A REVIEW OF THE DIXIE VALLEY, NEVADA, LIQUID-DOMINATED GEOTHERMAL RESOURCE AND THE RELATIONSHIP OF SELECTED GEOLOGIC CHARACTERISTICS TO POTENTIAL GEOTHERMAL PRODUCTION

BY

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ABSTRACT

Geothermal energy from liquid-dominated reservoirs located in the western United States may supply 20,000 MW from more than 40 power plants by the year 2,000, if utility management becomes convinced of the reliability and cost attractiveness of this energy source. A number of exploration programs are in progress to evalute the characteristics of this type of geothermal energy. For example, numerous exploration methods have been employed in Dixie Valley, Nevada, since 1967 with mixed results. However, with DOE support, additional data have recently become available. We have revised earlier structural models of the basin and have made recommendations for additional investigations that should clarify the geologic relationships within the reservoir. The principal geologic characteristics of the reservoir that may place limits on project economics appear to be the depth and area of producing zones, fluid quality and the amenability of the upper zones to accept large volumes of waste fluids. However, reservoir temperature, flow rates, recharge characteristics and other factors appear to be acceptable either for electrical power production of more than 1,000 MW, or for direct applications such as on-site agricultural processing.

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INTRODUCTION

Geothermal energy has become a significant alternative energy resource in the United States and in many other countries, and may be an economic source of energy for at least the next 40 years. Conservative U.S. Department of Energy (DOE) estimates of the domestic geothermal energy available for conversion to electricity range from 1,200 megawatts (MW) to 20,000 MW by the year 2,000. Geothermal energy is presently used to produce electricity on a large-scale commercial basis in The Geysers area, located approximately 70 miles north of San Francisco, California. This geothermal energy is in the form of dry steam, which is produced via wells from a vapor-dominated reservoir for direct feed to drive turbines. Although this large geothermal reservoir appears to be geologically unique within the United States, other geothermal areas located in many western states contain liquid-dominated (hot water) reservoirs. Such sources of geothermal energy are of significant economic potential and are being actively, although cautiously, pursued by industry.

Various estimates of energy available for conversion to electricity incorporate The Geyser's maximum production of 1,200 MW by 1985 as a minimum, and the 20,000 MW potential production by liquid-dominated geothermal reservoirs as a maximum. In terms of anticipated number of electrical power plants, 20,000 MW would be produced by 40 plants of 500 MW capacity. This is a capacity that utilities usually prefer on the basis of economies of scale and other related factors. However, power plant capacity, at any one location, will be low initially but will increase with time as the reservoir and other factors permit. In view of the large number of projected plants, such geothermal projections are, at best, estimates of what industry will do over the next few decades. In reality, expansion of power production from liquid-dominated geothermal reservoirs will depend upon the nature and relationship of the two principal partners within the geothermal industry, [i.e., the producers and the consumers (utilities)].

Because they are generally held responsible by their rate-payers to minimize both risk and costs, utilities are not disposed to take on any project involving either new technology or an untested energy resource. The risk must be substantially reduced to the level of accepted energy technology and resource development such as oil and gas or coal and lignite before utilities will respond to geothermal energy. For example, the false start into nuclear energy in the United States has prompted utilities to re-examine nuclear technology and project economics, and to monitor existing nuclear installations and operations before re-entering this field, which is inevitable for compelling economic reasons.

Producers, the geothermal exploration and development companies, are charged by their stockholders to risk capital on reasonable ventures for developing technology and potential energy sources that could provide revenues in the future. The impetus is compelling to explore and develop an energy resource having strong similarities to oil and gas, thereby using and expanding the technology of oil and gas companies.

RELIABILITY OF LIQUID-DOMINATED GEOTHERMAL RESERVOIRS

The factors that will determine whether geothermal energy is accepted by the utilities are: 1) favorable economics (for both the consumer and the producer), and 2) environmental acceptability (by society). The economics of future geothermal development depends upon numerous factors, any one of which could become a limiting factor. Some of the present problems with power plant financing by utilities will cease to exist when and if the long-term reliability and economic favorability of production from a liquid-dominated reservoir can be demonstrated by the producer in terms of: 1) sustained yield, 2) substantial fluid temperature, 3) favorable total cost of production and delivery to the power plant, and 5) favorable bus-bar price to the utility. The pressing problems that utility management must confront involve the design and efficiency of geothermal power plants, power distribution and other problems relating to utilization of the wet steam and hot water produced by a liquid-dominated reservoir. Further, the utility-related costs to adapt to a geothermal energy resource are sizeable, amounting to approximately 90 percent or more of the total cost of electrical generation and transmission. The cost of the energy to the utility, therefore, is small compared to the cost of generating electricity, and handling and disposing of spent fluids. Similar economic pressures are also present in nuclear- and coal-powered utilities, but both have their own unique problems that affect utilities when dicisions must be made in selecting the energy source to be utilized in the production of electricity.

Although the reliability of liquid-dominated reservoir has not been demonstrated to date in the United States, such a reservoir has been in production for more than 10 years in northern Baja, Mexico, at Cerro economic factors of electrical production are such that a comparison with domestic utility economics is difficult. Elders and others (1978) and Mercado (1975) report a relatively high production temperature of greater than 300°C (570°F). A similar geothermal occurrence is located along the same geologic trend in the Imperial Valley of southern California (Palmer 1975; Lombard and Nugent, 1975). Although exploration and development, combined with utility investigations, have been under review for the last few years, a full program of commercialization in the Imperial Valley has not proceeded because of high salinity and associated scaling problems in handling the produced fluids (Fernelius, 1975). These factors have combined to make production and utilization an economically marginal venture for the producer and consumer. However, research and development have been underway for some time and the results are encouraging (Swanson, 1978). One factor that has become apparent is that high temperature fluids may also contain high dissolved solids under some geologic conditions.

GEOTHERMAL POTENTIAL OF THE BASIN AND RANGE PROVINCE

In other regions of the western United States, many geothermal prospects are being examined in the hopes of locating reservoirs that do not produce fluids of high salinity along with their associated problems in production and utilization. Fluid temperatures greater than 200°C (414°F) with moderate to low dissolved solids appear to be ideal. Exploration has focused on the Basin and Range Physiographic Province of the western United States, an area of some 262,500 square miles (mi^2) encompassing all of Nevada, parts of eastern California, southeastern

Oregon, southern Idaho, western Utah, southern Arizona, and southwestern New Mexico (Grose and Keller, 1979).

The general geologic characteristics of the Basin and Range region that attract attention during an initial geothermal exploration program designed to locate potential liquid-dominated geothermal reservoirs are indicated in Table 1.

An exploration program in this area consists of a reconnaissance phase, and a detail phase, if merited. Over the years, substantial geologic data related to the Basin and Range region have been collected by scientists of academic institutions and state and federal agencies for various purposes. However, most of these data were not used to assess geothermal potential. In terms of the requirements for geothermal exploration and potential industrial development, the available geologic data can provide information that relates to many of the characteristics shown in Table 1. If sufficient evidence for geothermal potential can be established via geologic literature, a large area (e.g., on the order of 2,500 mi^2; i.e., 50 mi x 50 mi) is selected for a reconnaissance investigation of one or more of the favorable geologic characteristics (Goldstein, 1977).

