharge plus the production discharge. As explained in the prior section on the reservoir model, produced fluid comes from compression of the system and expansion of the fluid as system pressures decline. The system is not dewatered.

Use of a dynamic flow model to describe a Basi and Range geothermal system is analogous to using a general systems synthesis to describe surface water systems. In surface drainages there are numerous physical components that control streamflow from a precipitation event, e.g., soil type and moisture content, underlying bedrock, slope orientation, veg etation, humidity, wind speed, duration and intensity of the precipitation. To establish an analytical relationship between each of the components and also for the overall system is difficult, if not impossible. The general systems synthesis method develops empirical relations between the physical components that control the input-output relationship (Crawford and Linsley, 1964). The basis for the method is a lumped-parameter ordinary differential equation.

$$I(t) - O(t) = \frac{dS}{dT}$$

where I = input
O = output
S = change in storage
t = time (Domenico, 1972).

A lumped-parameter system is one where the inputs and outputs can be measured or estimated but the intermediate processes that interrelate them are unknown or unobservable. The unknown intermediate processes are important because of their combined effect on the input-output relationship but detailed knowledge of the process is not necessary as the intermediate processes are "blackboxed" in the analysis (Domenico, 1972).

There are several advantages to using a lumped-parameter method to describe a Basin and Range hydr thermal system. One is that the unknown intermedia processes that include location and elevation of th recharge zone, rate of conductive heat flow beneath the system, depths of circulation, transmissivity and storativity, rock/fluid ratios and energy gradi ents are all included in the "blackbox". The input would be the cold water recharge which could be calculated by knowing the energy (heat and mass) output of the system, assuming the system is in a state of equilibrium.

A second advantage is that a space coordinate system is not required when a lumped-parameter approach is used in problem formulation and solution in geothermal hydrology. Thus knowledge of flow paths, aquifer geometries and boundary locations is not necessary.

A third feature of lumped-parameter analysis is that such methods are used extensively in optimization studies where the emphasis is on extreme value problems such as maximizing economic returns with production rates. Such studies would be applicable in determining the maximum potential of a system where there are trade-offs with increased production, such as decreasing enthalpy with reinjection.

APPLICATION OF THE DYNAMIC FLOW MODEL

Exploration

Exploration efforts, while focusing on locating a productive target, also should be directed towards collecting data that aids in determining the total energy flux of the system. The natural energy flux can be considered the minimum rate at which energy can be extracted (Bodvarsson, 1964). This would include predicting the maximum temperature of the system by use of chemical geothermometers. Hydrologic studies, coupled with drill hole data, would be used to calculate energy flux by convection, conduction, advection, and radiation. A complete energy budget would place that of the hydrothermal system within the background energy flux of the region (Olmsted et al., 1975; Welch et al. 1981). Ordinarily this would be beyond the scope of an exploration program as would be a detailed survey of the conductive and radiative heat flow of the system. The convective energy is what would be exploited during production and is the factor of most concern to an exploration program. Table 1 presents the net heat and mass discharge for several hydrothermal systems in the Basin and Range province. The reader is strongly urged to read Welch and others (1981) and Morgan (1982) for examples of the detailed evaluation of the energy budget for two Basin and Range hydrothermal systems.

TABLE 1. Heat and mass discharge rates for selected Basin and Range hydrothermal systems.

	Max. Predicted Temp. in Reservoir, °C	Temp. Recharge Water °C	Net Enthalpy of Water, cal/g	Thermal Water Discharge, kg/s	Net Heat Discharge, cal/s x10[6]
STILLWATER (1.)	159	11	148	95	14
STILLWATER (2.)	159	11	148	55	8.2
GERLACH (1.)	171	11	160	34	5.4
SULPHUR HOT SPRINGS (1.)	186	8	180	8.9	1.6
LEACH HOT SPRINGS (1.)	155	9	147	12	1.7
LEACH HOT SPRINGS (3.)	180	10	170	9.0	1.5
BRADY'S (1.)	200	11	193	42	8.1
BUFFALO VALLEY HOT SPRINGS (1.)	125	9	116	8.0	.93
STEAMBOAT SPRINGS (4.)	228	10	218	71	13
LONG VALLEY CALDERA (5.)	210	10	200	300	69
	282	10	272	190	69

