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Geothermal Reservoir Categorization and Stimulation Study

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MASTER

GEOHERMAL RESERVOIR CATEGORIZATION AND STIMULATION STUDY

by

Harold L. Overton* and Robert J. Hanold

ABSTRACT

Analyses of the fraction of geothermal wells that are dry (dry-hole fraction), as defined by the ratio of flow failures to total full-size wells, indicate that geothermal reservoirs can be fitted into four basic categories:

- i. Quaternary to late Tertiary sediments, with age less than 2×10^7 years (almost no dry holes).
- ii. Quaternary to late Tertiary extrusives, with age less than 2×10^7 years (approximately 20% dry holes).
- iii. Mesozoic or older metamorphic rocks, with age at least 7×10^7 years (approximately 25-30% dry holes).
- iv. Precambrian or younger rocks, with uplift age of 1×10^6 years or more (data limited to Roosevelt Springs where 33% of the wells were dry).

Failure of geothermal wells to flow economically is due mainly to low-permeability formations in unfractured regions. Generally the permeability correlates inversely with the temperature-age product and directly with the original rock porosity and pore size. However, this correlation fails whenever high-stress fields provide vertical fracturing or faulting, and it is the high-stress/low-permeability category that is most amenable to artificial stimulation by hydraulic fracturing, propellant fracturing, or chemical explosive fracturing.

Category i geothermal fields (e.g., Cerro Prieto, Mexico; Niland, CA; East Mesa, CA) are not recommended for artificial stimulation because these younger sediments almost always produce warm or hot water. Most geothermal fields fit into category ii (e.g., Wairakei, New Zealand; Matsukawa, Japan; Ahuachapan, El Salvador) and in the case of Mt. Home, ID, and Chandler, AZ, possess some potential for stimulation. The Geysers is a category iii field, and its highly stressed brittle rocks should make this site amenable to stimulation by explosive fracturing techniques. The presence of noncommercial wells in the immediate vicinity of good producers would support stimulation experiments at The Geysers. Roosevelt Springs, UT, well 9-1 is in category iv and is a flow failure. It represents a prime candidate for stimulation by hydraulic fracturing because it has a measured temperature of 227°C, is cased and available for experimentation, and is within 900 m of an excellent geothermal producing well.

*H. L. Overton was responsible for the data collection and subsurface analysis portions of this report.

I. INTRODUCTION

Numerous geothermal fields with temperatures greater than 150°C have been drilled and flow tested around the world. Of these, 16 are currently producing electricity or are developed for production. Consequently, enough statistics are now available for some engineering analyses on the broad aspects of producing energy from hot subsurface reservoirs. The fields in operation have been drilled on the more obvious geothermal anomalies with high success ratios. In most regions, however, some dry holes did occur, and it is important to determine if some of these could be artificially stimulated to become productive.

A geothermal well can be an economic failure because of any of three principal factors:

1. Insufficient temperature of the produced fluid.
2. Insufficient fluid fraction or porosity.
3. Insufficient flow permeability (k).

Category 1 includes wells which may provide large quantities of low-temperature fluid; hence, artificial stimulation techniques would be ineffective. Category 2 wells are not considered attractive for stimulation because the well's ability to produce is restricted by low fluid volume in the reservoir, which can result in intermittent or discontinuous fluid production. Only Category 3 wells will be considered as dry holes for reservoir stimulation purposes. Here reservoir stimulation is defined as the creation of permeable paths by artificial techniques, such as selective chemical leaching, massive hydraulic fracturing, chemical explosive fracturing, or propellant-induced fracturing. These dry holes can be characterized as existing where large quantities of hot fluids are available but where flow paths are restricted and k is of the order of a few millidarcys or less. Low values of k can occur due to three distinct causes:

- The reservoir is formed from fine-grained sediments (as originally deposited) or low-permeability metamorphic and igneous rocks, and the stress field is uniform enough for them to remain unfractured.
- The reservoir consists of rocks which originally had high porosity but geochemical changes, such as silica or calcite introduction, reduced the permeability.

- Artificial changes caused the reservoir's natural permeability to be drastically reduced. Mud cake plastering, silica or carbonate deposition caused by pressure or temperature reduction, and plugging of pores by cement or drilling mud are examples.