The methods generally employed during the reconnaissance phase are shown in Table 2. The objective of this phase is to further reduce the area of interest to one or more areas of less than 100 mi^2 (i.e., 10 mi x 10 mi) for detailed exploration. Some of the programs indicated are

TABLE 1

FAVORABLE GEOLOGIC CHARACTERISTICS

FOR

PRELIMINARY DEFINITION OF GEOTHERMAL POTENTIAL

1. HIGH REGIONAL HEAT FLOW
2. THIN CRUST / SHALLOW HEAT SOURCE
3. EXTENSIONAL FAULTING
4. SEISMICITY
5. THERMAL SPRINGS
6. THICK BASIN-FILL DEPOSITS
7. YOUNG VOLCANISM

TABLE 2

TYPICAL GEOTHERMAL EXPLORATION METHODS

RECONNAISSANCE PHASE

STUDY AREA: 2500 SQUARE MILES (50 Miles × 50 Miles)

OBJECTIVE: REDUCE STUDY AREA TO ONE OR MORE SUBAREAS OF <100 SQUARE MILES FOR DETAILED EXPLORATION

METHODS:

A. AIRBORNE ACTIVITIES
   1. AEROMAGNETIC SURVEYS
   2. THERMAL INFRARED IMAGING STUDIES
   3. PHOTOGRAPHIC STUDIES
      - Low-medium altitude color & color I.R.
      - High altitude black & white

B. SURFACE ACTIVITIES
   1. GEOLOGICAL STUDIES
   2. GEOCHEMICAL STUDIES
   3. REGIONAL GRAVITY SURVEYS
   4. ROCK AGE-DATING SURVEYS
   5. PASSIVE SEISMIC SURVEYS
      - Regional Seismotectonic Studies
      - Microearthquake and ground noise studies
   6. HYDROLOGIC STUDIES
   7. REGIONAL MAGNETIC VARIOMETRY STUDIES
   8. HEAT FLOW STUDIES

usually supervised by the company geological staff but are implemented by a contractor or consultant. Depending upon the number and experience of the company's staff geologists, some of the programs, such as photographic investigations, geologic reconnaissance and mapping, hydrological surveys and hydrologic studies, are conducted by "in-house" staff, occasionally with a senior consultant's supervision or consultation. In the event highly favorable area(s) are defined, a detail phase is recommended. If approved by management, the budget would include provisions for some or all of the programs listed in Table 3. The programs included depend upon the particular characteristics of the project area, the recommendations of the senior geological personnel, and of course, upon the budgetary support of company management. The objective of the detail phase is to further reduce the area(s) to one or more subareas of a few square miles with a view toward drilling of selected targets, if merited.

Shallow drilling is conducted during the detail phase and usually consists of drilling a number of shallow holes for heat-flow measurements and geologic investigations. In addition, a few holes of intermediate depth are drilled for heat-flow and thermal-gradient measurements, and for ground-water sampling for chemical and isotopic analyses. As is often the case, additional airborne or ground programs to supplement previous work are conducted after programs involving thermal-gradient and heat-flow drilling have been conducted. If merited, deep drilling is conducted to test target areas and suspected subsurface zones of potential geothermal production. A number of programs will be required during deep drilling (e.g., geophysical logging, geological logging of cuttings,

TABLE 3

TYPICAL GEOTHERMAL EXPLORATION METHODS

DETAIL PHASE

STUDY AREA: <100 SQUARE MILES (10 Miles × 10 Miles)

OBJECTIVE: REDUCE STUDY AREA TO ONE OR MORE SUBAREAS OF 2 TO 4 SQUARE MILES FOR DRILL TESTS

METHODS:

A. AIRBORNE ACTIVITIES

1. HIGH-SENSITIVITY AEROMAGNETIC SURVEYS

B. SURFACE ACTIVITIES

1. GEOLOGICAL STUDIES
2. MAGNETIC SURVEYS
3. GRAVITY SURVEYS
4. ACTIVE SEISMIC SURVEYS
5. PASSIVE SEISMIC SURVEYS
   - Microearthquake
   - Teleseismic P-wave studies
   - Ground noise
6. RESISTIVITY STUDIES
7. SELF-POTENTIAL SURVEYS
8. HEAT FLOW STUDIES

temperature logging, pressure logging, flow measurements (induced or incipient), plus other programs involving small-scale production testing and waste fluid re-injection tests, etc.).

In order to be economically attractive for potential electrical power generation, the fluids should exhibit a temperature in excess of 200°C (414°F), be under reasonably high pressures, contain low dissolved solids and minimal exotic gases. Over the past few years a number of areas within the Basin and Range Province have met these general criteria. One prospect of particular interest is in Dixie Valley, Nevada, located 105 mi northeast of Reno and 55 mi northeast of Fallon, Nevada.

In 1967, a government-funded study was completed on Dixie Valley which indicated active faulting and other geologic characteristics conducive to a hydrothermal system (Thompson and others, 1967). Numerous hot springs and fumeroles were known in the area, and very hot water was reportedly responsible for closing of the Dixie Comstock Gold Mine (Willden and Speed, 1974). Over the ensuing years, as oil prices increased, the incentive to explore for geothermal energy also increased (Keplinger, 1976).

Therefore, during the period 1967 to 1976, seismic, microseismic and other geologic studies were completed. Investigations conducted by the U.S. Geological Survey, using hot-spring geothermometry, suggested a subsurface reservoir temperature of less than 150°C, while other regions evaluated exhibited significantly higher geothermetric temperatures, and were deemed to be of higher priorty than Dixie Valley (White and Williams, 1975).

In 1976, industry began exploration with a number of preliminary reconnaissance programs. Table 4 is a summary of exploration activities conducted through 1980 in Dixie Valley. In early 1977, Keplinger and Associates, Inc. (KAI) conducted a review of the available data on behalf of Millican Oil Company for purposes of evaluating a proposal to acquire an acreage position in Dixie Valley (Keplinger and Associates, Inc., 1977a). We concluded that on the basis of: 1) recent seismic activity (Ryall and Malone, 1971; Microgeophysics, Inc., 1976), 2) the presence of hot springs (i.e., the geothermetric model incorporating mixing of meteoric and reservoir waters indicated higher subsurface reservoir temperatures than suggested by U.S. Geological Survey), 3) abnormally high heat flow (Koenig and others, 1976), 4) presence of active extensional faulting (Thompson and Burke, 1973), 5) presence of thick basin-fill deposits (Thompson and others, 1967; Meister, 1967), 6) presence of favorable geologic conditions within the valley (Exploration Data Consultants, Inc., 1976), and 7) a favorable position of available acreage, Millican Oil Company should: 1) acquire the acreage, 2) attempt to acquire selected acreage along the western side of the valley via a U.S. Government "Known Geothermal Resource Area" (KGRA) bid sale, and 3) actively explore the area, with a view toward forming a joint venture with one of the four major companies actively engaged in exploration in Dixie Valley (Keplinger and Associates, Inc., 1977b).

In the latter part of 1977, we conducted a geological field reconnaissance program in the Stillwater Range area bordering Dixie Valley to the west (Keplinger and Associates, Inc., 1977c). One of the objectives