(1.) Olmsted et.al.,1975 (2.) Morgan, 1982 (3.) Welch et.al.,1981 (4.) modified from White,1968 (5.) Sorey et.al.,1978

Testing

Flow testing must be done with an understanding of the potential complex nature of the production zone. Allman and others (1979) noted that for testing at the Raft River hydrothermal project "complex hydrologic conditions must be presumed, until proven otherwise, to result in drawdowns that do not vary directly with the flow rate." It is possible there are multiple production zones with different static pressures, thus the borehole static pressure is an intermediate one. One may have to assume the production zone is both anisotropic and heterogeneous. Non-Darcian flow may contribute significantly to drawdown.

An empirical approach such as that used by Benson (1982) or Allman and others (1979) can be used in analyzing flow test data. This approach will not yield values for the hydraulic parameters of transmissivity and storativity. Such data, however, are not necessary for the empirical methods used as tools to predict overall system performance. Multi-rate tests should be done to determine the specific capacity at varying flow rates. Data from these tests can be analyzed to determine the amount of drawdown attributed to non-Darcian flow. Multiple well tests can be run to determine in a preliminary manner interference patterns during the initial stage of production.

An intuitive knowledge of the transmissivity of the production zone can be gained by simple observation of the well response during both production and recovery segments of the test. Note the observations made during the testing of WEN-1. Benson (1982) noted at "each flow rate the downhole pressure quickly stabilized and showed little or no change for the duration of the flow period". It also was noted when "the well is shut-in, the pressure immediately increases by nearly 95% of the total pressure drop" (Benson, 1982). Such responses are indicative of a highly transmissive production zone.

Development and Production

Prediction of production potential is filled with uncertainties making development of a Basin and Range hydrothermal system a high risk operation. The risk is partially the result of little being known of the deeper parts of the systems. If the greater amount of fluid is at great depths (1 to 5 km. below the production zone) and upflow to the production zone is along a fault plane, the production rate and pressure decline will be governed by the least transmissive section along the fault plane flow path as was shown in the geologic cross-section for the Humboldt House hydrothermal system (Fig 6). If the porosity and volume of the system are unknown it is impossible to accurately estimate the stored thermal energy that can be recovered by a sweep process of either natural flow or injection.

On the other hand, however, if the recharge zone is at a relatively great distance from the discharge zone and there is an extensive and deep network of "feeder" conduits, then the highly transmissive fractures in the production zones may be capable of sustained high yields.

Thus whether Basin and Range hydrothermal systems are viewed as reservoir systems or as flow systems, the actual yield or production rate will be governed by the transmissivity of the production zone.

It is impractical and uneconomical to drill-out and define all of the physical and hydrologic parameters of a Basin and Range hydrothermal system. What is required are empirical methods that operate without knowledge of the various intermediate parameters of the system. Such methods are those developed from the empirical production-decline curves developed by Arps (1945). Production-decline curves were developed to predict production rate declines and total oil recoverable for a given oil field. The general method is to use historical production rate-time data to fit a curve to predict future production rate declines.

Two of the basic assumptions are:

1) the extrapolation procedure is strictly empirical and a mathematical expression of the curve based on physical considerations can be set up only for a few simple cases and,

2) whatever factors governed the trend of a curve in the past will continue to govern its trend in the future in a uniform manner (Gentry and McCray, 1978).

The method "black-boxes" unknowns such as the physical characteristics of the system, fluid characteristics and the drive mechanism. Figure 9 illustrates the empirical "black-box" approach to a Basin and Range hydrothermal system.