Only those geothermal fields that have been flow tested were considered to provide pertinent information for reservoir stimulation purposes. The geothermal areas of interest identified during this study are listed in Table I. The ratio of producible wells (for commercial power purposes) to total wells and the dry-hole fraction (number of dry holes divided by the total number of wells) are included in Table I. Not all wells that are nonproducing are necessarily dry; for example, nonproducing wells also include test holes and wells marginal because of low-temperature fluid production. Injection wells are considered to be producible. It should be stressed that the statistics in this report do not reflect exploration success but rather only the dry-hole fraction in an established field.

Based on well statistics collected from cooperative operators and from correspondence and the technical literature, data were grouped in the following categories with an aim toward analyzing flow performance.

- Geological Features
- Hydrogeochemical Data
- Thermal Data
- Hydrological Data
- Reservoir Properties - Rock Parameters.

Data have been arranged so that they can be computerized if necessary, and although geological classifications are included, the highest priority was given to direct numerical measurements. Evaluation of reservoirs for possible artificial stimulation was primarily based on the following data:

- Subsurface temperatures by thermometer measurement
- Permeability from fluid flow tests
- Free fluid fraction (effective porosity) from well logs.

TABLE I
SUMMARY OF GEOTHERMAL INSTALLATIONS INCLUDED IN WELL STIMULATION STUDY

Electrical Geothermal Installations				Installations Under Test or Construction			
Field	Generating Capacity (MW)	Potentially Producing Wells/ Total Wells	Dry-Hole Fraction	Area	Planned Generating Capacity (MW)	Potentially Producing Wells/ Total Wells	Dry-Hole Fraction
Cerro Prieto, Mexico	75	30/37	0.03	Ahuachapan, El Salvador	60	17/23	0.22
Hatchobaru, Japan	5.5	7/9	--	Brawley, California	--	3/3	0
Kawerau, New Zealand	10	11/16	0.13	Broadlands, New Zealand	150	17/28	0.29
Larderello, Italy	365	190/511	--	Chandler, Arizona	--	0/2	1.0
Matsukawa, Japan	20	6/12	0.17	East Mesa, California	--	5/7	0
Mt. Amiata, Italy	25	--/60	--	El Tatio, Chile	17 (est.)	3/7	0.57
Namafjall, Iceland	3.4	7/7	0	Kawah, Java	--	2/4	0.25
Onikobe, Japan	20	10/--	--	Kizildere, Turkey	0.5	12/16	0.19
Otake, Japan	12	11/11	0	Krafla, Iceland	55	--/2	--
Pauzhetsk, USSR	5	18/20	0.1	La Bouillante, Guatemala	30	3/4	0.25
The Geysers, California	> 500	89/110	~ 0.07	Momotombo, Nicaragua	--	3/7	0.43
Tiwi, Philippines	10.5	--	--	Mt. Home, Idaho	--	1/1	0
Travale, Italy	15	25/27	0.07 (0.2 last 5 wells)	Niland, California	--	4/5	0 or 0.2
Wairakei, New Zealand	165	--/108	--	Olkaria, Kenya	14	--/8	0.25
				Raft River, Idaho	--	3/3 (stimulation required)	0
				Roosevelt Springs, Utah	--	4/6	0.33
				Tauhara, New Zealand	106	--/15	--
				Valles, New Mexico	--	12/16	0.25
				Waiotapu, New Zealand	(postponed)	--/7	--

II. DATA SOURCES

Primary sources of data for this study were the Proceedings of the International Geothermal Conferences at Pisa and San Francisco. These detailed, comprehensive volumes contain a wealth of current data on geothermal fields throughout the world. Personal visits by participating staff to many of the active fields in the United States, Mexico, and Turkey provided additional first-hand data. Supporting information was also obtained by direct correspondence with active participants and from other technical literature sources.

The U. S. Department of the Interior Geological Survey (USGS) has in effect a program to compile geothermal data from active fields and wells. This computerized data file (GEOTHERM)* is categorized as follows: (a) field data, (b) surface water sample data, (c) well data, (d) steam sample data, (e) water sample data from wells, (f) isotopic data, (g) space and process heating, and (h) binary system data. Information currently available from the GEOTHERM data file includes location, number of wells (producing, total, testing, injection, etc.), flow rates, temperatures and gradients, geological descriptions, and depths from category (a). Category (c) includes well locations, depths, pressures, temperatures, flow rates, and casing data. For this report, data on New Zealand fields and The Geysers were provided from the files of GEOTHERM.