TABLE 4
GEOTHERMAL EXPLORATION ACTIVITIES
DIXIE VALLEY, NEVADA

1967-1980

RECONNAISSANCE PHASE		TRANSITION PHASE	DETAIL PHASE	DRILLING & TEST PHASE	?COMMERCIAL PHASE?
1967	1976	1977	1978	1979	?
A. AIRBORNE ACTIVITIES PHOTOGEOLOGIC STUDIES HIGH ALTITUDE B & W SINGLE-LEVEL GRAVITY SURVEY	A. AIRBORNE ACTIVITIES NONE	A. AIRBORNE ACTIVITIES MULTI-LEVEL AEROMAGNETIC SURVEY	A. AIRBORNE ACTIVITIES MULTI-LEVEL AEROMAGNETIC SURVEY PHOTOGRAPHIC STUDIES LOW-SUN ANGLE SNOW-LAPSE SURFICIAL GEOLOGY FAULT SCARP GEOLOGY	A. AIRBORNE ACTIVITIES PHOTOGRAPHY LINEAMENT ANALYSIS	
B. SURFACE ACTIVITIES MICROSEISMIC STUDIES SEISMIC REFRACTION STUDIES STRESS-STRAIN ANALYSIS	B. SURFACE ACTIVITIES GRAVITY SURVEY MAGNETIC SURVEY GEOLOGIC STUDIES BOREHOLE LOGS MICROSEISMIC STUDIES ELECTRICAL RESISTIVITY (DIPOLE-DIPOLE) STUDIES	B. SURFACE ACTIVITIES STRUCTURAL ANALYSIS STUDIES HYDROGEOCHEMICAL STUDIES GEOLOGIC STUDIES RANGE GEOLOGY & STRUCTURE	B. SURFACE ACTIVITIES SCALAR MAGNETOTELLURIC STUDIES GEOLOGIC STUDIES HYDROGEOCHEMICAL STUDIES STRUCTURAL ANALYSIS RESERVOIR MODELING	B. SURFACE ACTIVITIES GEOLOGIC STUDIES GEOCHEMICAL SURVEYS STRUCTURAL-TECTONIC ANALYSIS STUDIES PETROLOGIC ALTERATION STUDIES HYDROGEOCHEMICAL STUDIES	
C. DRILLING ACTIVITIES NONE	C. DRILLING ACTIVITIES SHALLOW GRADIENT HOLES (~300' TD)	C. DRILLING ACTIVITIES NONE	C. DRILLING ACTIVITIES INTERMEDIATE GRADIENT HOLES (~1500' TD)	C. DRILLING ACTIVITIES SHALLOW TEMPERATURE SURVEY (3' TD) INTERMEDIATE GRADIENT HOLES (1500' TD) DEEP TESTS (9000' TD)	
D. ECONOMIC ACTIVITIES UNKNOWN	D. ECONOMIC ACTIVITIES UNKNOWN	D. ECONOMIC ACTIVITIES PRELIMINARY STUDIES	D. ECONOMIC ACTIVITIES PRELIMARY STUDIES	D. ECONOMIC ACTIVITIES UNKNOWN	

of the program was to briefly investigate the range geology and associated structures with a view toward defining a preliminary geologic model that could be applied to Dixie Valley where rock types and structural relationships are obscurred by the overlying alluvial and lacustrine sediments.

During late 1977, Millican Oil consumated a joint-venture agreement with Southland Royalty, which had recently acquired adjoining acreage in Dixie Valley. During 1978 and 1979, the joint venture contracted for a series of multi-level and single-level aeromagnetic surveys. Geologic supervision was provided by consultants representing Millican Oil (KAI) and Southland Royalty [Energy and Natural Resource Consultants, Inc. (ENRC)]. A magnetotelluric survey covering western Dixie Valley was also conducted by the joint venture (Senturion Sciences, 1978b). The aeromagnetic survey identified a number of structural features but provided interpretations that conflicted with previous concepts of Basin and Range geology. We reviewed the magnetic interpretations and questioned Senturion Sciences' (1977, 1978a) interpretation of key geologic features in the valley such as the dip angle of the western range-front fault and the existence of a young thrust fault postulated in the central part of the valley (Keplinger and Associates, Inc., 1978).

During 1977 and 1978, we collected a time-series of water samples from two hot springs and one cold spring. This hydrochemical survey consisted of sampling each of the springs twice a day over a seven-day period and then intermittently through 1978. Seventeen chemical and physical parameters were analyzed or recorded. We made standard geothermetric calculations using the silica and calcium-sodium-potassium methods (Fournier, 1973; Fournier and Truesdell, 1973). An indicated minimum reservoir temperature of 175°C was derived using the latter method. However, the methods produced conflicting results and supported the view that the samples were composed of a mix of recharge and thermal waters in the area of the hot springs sampled (Keplinger and Associates, Inc., 1977b, 1978).

The hydrochemical data indicated that the two hot springs (separated by approximately one mile): 1) contain low HCO_3 (58 to 106 ppm), 2) contain anomalously high lithium (0.7 ppm) and boron (1.0 ppm), and 3) exhibit low total dissolved solids (TDS), ranging from 750 ppm (for the 68°C spring samples) to 1,500 ppm (for the 57°C spring sampled). It was apparent that the samples were composed of two (mixed) chemical types of ground water; one type was derived from a shallow meteoric (cold) source and the other from a deep thermal source. The volumetric contribution that each type makes to the whole sample was uncertain. For example, low bicarbonate content indicated minimal contribution via typical shallow recharge. The low TDS content also indicated minimal contribution by shallow recharge derived from surface run-off over large areas of the relatively mineralized Stillwater Range nearby. Based on these interpretations, we reasoned that recharge from the Stillwater Range was derived from high elevations via deep fracture zones in communication with the springs' hydraulic systems. Additional recharge could also be expected water containing low TDS. In addition, boron and lithium are common constituents in deep, thermal ground water (Koga and Noda, 1975). If the samples had been diluted by large volumes of meteoric recharge water, both elements would not have been detected. However, if both elements had been derived from a specific rock type containing such elements, their significance as an indicator of thermal water would be masked, if not eliminated. Therefore, two summary interpretations became possible. The mixed samples were composed of: 1) water derived from boron- and lithium-enriched rocks present either in a shallow, cold water reservoir within the basin or in the range nearby, and 2) water derived from a deep, thermal reservoir containing boron, lithium and low TDS.

Additional interpretations of the hydrochemical data indicated that SiO_2 decreases as calcium increases, suggesting an influx of cold recharge water from the Stillwater Range nearby and/or other recharge areas within the basin. Therefore, we concluded that the cold water component of the samples predominates, and that either boron is present in the rocks of the recharge area or that the deep thermal water contains appreciable quantities of that element (as well as lithium).

Two 1,500 foot (ft) temperature-gradient holes were drilled and logged during 1978, both near the range-front fault. The northern most hole (H-1), located on Millican acreage, encountered a bottom-hole temperature of approximately 100°C, while the southern hole (H-2), located on Southland Royalty acreage, encountered a bottom-hole temperature of approximately 50°C (Keplinger and Associates, Inc., 1978).

At this stage of exploration, the geologic model of the basin incorporated the range-front fault system as a significant zone of groundwater recharge from the Stillwater Range to the basin. Bounding faults of down-dropped blocks to the east of the range-front faullt zone serve as avenues for upwelling, high-temperature fluids. Some of these faults permit hot fluids to reach the surface, forming hot springs. Although speculative in nature, the model incorporated all available data believed to be reliable at the time. We concluded that two types of geothermal reservoirs could be present, an "upper" hot-water reservoir located in the lower intervals of upper Cenozoic alluvial fill and/or upper intervals of Tertiary volcanics, and a "lower" steam-dominated (?) reservoir at the base of a Jurassic intrusive complex or in upper Traissic quartz arenites and/or metamorphic rocks.

By mid-1978, the geologic complexity of the basin was apparent to the Millican Oil and Southland Royalty joint venture. Conflicting interpretations and inconclusive data regarding the structural model of the basin, and inconclusive data regarding spring chemistry led the joint venture to conclude that a comprehensive, multi-disciplinary investigation was required before targets of sufficient merit could be selected for deep drilling. During this period, DOE had announced that the government would support, in part, case studies on northern Basin and Range geothermal systems via a comprehensive geothermal reservoir assessment program through the stage of deep drilling.

In response to RFP No. ET-78-R-08-0003, a proposal was presented to DOE as a cooperative venture between Millican Oil, Southland Royalty, and the Minerals Research Institute of the Mackay School of Mines, University of Nevada, Reno (MMRI-UNR). A comprehensive, multiphase academic-industrial effort was proposed with three principal objectives. The first objective was to conduct a major review of all available data and interpretations, and the second was to formulate and conduct field studies designed to address many of the questions raised previously. Practical guidance by industry personnel was envisioned to ensure that a proper balance between academic endeavors and industrial requirements was achieved, especially with respect to selecting target areas for subsequent drilling. The third objective was to conduct an intermediate to deep drilling program.