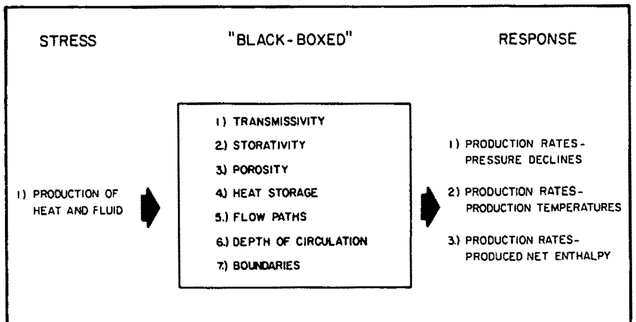

FIGURE 9 Stress-response relationship of a Basin and Range hydrothermal system.

Rivera (1977) applied decline-curve analysis to historical production data from the Cerro Prieto field. Figure 10 shows a production rate decline of the harmonic curve type. Future production rates can be estimated by either extrapolating the general trend of curve (1) or by an exponential extrapolation based on data from the last year, curve (2) (Rivera, 1977). The latter results in a more conservative prediction. Rivera (1977) also noted that when coupled with flowing pressure and temperature surveys the decline curves provided an auxiliary tool in diagnosing some well problems.

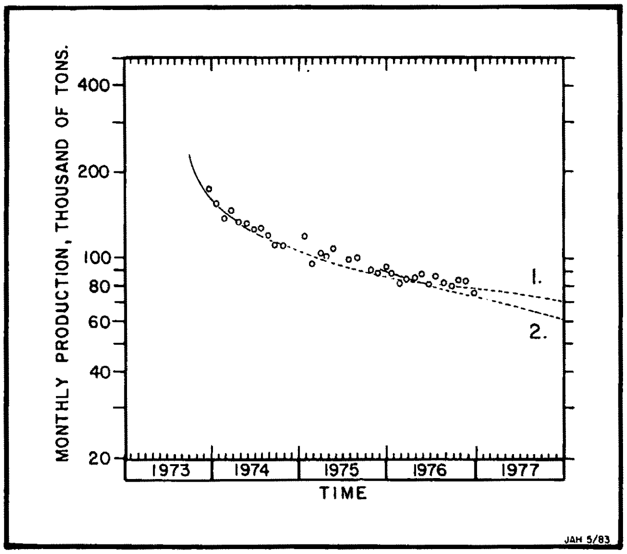

FIGURE 10. Production rate versus time for well B, Cerro Prieto (from Rivera, 1977).

Zais and Bodvarsson (1980) used a nonlinear lea squares program to fit an exponential equation to production rate data from Wairakei (Fig. 11). The concluded many wells and fields can be considered to be declining exponentially.

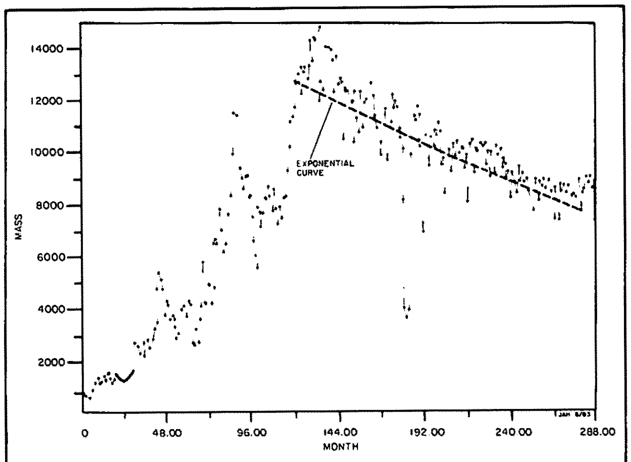

FIGURE 11. Wairakei total production, 1953-1976, with exponential fit 1964-1976. (Zais and Bodvarsson, 1980).