Additional technical data are available from the National Geothermal Information Resource (GRID)** project under way at Lawrence Berkeley Laboratory. This project has been established to serve as a focal point for collection, organization, and dissemination of information and numerical data pertaining to geothermal energy. The six major areas that are included are: exploration, physical chemistry, utilization, environmental, institutional, and reservoir characterization. Efforts are also being devoted to setting up GEODOC, a computer-based file, which contains descriptive cataloging and indexing information for all documents processed by the National Geothermal Information Resource Group.

* Data are available from:
U.S.G.S., Reston, VA 22092
James Swanson, Project Chief
(703) 860-6604

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Lawrence Berkeley Laboratory
Berkeley, CA

III. CATEGORIZATION OF RAW DATA

The data essential to evaluate a subsurface geothermal reservoir include the producing fluid temperature, a fluid flow index (generally interpreted to be the formation permeability), and the free fluid fraction of the reservoir. Fluid temperature (T) determination can be obtained from a reservoir-equilibrated static temperature measurement taken a few days after cessation of drilling or from analysis of continuous T versus time data curves. Although a true in situ permeability (k) determination (including its dependence on temperature and pressure) is difficult, relevant data are obtainable from well-flow tests, draw-down experiments, and laboratory analyses of core samples. Although laboratory core sample analysis can yield the temperature and pressure dependence, the effects of large-scale fractures near the wellbore will not be included. Formation alterations that occur as a result of chemical leaching or pore plugging by mineral deposition tend to make permeability a dynamic property that may vary with the time of production. Fluid fraction or porosity (ϕ) determination is a relatively straightforward reservoir indicator. It has less variation and is most easily measured by several developed well-logging techniques.

These primary reservoir variables (T, k, and ϕ) are directly related to the thermal output of a geothermal system. The rate of thermal energy production from a reservoir is equal to the product of the fluid mass flow rate ($\dot{m}$), the fluid specific heat (C_p), and the useful temperature drop ($T - T_r$), where T_r is the fluid rejection temperature at the surface:

$$\dot{Q} = \dot{m} C_p (T - T_r),$$

which can be expressed as

$$\dot{Q} \propto k (T - T_r).$$

The total thermal energy available from the fluid in a reservoir is equal to the product of the fluid volume (V_f), the fluid density and specific heat (ρC_p), and the useful temperature drop ($T - T_r$):

$$Q_{\text{total}} = V_f \rho C_p (T - T_r),^*$$

*This assumes no heat extraction from the reservoir rock by circulation of recharge fluid.

which can be expressed as

$$Q_{\text{total}} \propto \phi (\text{rock volume containing fluid}) (T - T_r).$$

Another significant variable contained in the above equation is the rock volume containing usable fluid, which cannot be estimated with confidence for undeveloped geothermal fields. It may be broken down into two components: areal extent and mean reservoir thickness. The latter can be determined in principle at the location of each logged well that completely penetrates the reservoir. The areal extent of the field can be defined only when its boundaries have been exceeded by production or exploratory wells. Additional information that bears qualitatively upon the analysis of a geothermal field has been grouped into the five categories presented below. Detailed data forms for many of the geothermal reservoirs investigated in this study are presented in Appendix B with the data grouped in these same five categories.

A. Geological Features

- Classification and thicknesses of sedimentary, metamorphic, and igneous units.
- Gross geometric or discontinuity features, such as faulting, fracturing, and unconformity, caused by tectonics and erosion.
- Visual evidence of recent volcanism including silicic domes and ash flows.

These data help to determine the variations of T , k , and ϕ between wells and to place limits on the reservoir volume.

B. Hydrogeochemical Data

- Total dissolved solids.
- Spring or well water analysis by cations, anions, silica, and boron.
- Water temperature, resistivity, and pH.
- The presence of exotics such as hydrogen.

These data indicate special problems or benefits that may occur with production, such as scaling, corrosion, or mineral assets.