A contract was awarded to the joint venture, and the investigations and field studies were begun in early 1979 (Contract No. DE-AC0879-ET27006). Millican Oil Company was subsequently purchased by a non-geothermal company and the lands held were transferred to a third party. A series of final reports were issued by the Mackay Minerals Research Institute in 1980 (MMRI-UNR, 1980). The final report was subsequently compiled and submitted to DOE (Denton and others, 1980). Based on these investigations and on the new data provided, we conducted a brief evaluation to assess the state of knowledge that now exists on the Dixie Valley geothermal prospect and on the associated geologic framework. A detailed review is presently underway (Campbell and Wielchowsky, in prep.).

GEOLOGY OF THE GEOTHERMAL SYSTEM

Stratigraphy and Structure

We have established possible reservoir rock type(s) and geometry in Dixie Valley based on surface outcrop in the adjacent ranges (see Figure 1), and on geophysical, geomorphic and well data collected in the basin. In mapping the surface distribution of rock types, we relied heavily on the published work of Page (1965), Willden and Speed (1974), and Johnson (1977). Our subsurface analysis is based in part on the data of Thompson and others (1967), Smith (1968), Thompson and Burke (1973), Senturion Sciences (1977, 1978a and b), and Denton and others (1980).

We have divided the rocks in the Dixie Valley area into four informal units based primarily on composition, strength/ductility, and age (Keplinger and Associates, Inc., 1977b). Figures 2 and 3 show the vertical distribution of these units, and Figure 1 shows lateral distribution at the surface. From oldest to youngest these units include:

1. Triassic Metasedimentary Rocks

   Triassic-age rocks consist of slate and phyllite with minor quartzite, limestone, siltstone and mudstone. This unit is multiply deformed and is estimated to be up to 10,000 ft thick (Page, 1965; Willden and Speed, 1974).

2. Jurassic Mafic Intrusive, Mafic Extrusive, and Sedimentary Rocks

   This unit is characterized by the Humboldt gabbroic complex of Speed (1962, 1976), and includes gabbroic to dioritic intrusives and basaltic and andesitic flows, tuffs, and breccias with minor quartzites and calcareous sandstones. The total

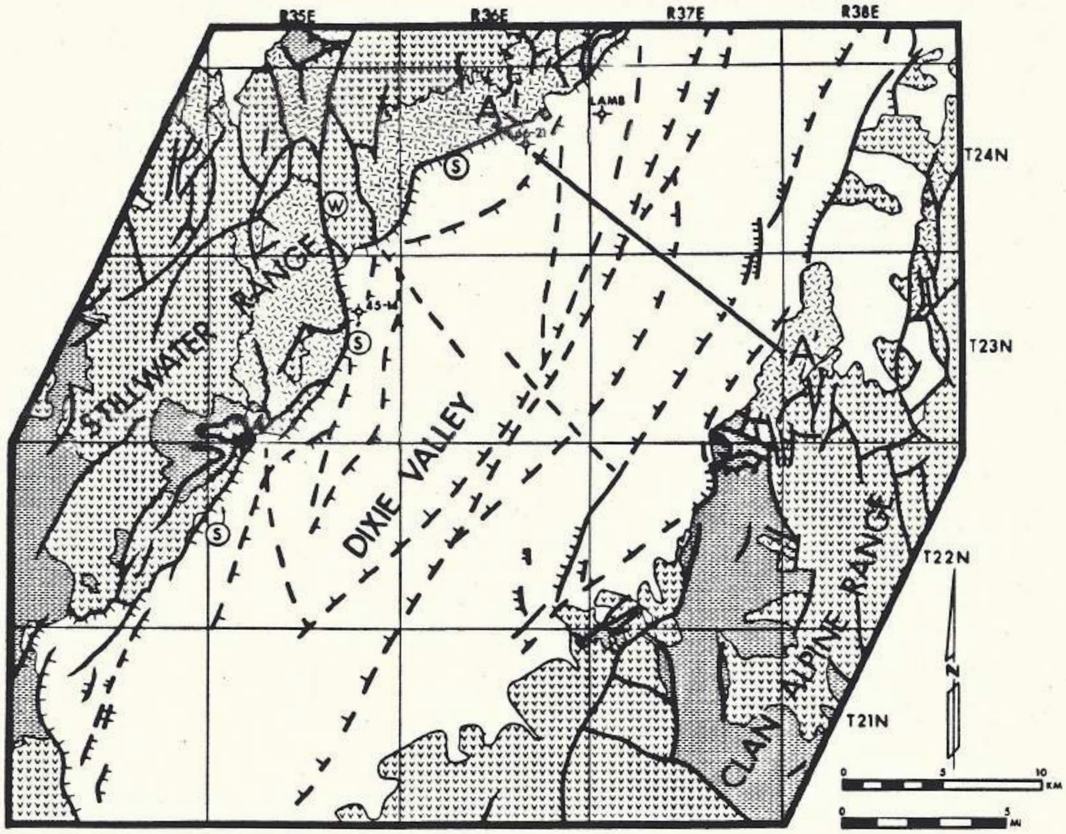


FIGURE 1

GENERALIZED GEOLOGIC MAP OF DIXIE VALLEY, NEVADA
(MODIFIED FROM WILLDEN AND SPEED, 1974; KEPLINGER AND ASSOCIATES, 1977, 1978; SENTURION SCIENCES, 1977, 1978; MMRI-UNR, 1980)