Zais and Bodvarsson (1980) also applied Coats' (1964) influence function method to the Wairakei data. The method is a black-box one that, given historical production and pressure data, can calculate an influence function and extrapolate it without proposing a specific reservoir model. Thu either production or pressure can be predicted, gi the other. For the Wairakei data, a one year extra polation resulted in a calculated pressure drop of 539 psi since the beginning of production whereas observed pressure drop was 543 psi. Thus it is no surprising Castanier and Sanyal (1980) suggested s empirical techniques coupled with modern methods o linear programming are promising tools for future

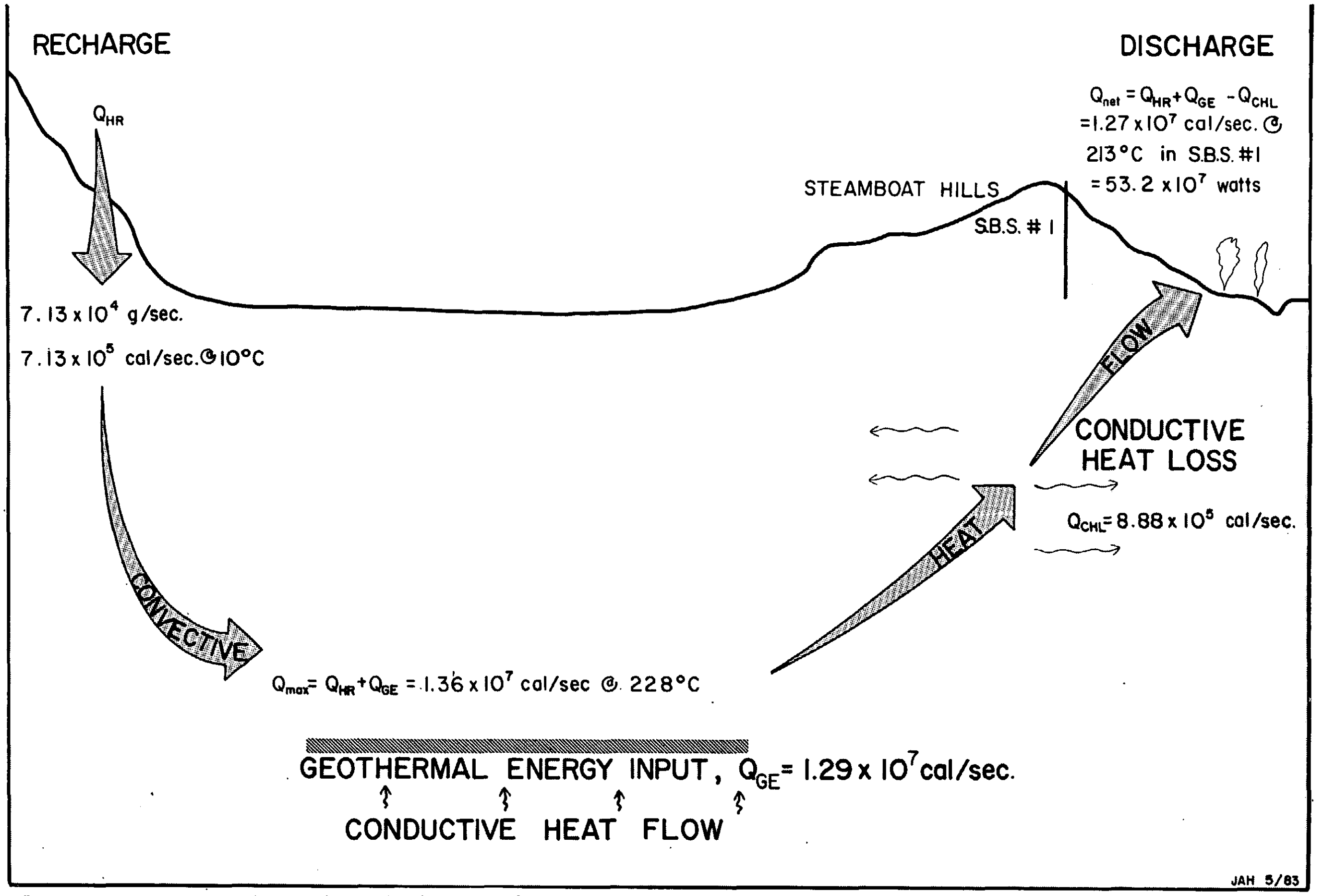

FIGURE 12. Convective and conductive heat flow within the Steamboat Springs hydrothermal system.