C. Thermal Data

- Reservoir-equilibrated temperature or T-versus-time curves.
- Temperature-versus-depth graphs.
- Spring and shallow well temperatures.
- Intensity of hot springs and seeps.
- Geochemical thermometers.

Thermal parameters help to establish the extent of the thermal anomaly as well as the magnitude of temperatures encountered.

D. Hydrological Data

- Annual precipitation and mean surface temperature.
- Ground elevation and water table depth.
- Spring and shallow well flow rates.
- Well pressure-depth measurements.

These data help to show the range of permeabilities and the pressure performance which is possible in a given basin. Reservoir recharge, although not predictable at present, is certainly a function of precipitation and water table levels.

E. Reservoir Properties - Rock Parameters

- Water compositions or concentration of dissolved material.
- Productive interval, h_r , or thickness open to flow.
- Rock porosity by all possible measurements.
- Reservoir rock type and fracture indications.
- Maximum flow rate and pressure data.
- Permeability by flow test.
- Indications of barriers, discontinuities, or other peculiarities.

Reservoir properties are usually unlike those in shallow wells nearby and must be incrementally measured by logging, coring, or pressure testing.

IV. GEOLOGICAL CATEGORIZATION OF GEOTHERMAL FIELDS

Data contained in Table I illustrate the ratio of producible wells to total wells and the dry-hole fraction for those geothermal fields for which statistics were available. For this study producing wells include only those which yielded commercial quantities of hot fluids at some time in the history

of the field, regardless of present status. Marginal wells are included as producers, whereas dry holes include only those wells that had no flow or insufficient flow for commercial production. Table II contains a further breakdown of geothermal fields by well categories using the following code:

<u>Dry</u>	Minimal or no fluid flow
<u>Inj</u>	Used for injection, assumed to be reservoir-connected
<u>Marg</u>	Produces marginally
<u>Obs</u>	Observation well, reservoir-connected
<u>Prod</u>	Produced warm or hot fluids at some period
<u>Strat</u>	Slim hole, not included in statistics
<u>Test</u>	Information incomplete
<u>WC</u>	Wildcat or well outside field boundaries

Inspection of Tables I and II shows that the dry-hole fraction is usually less than 0.3; it exceeded 0.4 in only three cases, when failures were based entirely on lack of sufficient flow permeability. When the geothermal fields were analyzed further on the basis of geologic age and rock type, four basic categories could be identified. The geologic categorization of these geothermal fields is illustrated in Table III, based on the following category generalizations:

- i. Quaternary to late Tertiary sediments, with age less than 2×10^7 years.
- ii. Quaternary to late Tertiary extrusives, with age less than 2×10^7 years.
- iii. Mesozoic or older metamorphic rocks, with age at least 7×10^7 years.
- iv. Precambrian or younger rocks, with uplift age of 1×10^6 years or more.

From the data presented in Table III and the geothermal field subsurface characteristics (including mass flow rate, fluid temperatures, permeability, and porosity) given in Table IV, the following general conclusions concerning the geologic categorization of geothermal fields can be drawn.

Category (i) fields have very few dry holes, due to the large porosity and lower cementation of grains in these Quaternary to late Tertiary sediments. This feature is typical of the intermontane basins (Imperial Valley and