EXPLANATION

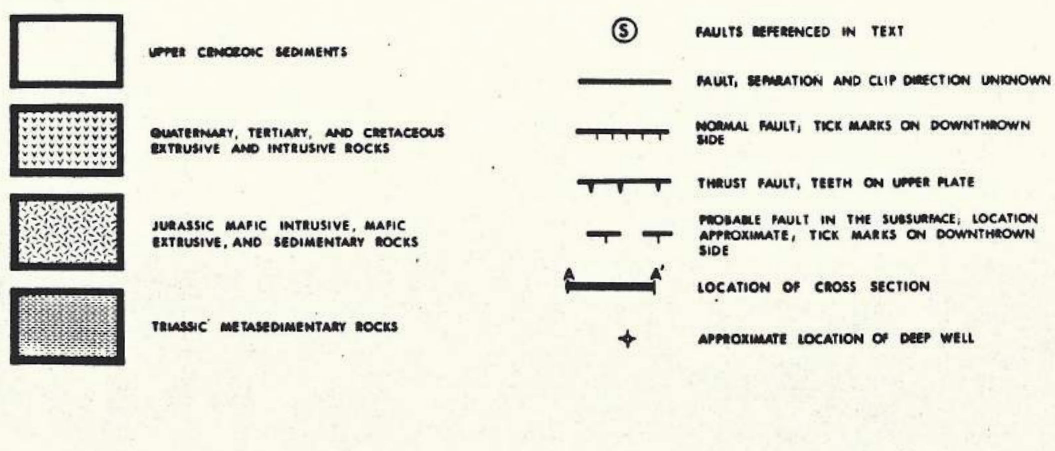
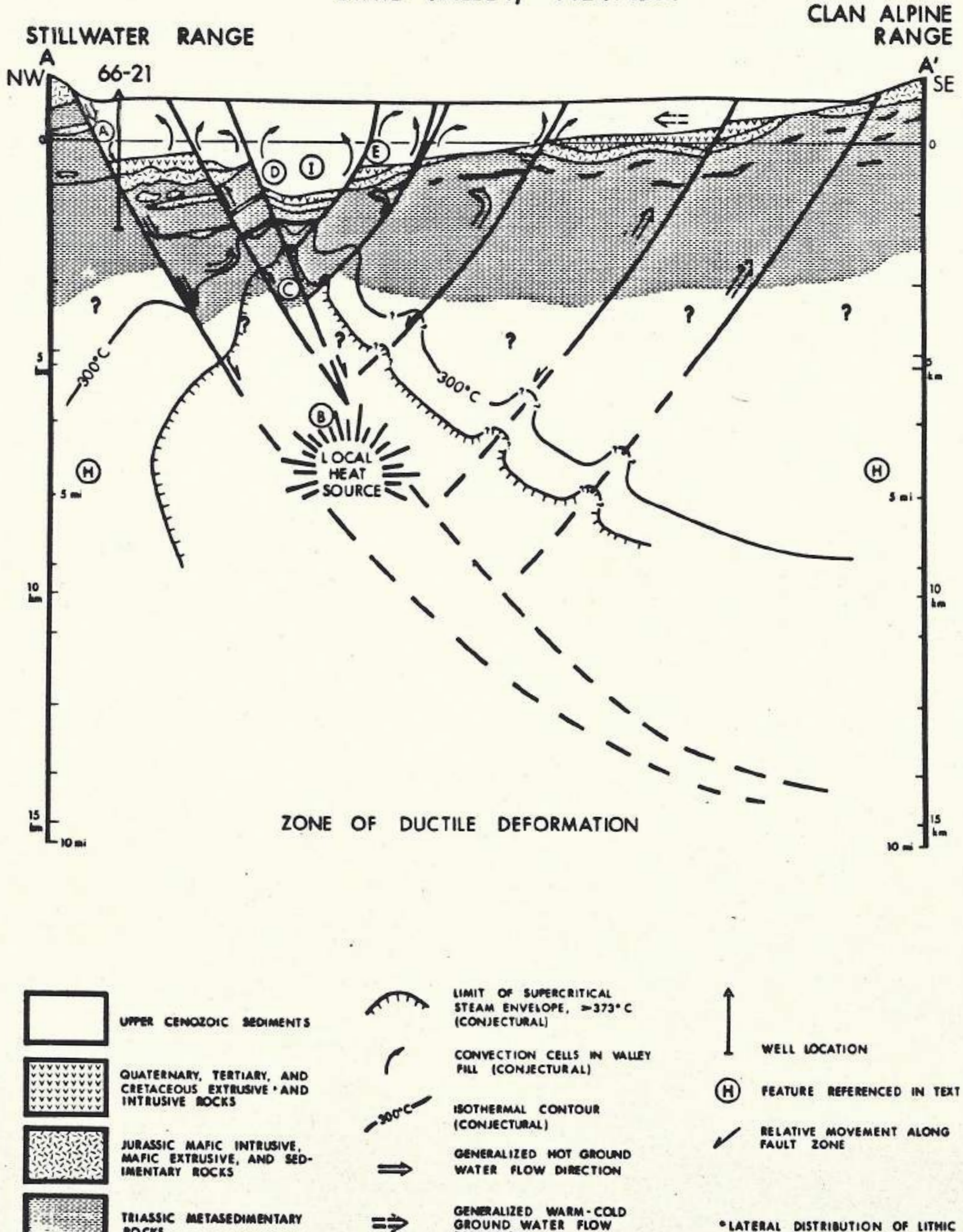


FIGURE 2

GENERALIZED CROSS SECTION*
AND CONCEPTUAL GEOTHERMAL CONVECTION SYSTEMS
DIXIE VALLEY, NEVADA



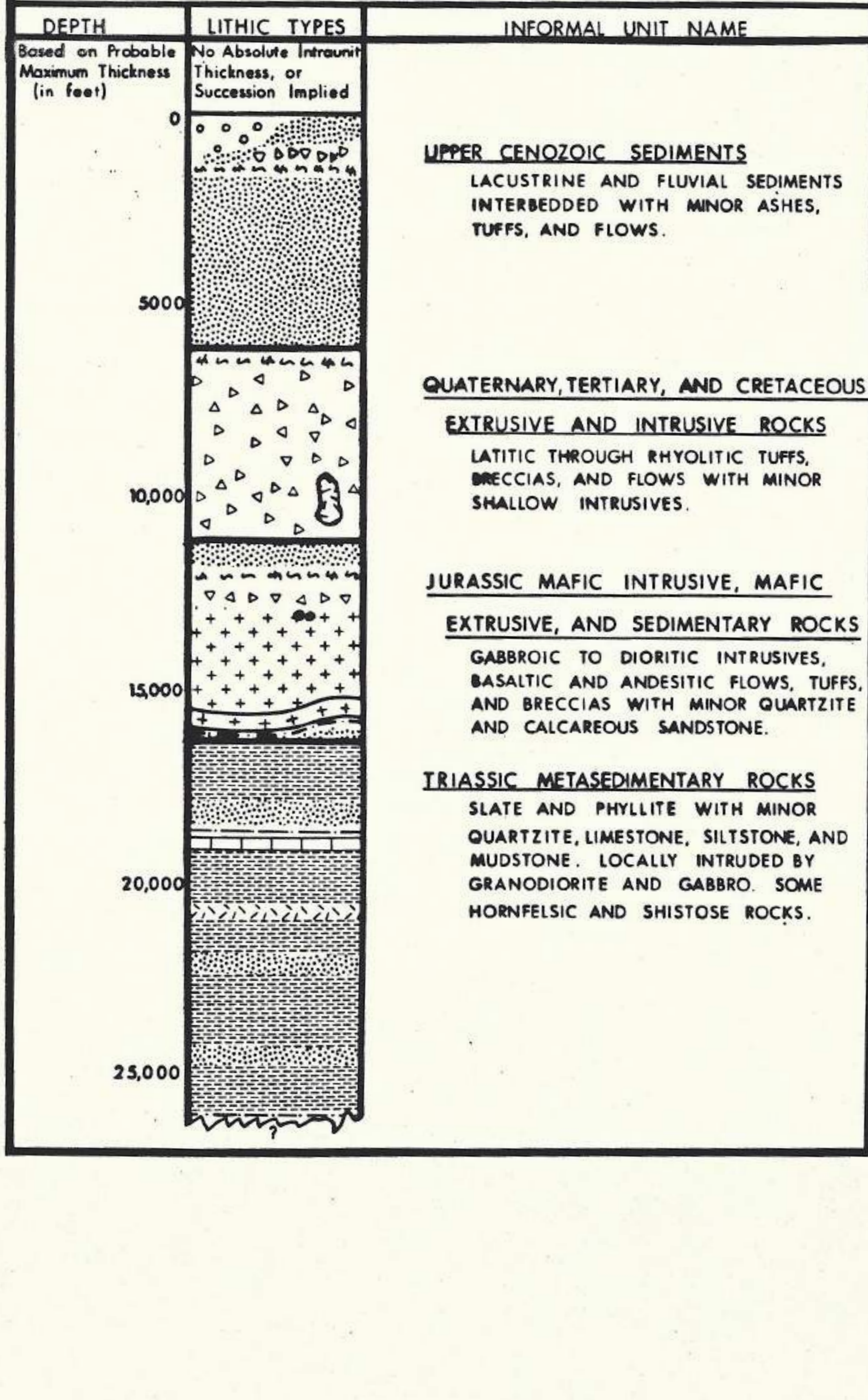


FIGURE 3
GENERALIZED STRATIGRAPHIC COLUMN, DIXIE VALLEY, NEVADA

thickness of the unit has been estimated to be greater than 5,000 ft (Speed, 1976); however, the gabbroic complex is lopolithic and therefore thins to the north and the south in Dixie Valley. Field mapping and well information indicate that rocks in this unit tend to be less fractured than those of the other units.

3. Quaternary, Tertiary, and Cretaceous Extrusive and Intrusive Rocks

Several sequences of Cenozoic volcanic rocks include latitic through rhyolitic, Miocene-age tuffs, breccias, and flows. Younger and older volcanic and shallow intrusive rocks, ranging from basalt to rhyolite composition, also crop out in the ranges. These rocks have been observed to be highly altered and fractured both in outcrop and in well bores. The total thickness of this unit approaches 4,000 ft. In two deep wells on the west side of Dixie Valley the contact between these volcanic and the overlying sediments is marked by a highly-altered red clay (MMRI-UNR, 1980).