Steamboat Springs can be used as an example of how the empirical method could be applied to Basin and Range hydrothermal systems. White (1968) calculated total thermal fluid discharge at 71 liters/sec. From testing by Phillips Petroleum Company chemical geothermometers indicate a maximum temperature of 228°C. Using a recharge temperature of 10°C, the geothermal energy input is 1.29×10^7 cal/sec. (see Fig. 12). A calculated energy discharge is 53.2 $\times 10^7$ watts or 1.27×10^7 cal./sec. at 213°C in Steamboat Springs #1. Development of the resource can be viewed as a stress (pumping) applied to the system which responds (pressure decline). Ideally the system would be stressed or developed to the maximum level possible without adverse effects in its response. Conditions that might set upper limits on production rates include:

1) reduction in enthalpy due to cold water influx;
2) pressure declines such that flashing occurs within the formation, resulting in scaling outside the borehole;
3) pressure declines such that deeper wells would have to be drilled to maintain the same production rate.

Development of a hydrothermal system for electricity may occur in stages. The initial plant might

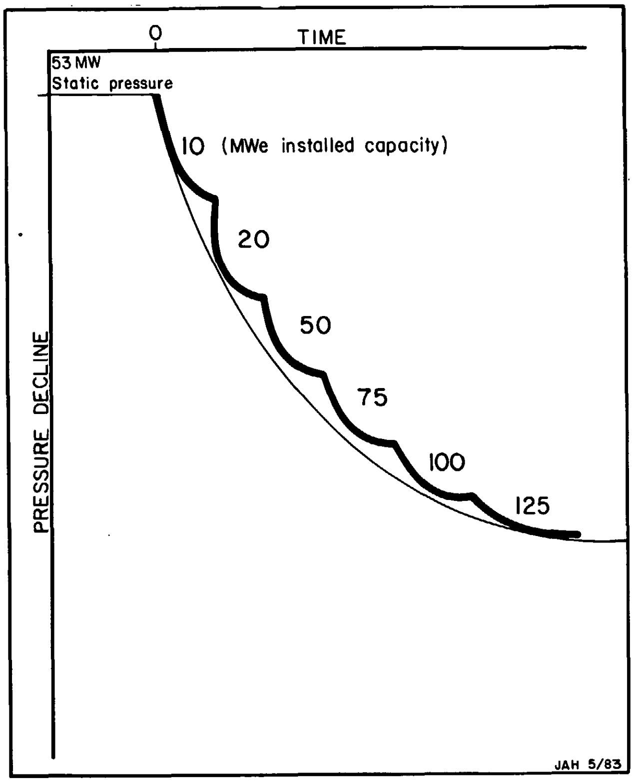

FIGURE 13. Possible production-pressure decline curve for step-wise increases in generating capacity.

have a 10 Mw capacity. After a number of years of successful production additional wells would be drilled and additional generating capacity added. In essence this development is similar to a multiple rate flow test on an individual well. With several steps for historical data empirical relationships between production rates and pressure declines should give a reliable prediction of the system response to the next step-up in production (Fig. 13).

Limited prior production history results in a wider range of interpretations than that based on a longer period of historical data (Genty and McCray, 1978). This is true for both the distributed parameter method and the lumped parameter method. With a historical record of production the distributed parameter model can be calibrated and verified by reasonably adjusting the hydraulic parameters until the model response matches the historical response (Wang and Anderson, 1982). With empirical methods such as the Arps curve a new curve is fitted to the additional historical data to more closely establish the equation that defines the curve in the future.

Injection

The uncertainties of predicting system response to production also are to be found in injection in fracture dominated hydrothermal systems. Horne (1982), in a review of injection histories of five geothermal fields in Japan, noted the major impact of injection was a rapid interference with production wells. Among his conclusions were as follows:

1) Where interwell flow occurs, thermal interference can be very detrimental to the performance of the production wells.

2) While only one field benefitted by pressure maintenance, three had reduced performance by thermal interference.

3) An estimate of recoverable energy based on percentage of in-place heat will not be correct if short circuiting takes place between injection and production wells.

Later, in a summary of worldwide experiences in water injection into fractured geothermal systems, Horne (1982) made the following conclusions, among others.