4. Upper Cenozoic Sediments

Plio-Pleistocene and younger lacustrine and fluvial sediments, interbedded with minor ashes, tuffs and flows, may reach a thickness of 5,000 ft in the deeper parts of Dixie Valley (Smith, 1968; MMRI-UNR, 1980).

Dixie Valley is dominated by extensional structures that may have begun to move as early as 17 million years ago (MMRI-UNR, 1980), and that are still active today (Thompson and others, 1967). Figure 2 shows a complex pattern of normal faults that are classically attributable to regional extension (e.g., see Harding and Lowell, 1979). We show the probable general configuration of these faults at depth based on surface outcrop, sesimic reflection and refraction, magnetic, gravity, magneto-telluric, well, and geomorphic data as well as regional seismicity, microseismicity, and resistivity (e.g., see MMRI-UNR, 1980 for summaries).

This cross section varies significantly from those of previous authors (e.g., see MMRI-UNR, 1980) because we feel that grabben-floor and adjacent range assymetry, coupled with all other data, require that most of the brittle deformation be accomplished by movement on listric normal faults on the west side of the valley (see S in Figure 1). Earlier structural events (i.e., thrusting and possible strike slip) have affected the rocks of this region; however, the configuration of the present system is controlled primarily by extensional tectonics (e.g., see Figure 2). We see no evidence for Miocene or younger contractional features as suggested by others (e.g., Senturion Sciences, 1977, 1978a).

Geothermal Reservoir Model

Because the general nature of the stratigraphy and structure of the Dixie Valley area is now known with some degree of confidence, we are able to construct a reasonably well constrained model of the geothermal reservoir. The geologic cross section shown in Figure 2 serves to illustrate this geothermal system.

The reservoir is recharged by ground water descending along the major range-front fault zone and associated fractures bounding Dixie Valley on the west (see (A) in Figure 2). Other important areas of recharge include ground-water movement from the northeast and southwest through the Cenozoic sediments of the valley fill, and from the east through both the valley fill and fractures in bedrock. These ground waters are heated at depth, possibly by "local" heat sources (see (B) in Figure 2), and rise along permeable fault zones and fractures (see (C) in Figure 2) until they either meet a barrier to vertical migration (see (D) in Figure 2) or reach the surface via hot springs. If the fluids meet a barrier to vertical migration, they then move laterally through highly fractured rock, such as the Tertiary extrusives, or are trapped by permeability barriers such as the lateral pinchout of fractured rock. The normal faults near (D) are sealed possibly as a result of the development of cataclastic gouge in the felsic volcanics, whereas these same faults may have produced a permeable gouge in the Triassic-age siliciclastics (slates). A probable barrier to vertical migration in Dixie Valley consists of altered "red clay" at the base of the valley fill and at the top of the younger volcanics (see (D) in Figure 2). This seal may consist of altered lacustrine clay and/or of volcanics that have been altered by the hot reservoir fluids.

With this reservoir model, we can now explain the general distribution of hot fluids and lithic types in the three deep wells in Dixie

Valley (i.e., see Wells 45-14, 66-21, and "Lamb" in Figure 1; MMRI-UNR, 1980). Well 45-14 encountered: 1) approximately 1,000 ft of upper Cenozoic sediments, 2) no altered red clay, 3) about 1,000 ft of Tertiary (?) volcanics, 4) no major body of Jurassic intrusive rocks, and 5) roughly 6,000 ft of Triassic metasedimentary rocks. The reported bottom-hole temperature (i.e., 196°C), pressure, and flow rate are apparently below "commercial" minimums. This well cut the major range-front fault zone on the west side of Dixie Valley at a depth of approximately 4,800 ft.

Well 66-21 (see Figure 1) encountered: 1) about 4,000 ft of upper Cenozoic sediments, 2) an altered red clay zone at the base of these sediments and at the top of a 1,000 ft interval of Tertiary volcanics, 3) about 1,000 ft of Jurassic intrusive rocks, and 4) approximately 3,000 ft of Triassic metasedimentary rocks. Fluid temperatures and pressures are relative high in the volcanics although not unusually high at the base of the red clay (i.e., 118°C; 35.5 psig; flow test: 70,000 pounds/hr). The range-front fault cut this well at a depth of about 6,500 ft. A bottom-hole temperature of 219°C was reported, but mass-flow tests apparently were not conducted.

The "Lamb" well encountered: 1) approximately 5,000 ft of upper Cenozoic sediments, and 2) an altered red clay near the bottom. Little direct information is available for the lower intervals of this well because such data is apparently considered proprietary in nature. However, fluid reservoir temperatures of 235°C to 275°C, very high pressures and an attendant low water-steam ratio have been reported by a local operator.

Based on the reservoir model illustrated in Figure 2, we suggest that the lack of high-temperature/pressure fluids in wells 45-14 and 66-21, and the lack of altered red clay in well 45-14 is directly related to the fact that these wells were drilled through a major recharge zone for the system (i.e., the range-front fault zone). The high fluid temperatures/pressures encountered in the "Lamb" well are directly related to its structural position on the fractured, down-dropped side of two faults east of the major range-front fault zone. Furthermore, the upwelling of hot fluids along the second or third fault to the east of the range-front fault has caused the formation of an altered red clay seal, thus providing favorable reservoir conditions. In the model proposed, we do not imply that all fluid movement along the range-front fault zone is downward because lateral variations in fluid movement certainly exist.

If the essential elements of this model are correct, then the eastern side of the central graben in Dixie Valley may also be prospective (see (E) in Figure 2). One critical factor that we cannot quantitively model at this time is subsurface fluid temperature using hydrochemical data derived from hot or warm springs in that part of the system. We suggest that spring data cannot resolve with confidence the question of fluid temperature at depth in all geothermal systems. For example, previous estimates of subsurface temperatures in the Dixie Valley area by the U.S. Geological Survey and others (White and Williams, 1975; Keplinger and Associates, Inc., 1977b), incorporating standard geothermetric methods, were low because quantitative estimates of the extent of subsurface mixing of recharge waters with upwelling thermal water are prone to gross error.

This model includes only one principal heat source. The results of previous magnetotelluric investigations (Senturion Science, 1978b) indicate heat sources at depth below both the western and eastern margins of Dixie Valley (see (H) in Figure 2). If the magnetotelluric method permits definition of deep heat sources, such sources must first heat the ground water located within fault blocks of the Stillwater and Clan Alpine Ranges (see (H) in Figure 2). Then, this hot water must move laterally into the basin. This situation, however, appears unlikely because the up-thrown block of most normal faults tends to be less fractured than the down-thrown block and permeability is usually greatest parallel to fault zones rather than perpendicular to them. An alternate explanation must be sought which would account for the indicated changes in the electromagnetic field in these locations.

A number of questions generated by recent investigations (MMRI-UNR, 1980) remain to be answered in detail. For example, the White Rock Canyon fault, postulated to be a crustal-scale, strike-slip, post-Jurassic feature (see (W), Figure 1), may indeed be a controlling factor in the development of a refined geothermal reservoir model (MMRI-UNR, 1980). If the fault is a major basement-involved structure it may have been reactivated during the latest Miocene, or later, as an extensional feature. Reactivation of older strike-slip faults as grabens by later extension is known in other parts of the world (e.g., Cevennes fault of southern France; Bodeur, 1976). Hot springs do not occur south of this fault and hydrochemical data obtained by previous investigations from both sides of the fault are significantly different (MMRI-UNR, 1980). However, aeromagnetic and well data are either problematical or too sparce to convincingly demonstrate the existence of this proposed type of fault. In addition, we have been unable to find evidence for the smaller-scale structures that usually characterize this deformational style (e.g., en echelon features, synthetic and antithetic shear fractures that are consistent with the proposed left slip, horizontal slickensides, etc.). Additional work is clearly needed on both the fault systems and related hydrochemcial relationships.

A detailed evaluation of the red clay zone and other potential cap rocks is also needed. An interpretation of the available geophysical well logs by experienced personnel and additional petrologic work may yield significant information.

Much additional information is required on the hydrogeological conditions within Dixie Valley and on the bordering Stillwater and Clan Alpine ranges to clarify many of the apparent inconsistencies identified previously (MMRI-UNR, 1980). For example, although boron has been reported in Dixie Valley hot springs and wells, the element has also been reported in significant quantities (200-300 ppm) in whole-rock analyses of Triassic clastic metasediments and carbonates of the Stillwater Range (Keplinger and Associates, Inc., 1977c). The source of the boron contained in the hot spring and wells may be Quaternary lacustrine deposits within Dixie Valley (Horton, 1964), or Triassic-age rocks within the reservoir. Obviously, any emphasis on boron as a guide to defining a high temperature geothermal reservoir must be made with caution.

The geochemical samples and data produced during the DOE investigations (MMRI-UNR, 1980) provide an unusual opportunity to investigate a hydrothermal system and the associated hydrothermal minerals formed along fault/fracture zones. Such investigations may be able to define previous temperature regimes and conditions within the reservoir that have led to the development of the present geothermal system.

Future investigations in Dixie Valley should also focus on obtaining reliable fluid samples for isotopic analysis from either existing wells or from wells to be drilled. In addition, detailed seismic surveys are required to establish the structural relationships within Dixie Valley. The additional work recommended for Dixie Valley would be a timely and cost effective venture because drilling of deep wells may appear to be the next stage of development on some properties. However, the cost of one improperly located deep well would pay for most, if not all of the above-mentioned investigations. Although the urge is compelling to drill before a suitable geological and hydrogeologic foundation has been established, the gain in terms of overall cost effectiveness would be substantial if these investigations were conducted to more clearly define the Dixie Valley geothermal system before additional deep drilling is undertaken. The need for establishing an acceptable geologic foundation for Dixie Valley becomes apparent when a preliminary economic assessment is conducted.

IMPACT OF GEOLOGIC CONDITIONS ON PROJECT ECONOMICS

Based on the available information, the characteristics of the Dixie Valley geothermal reservoir have not yet been sufficiently defined to permit a reliable economic assessment of its commercial potential for either electrical generation or direct industrial application. The geologic factors that will be important to future economic assessments of the prospect area are listed in Table 5. Any of these factors could limit project development. In general, a relatively shallow reservoir of moderate temperature (200°C) containing fluids of less than 5,000 ppm TDS is more attractive than a deep, high temperature (300°C) reservoir of high salinity. The importance of reservoir temperature is illustrated in Figure 4. For example, to supply a hypothetical 200 MW power plant, the number of wells required will depend, in part, on reservoir temperature, which varies with pressure.

The cost of producing electric power declines with increasing fluid temperature. High temperature wells produce fluid (a water-steam mixture) at greater flow rates than low-temperature wells; consequently, less fluid is required to generate the same amount of power at the plant, and fewer wells are required to supply the fluid (see Table 6). Under saturated conditions, four of the factors shown in Table 5 (i.e., wellhead temperature and pressure, and fluid enthalpy and water-steam ratio) are interdependent (Armstead, 1978). The relationship between these variables are illustrated in Figure 5. However, the fluid yield (or mass flow) will differ from well to well and from field to field, and must be determined by well test measurements. Such measurements will vary with wellhead pressure and will be dependent upon the temperature at depth and upon the resistance to flow encountered within the aquifer and up the well.

TABLE 5

TYPICAL GEOLOGIC FACTORS AFFECTING PROJECT ECONOMICS

1. WELLHEAD TEMPERATURE
2. WELLHEAD PRESSURE
3. WELL YIELD (Mass Flow) OF STEAM/WATER
4. FLUID ENTHALPY
5. DEPTH TO PRODUCING ZONES
6. AREA OF PRODUCING ZONES
7. FLUID QUALITY (COMBINED WATER-STEAM RATIO FACTOR AND SALINITY FACTOR)
8. AMENABILITY OF RESERVOIR TO ACCEPT HIGH VOLUMES OF WASTE FLUIDS

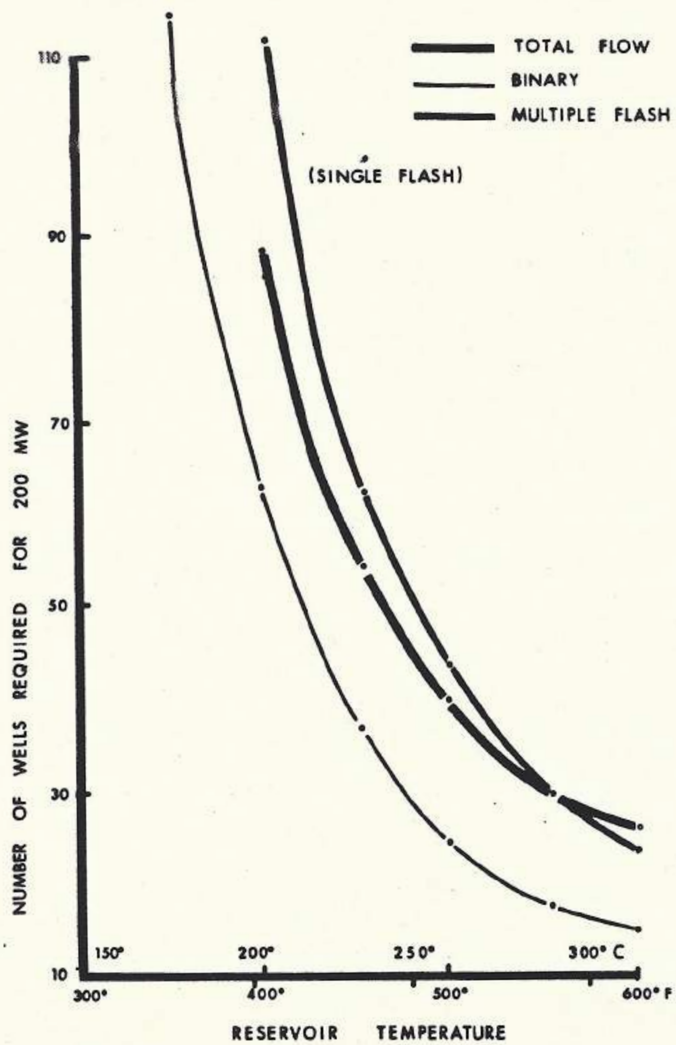


FIGURE 4: Effects of Reservoir Temperature on Required Number of Wells to Produce 200 MW (From Sacarto, 1976)

WELLHEAD TEMPERATURE °C	WELLHEAD FLOW RATE 10^3 lb/hr	MW(Thermal)/WELL[a] Maximum	MW(Thermal)/WELL[a] Actual	MWe/WELL Gross	MWe/WELL Net	ELECTRICIAL EFFICIENCY I[b] Gross	ELECTRICIAL EFFICIENCY I[b] Net
125	250	14.3	11.9	.5	.4	4.2	3.4
	500	28.6	23.6	1.0	.8	4.2	3.4
	750	43.0	34.9	1.4	1.2	4.0	3.4
150	250	17.7	14.6	.9	.7	6.2	4.8
	500	35.4	29.2	1.8	1.5	6.2	5.1
	750	53.1	43.0	2.6	2.2	6.0	5.1
200	250	24.6	20.0	2.0	1.6	10.0	8.0
	500	49.3	40.0	3.9	3.2	9.7	8.0
	750	73.9	56.0	5.5	4.5	9.8	8.0
250	250	32.0	26.0	2.9	2.4	11.2	9.2
	500	64.0	49.4	5.5	4.6	11.1	9.3
	750	93.9	70.5	7.9	6.6	11.2	9.4

[a] THE MAXIMUM IS BASED ON THE SPECIFIED WELLHEAD FLOW RATE. THE ACTUAL IS BASED ON THE REDUCED AVERAGE FLOW USING 20% EXCESS PRODUCING WELLS. THE VARIATION IN CONVERSION EFFICIENCY WITHIN A TEMPERATURE CATAGORY IS CAUSED BY ROUNDING TO AN INTEGER No. OF WELLS.