1) Nonproducing fields tend to show slower rates of tracer return than producing fields, creating a difficulty in the prediction of production reinjection breakthrough from pre-production tests.

2) There appears to be a correlation between tracer return rates and subsequent thermal breakthrough in the field.

It is thought these findings are very significant in respect to Basin and Range hydrothermal systems. It is highly recommended anyone planning an injectio program in the Basin and Range read the last two ref erences.

SUMMARY

In spite of a decade of intense research and exploration much remains unknown concerning specific components of Basin and Range hydrothermal systems, either individually or as a group. To date no singl Basin and Range system has been identified in its en tirety. Recharge zones, flow paths and depths of circulation can be identified only by circumstantial evidence or by calculations using reasonable assumptions concerning the individual system.

Enough knowledge has been gained, however, to define these systems in broad conceptual terms. Controlled by the extensional tectonics of the Basin and Range, the hydrothermal systems are dynamic flow systems with relatively limited reservoir capacity. Thus in evaluating the development potential the amount of energy stored in the systems is not as important as the rate at which energy can be extracted from the relatively shallow discharge zone Because Basin and Range hydrothermal systems are flow systems and not reservoir systems, petroleum engineering techniques for reservoir analysis are in appropriate, both from a conceptual and an engineeri standpoint. Standard flow test analysis probably re sults in an exaggerated estimate of fluid in place and ignores the more important aspect of the "deliverability" of the systems.

Using the concept of a dynamic flow system, Basin and Range hydrothermal systems can be evaluated by empirical methods not requiring a specific detailed model of the system. Large-scale development of and production from a Basin and Range hydrothermal system will depend on the unknown transmissive characteristics of the deeper parts of the system. Realistic evaluations can be made using empirical curves that relate system response to production stress. As with many predictive methods, a longer period of record will result in a more accurate prediction of future system response.

ACKNOWLEDGMENTS

The author wishes to acknowledge the support give him by Phillips Petroleum Company during the prepara tion of this paper. Dick Benoit of the Reno office was liberal with his suggestions and comments and th author thanks him for his continuous interest. The author also expresses his appreciation to Frank Olmsted and Ed Sammel of the USGS for their technica review of the paper. Views and opinions expressed i this paper are solely those of the author.

BIBLIOGRAPHY

Allman, D. W., Goldman, D., and Niemi, W. L., 1979, Evaluation of testing and reservoir parameters in geothermal wells at Raft River and Boise, Idaho: Geothermal Resources Council, Transactions, v. 3, pp. 7-10.

Arps, J. J., 1945, Analysis of decline curves: Am. Inst. of Mining and Metallurgical Engineers, Pet. Div., Transactions, v. 160, pp. 228-247.

Bailey, R. A., Dalrymple, G. B., and Lanphere, M. A., 1976, Volcanism, structure and geochronology of Long Valley caldera, Mono County, California: Jour. Geophysical Research, v. 81, no. 5, pp. 725-744.

Baza, J. R., 1980, Steamboat Springs flow test evaluation: report prepared for Phillips Petroleum Company, 15 p.

Benoit, W. R., and Butler, R. W., 1983, A review of high-temperature geothermal developments in the northern Basin and Range province: Geothermal Resources Council, Basin and Range Symposium, this publication.

____________, Hiner, J. E., and Forest, R. T., 1982, Discovery and geology of the Desert Peak geothermal field: a case history: Nev. Bureau of Mines and Geology, Bull. 97, 82 p.

Benseman, R. F., 1959, Estimating the total heat output of natural thermal regions: Jour. Geophys. Research, v. 64, no. 8, pp. 1057-1062.

Benson, S. M., 1982, Well test data analysis from a naturally fractured liquid-dominated hydrothermal system: Geothermal Resources Council, Transactions, v. 6, pp. 237-240.

Blackwell, D. D., and Czang-Go Baaz, 1973, Heat flow in a "blind" geothermal area near Marysville, Montana: Geophysics, v. 38, no. 5, pp. 941-956.

Bodvarsson, Gummar, 1964, Utilization of geothermal energy for heating purposes and combined schemes involving power generation, heating, and/or by-products: United Nations Conf. New Sources Energy, Rome 1961, Proc., v. 3 (Geothermal Energy 2), pp. 429-448.

Castanier, L., and Sanyal, S. K., 1980, Geothermal reservoir modeling - a review of approaches; Geothermal Resources Council, Transactions, v. 4, pp. 313-315.

Coats, L. R., McCord, J., and Drews, W., 1964, Determination of aquifer influence functions from field data: Jour. of Pet. Tech., Dec.

Craig, H., Boato, G., White, D. E., 1956, Isotopic geochemistry of thermal waters, chapter 5 in Nuclear processes in geologic settings: National Research Council Comm. Nuclear Sci., Nuclear Sci. Ser. Rept. 19, pp. 29-38.

Crawford, N. H., and Linsley, R. K., 1964, A conceptual model of the hydrologic cycle: Inter. Assoc. Sci. Hydrology, Publ. 63, pp. 573-587.

Denton, J. M., Bell, E. J., and Jodry, R. L., 1980, Geothermal reservoir assessment case study - northern Dixie Valley, Nevada: U. S. Dept. of Energy DOE/ET/27006-1, 117 p.

Desormier, W., 1979, Report on the Humboldt House geothermal project, Pershing County, Nevada: report prepared for Phillips Petroleum Company, 15 p.

________, 1983, Steamboat Springs Geothermal Project: Geothermal Resources Council Field Trip Guidebook for the Role of Heat in the Development of Energy and Mineral Resources in the Northern Basin and Range Province, 7 p.

Domenico, P. A., 1972, Concepts and models in groundwater hydrology: McGraw-Hill, 405 p.

Duffield, W. A., and Bacon, C. R., 1981, Geologic map of the Coso volcanic field and adjacent areas, Inyo County, California: U. S. Geol. Survey Misc. Invest. Map I-1200.

Edmiston, R. C., 1982, A review and analysis of geothermal exploration drilling results in the northern Basin and Range geologic province of the USA from 1974 through 1981: Geothermal Resources Council Transactions, v. 6, pp. 11-14.

Epperson, I. J., 1982, Beowawe, Nevada, well testing; history and results: Geothermal Resources Council, Transactions, v. 6, pp. 257-280.

Flynn, T., Trexler, D. T., and Koenig, B. A., 1982, The Kemp thermal anomaly; a newly discovered geothermal resource in Pumpernickel Valley, Nevada: Geothermal Resources Council, Transactions, v. 6, pp. 121-124.

Fournier, R. O., and Thompson, J. M., 1980, The recharge area for the Coso, California geothermal system deduced from deuterium and oxygen-18 in thermal and non-thermal waters in the region: U. S. Geol. Survey Open-File Rpt. 80-454, 24 p.

Garside, L. J., and Schilling, J. H., 1979, Thermal waters of Nevada: Nev. Bur. of Mines and Geology, Bull. 91, 163 p.

Gentry, R. W., and McCray, A. W., 1978, The affect of reservoir and fluid properties on production decline curves: Jour. of Pet. Tech., Sept. pp. 1327-1341.

Goyal, Kishav, 1982, personal communication, Phillips Petroleum Company.

Hill, D. G., Layman, E. B., Swift, C. M., and Yungul, S. H., 1979, Soda Lake, Nevada, thermal anomaly: Geothermal Resources Council Annual Meeting, 1979, Transactions, v. 3, pp. 305-308.

Horne, Roland N., 1982, Geothermal reinjection experience in Japan: Jour. of Pet. Tech., March, 1982, pp. 495-503.

__________, 1982, Effects of water injection into fractured geothermal reservoirs a summary of experience worldwide: Geothermal Resources Council Special Report no. 12, pp.47-63.

Hose, R. K., and Taylor, B. E., 1974, Geothermal systems of northern Nevada: U. S. Geol. Survey Open-File Rpt. 74-271, 27 p.

Morgan, D. S., 1982, Hydrogeology of the Stillwater geothermal area, Churchill County, Nevada: U. S. Geol. Survey Open-File Rpt. 82-345, 95 p.