[b] FOR BINARY ISOBUTANE CYCLE.

TABLE 6: EFFECT OF WELLHEAD TEMPERATURE AND WELLHEAD FLOW RATE ON POWER CONVERSION EFFICIENCY
(FROM BLOOMSTER AND KNUTSEN, 1975)

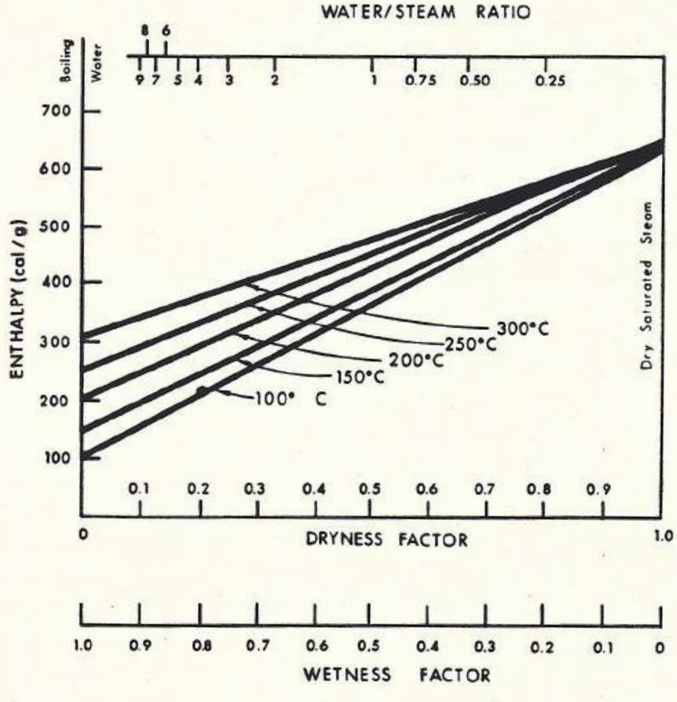


FIGURE 5: RELATIONSHIP BETWEEN ENTHALPY, TEMPERATURE, AND QUALITY FOR SATURATED WATER/STEAM MIXTURES (Based in part on Steam Tables)

Well costs are depth dependent and are directly related to the producer's cost of production. The effect of well cost is much greater on a project utilizing low and intermediate temperature fluid than on high temperature resources. In general, well cost is one of the most important factors in determining the economic attractiveness of an intermediate temperature reservoir. Well spacing also affects the producer's cost and depends upon the area within which production of acceptable characteristics can be generated. A well spacing of 10 to 20 acres is typical in presently operating systems (Goldsmith, 1976).

The effects of severely corroding or incrusting fluids may cause frequent well replacement, either due to damaged well structures, formation plugging or pipeline scaling. The useful life of a well is usually considered to be approximately 10 years. Because of the effects of well "aging", declines in well productivity can be expected and allowances must be made for such declines. An initial flow rate may decline by as much as 20 percent over the first year of operation and by 5 percent over the ensuing years until a production rate of approximately 50 percent of the initial rate is reached. Subsequent production would tend to stabilize. However, well replacement would usually be required before the period of stabilization has arrived.

In Dixie Valley, production testing is presently underway. Bottomhole temperatures of 235°C to 275°C and a total mass flow of 500,000 pounds/hr. have been reported by local operators. High pressure and a low water-steam ratio have also been reported; estimated enthalpy and mass flow appear to be favorable. With regard to fluid quality, data derived from reliable sampling of the reservoir water are not yet available. However, in briefly assessing the available information and the hydrogeological setting, fluid quality and recharge also may be favorable.

The four geologic factors that may restrict large-scale development are: 1) depth to producing zones, 2) area of production, 3) produced fluid quality, and 4) effectiveness of disposing large volumes of waste fluid, presumably injected into intervals of the valley fill above the producing zones. Based on the reservoir model illustrated in Figure 2, two of the four potentially limiting geologic factors (i.e., depth and area of production) appear to be favorable in certain areas of Dixie Valley. Well depths up to 10,000 ft, within an area of approximately 6,000 to 10,000 acres (10 to 15 mi^2), appear to be prospective. On the speculative basis of one production well per 20 acres, approximately 1,000 MW could be produced from 150 wells in a 3,000 acre (4.7 mi^2) field, given certain assumptions (e.g., a 275°C temperature, a flow rate of 318,000 pounds/hr, and well production rate of 6.7 MW/well). Adjustments in any of these conservative assumptions would also alter the number of wells required and/or the power production. A postulated depth of production in excess of 10,000 ft may be a project limiting factor, although testing is continuing in Dixie Valley. Such testing will provide significant data on which detailed economic evaluations will be made.

The third potentially limiting geologic factor involves the quality of the fluids to produced during project development. Very little direct information is presently available, but with additional sampling, combined with other hydrogeological investigations, the chemical nature of these fluids will be defined, both in terms of the scaling potential of the produced fluids and the amenability of the waste fluids to re-injection.

The fourth potentially limiting geologic factor involves waste fluid disposal. Large volumes of "spent" waste fluids are produced as a result of utilizing liquid-dominated geothermal energy sources. Disposal of spent fluids is also necessary in utilizing the geopressured geothermal resources in Texas and Louisiana (Gustavson and Kreitler, 1977; Bachman, 1979). These fluids must either be treated to produce relatively fresh water for comsumption and irrigation, (Fernelius, 1975), or be disposed of via surface water courses or via injection wells. Some elements contained in many geothermal waste streams are toxic, even in very low concentrations, (i.e., ppb and ppm range). For example, a boron content of approximately 1.0 ppm may pose a problem to irrigation.

Disposal via surface water is usually not possible for environmental reasons. Injection of waste fluids into shallow subsurface reservoirs is usually considered to be the most acceptable method of disposing of such fluids, both for reasons of lower environmental impact and economics. Subsurface waste water injection systems in geothermal applications require special attention to: 1) well location, especially in terms of locating injection wells in areas that will not significantly affect fluid production temperatures, 2) injection zone selection, in terms of assuring that zones of optimum thickness and permeability are selected, 3) well design, 4) waste fluid compatability with the mineral assembleages within the rocks and contained fluids of the injection zone, in terms of the chemical and physical factors that may promote zone plugging, and 5) operation and maintenance of the injection system over the life of the project. Warner and Campbell (1977) present an extensive review of the technology associated with waste fluid injection systems. Before such systems are designed, the nature of the hydrogeological systems present in Dixie Valley should be determined to ensure efficient disposal of fluids without negative consequences. The need to conduct detailed hydrogeological investigations in Dixie Valley is pressing and, when accomplished, will provide information on the geothermal system as well as on the amenability of the produced fluids to subsurface disposal.

In the event such factors as well depth, flow rate, temperature, fluid quality, or waste water disposal limit the economic attractiveness of electrical production in Dixie Valley, the reservoir appears to be suited to direct thermal use in such applications as agricultural processing. Large areas could be developed in certain highly permeable, shallow intervals of the reservoir (see (I) , Figure 2), assuming the indicated favorable economic conditions can be confirmed. A trend toward relocating related industries in remote areas in of the western United States is apparent (Reistad, 1978; Packer and others, 1980).

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