Nehring, N. L., 1980, Geochemistry of Steamboat Springs, Nevada: U. S. Geol. Survey Open-File Rpt. 80-887, 61 p.

Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S. M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah: Univ. of Utah Research Institute ESL-12, 125 p.

Olmsted, F. H., Glancy, P. A., Harrill, J. R., Rush, F. E., and Van Denburgh, A. S., 1975, Preliminary hydrogeologic appraisal of selected hydrothermal systems in northern and central Nevada: U. S. Geol. Survey Open-File Rpt. 75-56, 274 p.

Parchman, W. L., and Knox, J. W., 1981, Exploration for geothermal resources in Dixie Valley, Nevada; a case history: Geothermal Resources Council Bull., v. 10, no. 5, pp. 3-6.

Ramey, H. J., Jr., 1965, Non-Darcy flow and wellbore storage effects in pressure build-up and drawdown of gas wells: Jour. of Pet. Tech., v. 17, no. 2, pp. 223-233.

Rivera, R. J., 1977, Decline curve analysis a useful reservoir engineering tool for predicting the performance of geothermal wells: Geothermal Resources Council, Transactions, v. 1, pp. 257-259.

Rohrs, D. T., and Bowman, J. R., 1989, A light stable isotope study of the Roosevelt Hot Springs thermal area, southwestern Utah: Univ. of Utah Topical Rpt. 78-1701, DOE/DGE contract DE-AC07-78ET28392, 89 p.

Sammel, E. A., and Craig, R. W., 1981, The geothermal hydrology of Warner Valley, Oregon: A reconnaissance study: U. S. Geol. Survey Prof. Paper 1044-I, 47 p.

Schaff, S. C., 1976, The 1968 Adel, Oregon earthquake swarm: M. A. Thesis, University of Nevada, Reno, 63 p.

Silberling, N. J., and Wallace, R. E., 1967, Geologic map of the Imlay quadrangle, Pershing County, Nevada: U. S. Geol. Survey, map GQ-666.

Skau, C. M., and Brown, John, in preparation, The quality of natural waters in the east side Sierra Nevada: Desert Research Institute, Univ. of Nevada, Reno, 206 p.

Sorey, M. L., 1975, Numerical modeling of liquid geothermal systems: U. S. Geol. Survey Open-File Rpt. 75-613, 66 p.

_____, M. L., and Lewis, R. E., 1976, Convective heat flow from hot springs in the Long Valley caldera, Mono County, California: Jour. of Geophy. Research, v. 81, no. 5, pp. 785-791.

_____, M. L., Lewis, R. E., and Olmsted, F. H., 1978, The hydrothermal system of Long Valley caldera, California: U. S. Geol. Survey Prof. Paper 1044-A, 60 p.

Urban, T. C., and Diment, W. H., 1982, An interpretation of precision temperature logs in a deep geothermal well near Desert Peak, Churchill County, Nevada: Geothermal Resources Council, Transactions, v. 6, pp. 317-320.

Wang, H. F., and Anderson, M. P., 1982, Introduction to groundwater modeling: W. H. Freeman and Company, 237 p.

Welch, A. H., Sorey, M. L., and Olmsted, F. H., 1981, The hydrothermal system in southern Grass Valley, Pershing County, Nevada: U. S. Geol. Survey Open-File Rpt. 81-915, 193 p.

White, D. E., 1968, Hydrology, activity, and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada: U. S. Geol. Survey Prof. Paper 458-C, 109 p.

White, D. E., Thompson, G. A., and Sandberg, C. H., 1964, Rocks, structure, and geologic history of Steamboat Springs thermal area, Washoe County, Nevada: U. S. Geol. Survey Prof. Paper 458-B, 63 p.

Young, H. W., and Lewis, R. E., 1980, Hydrology and geochemistry of thermal ground water in southwestern Idaho and north-central Nevada: U. S. Geol. Survey Open-File Rpt. 80-2043, 40 p.

Zais, E. J., and Bodvarsson, G., 1980, Analysis of production decline in geothermal reservoirs: Lawrence Berkeley Laboratory, Univ. of California, LBL-11215, 75 p.