TABLE II

BREAKDOWN OF GEOTHERMAL INSTALLATIONS BY WELL CATEGORIES*

<u>GEOTHERMAL INSTALLATION</u>	<u>DATA SOURCES**</u>
<u>Ahuachapan, El Salvador:</u> 23 wells, $T_{\max}$ 248°C; <u>Prod:</u> Ah-1, 4, 5, 6, 7, 20, 21, 22, 24, 25, 26; <u>Marg:</u> AH-3, '8, 9, 13, 16; <u>Inj:</u> AH-29; <u>WC:</u> AH-10; <u>Dry:</u> AH-2, 11, 12, 14, 15, (15 collapsed); <u>Strat:</u> 24 Gradient holes.	Pisa 2 no. 2, p. 1392; SF. p. 1853; Dominico- private communication
<u>Brawley, California:</u> 3 wells; <u>Test:</u> Veysey no. 1 and 2; <u>Dry:</u> None.	on-site visit
<u>Broadlands, New Zealand:</u> 28 wells (incl. one deep hole), $T_{\max}$ 307°C; <u>Prod:</u> ER-2, 3, 4, 7, 8, 9, 11, 13, 17, 18; <u>Marg:</u> 1, 6, 10, 12, 14, 15, 16; <u>Dry:</u> 8 wells.	Pisa 2 no. 1, p. 234, 248; Pisa 2 no. 2, p. 1314; SF. p. 378, 1113
<u>Cerro Prieto, Mexico:</u> 37 wells, $T_{\max}$ 370°C; <u>Prod:</u> M-3, 5, 6, 7, 8, 9, 10, 11, 13, 15, 20, 21, 25, 26, 29, 30, 31, 34, 38, 39; <u>Standby:</u> E-4, J-3, 6, K-3, 9, P-2, 2A, plus new drillings; <u>Strat:</u> 42 holes, <u>WC:</u> M-4; <u>Dry:</u> 1 well.	Pisa 2 no. 1, p. 27; SF. p. 518, 544
<u>Chandler, Arizona:</u> 2 wells, $T_{\max}$ 178°C <u>Dry:</u> PR-1, 2.	Overton
<u>East Mesa, California:</u> 7 wells, $T_{\max}$ 202°C; <u>Prod:</u> 5-1, 6-1, 6-2, 8-1, 31-1; <u>Test:</u> Magma Sharp, Shafer no. 1; <u>WC:</u> Am. Petrofina no. 1; <u>Dry:</u> None.	NTIS PB-243756

* See page 9 for well category code.

** Pisa refers to "Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources," Pisa, Italy, 1970.
 SF refers to "Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources," San Francisco, CA, 1975.

TABLE II (cont)

<u>El Tatio, Chile</u> : 7 wells, $T_{\max} 262^{\circ}\text{C}$; <u>Prod</u> : 2 commercial and 1 marginal - no. 7, 10, 11 (No. 8, 9 collapsed); <u>Strat</u> : 11 gradient holes, 6 slim holes to 600 m; <u>Dry</u> : 4 wells by natural flow.	SF. p 175
<u>Hatchobaru, Japan</u> : 9 wells, $T_{\max} 218^{\circ}\text{C}$; <u>Prod</u> : H-1, 2, 3, 4, 6 + new drillings; <u>Strat</u> : 1-1030 m.	Pisa 2 no. 1, p. 208, SF. p. 674, 1643
<u>Kawah, Java</u> : 4 wells, $T_{\max} 239^{\circ}\text{C}$; <u>Prod</u> : no. 6, 7; <u>Strat</u> : 8, 9 (no. 8 had 180°C), 5 slim holes in 1926; <u>Dry</u> : 1 well.	SF. p. 758, 1056
<u>Kawerau, New Zealand</u> : 16 wells, $T_{\max} 285^{\circ}\text{C}$; <u>Prod</u> : KA-1, 4, 7A, 8, 10, 11, 12, 14, 16, 17; <u>Marg</u> : KA-3; <u>Dry</u> : KA-5, 13; <u>Strat</u> : KA-2, 9; <u>WC</u> : KA-6A.	Geotherm, Mar 75; Pisa 2 no. 1, p. 243
<u>Kizildere, Turkey</u> : 16 wells, standby, $T_{\max} 204^{\circ}\text{C}$; <u>Prod</u> : KD-1, 1-A, 6, 7, 13, 14, 15, 16; <u>Marg</u> : 2, 3, 4, 9 (cement failure no. 8); <u>Dry</u> : KD-5, 12, 111; <u>Strat</u> : 69 gradient holes.	Pisa 2 no. 1, p. 124, 553, Pisa 2 no. 2, p. 1463
<u>Krafla, Iceland</u> : 2 wells, $T_{\max} 298^{\circ}\text{C}$.	SF. p 441
<u>La Bouillante, Guatemala</u> : 4 wells, $T_{\max} 240^{\circ}\text{C}$; <u>Prod</u> : Bo-1, 2; <u>Marg</u> : no. 4; <u>Dry</u> : no. 3.	Pisa 2 no. 1, p. 71, SF. p. 105
<u>Larderello, Italy</u> : 511 wells, $T_{\max} 300^{\circ}\text{C}$; <u>Prod</u> : 181; <u>Obs</u> : 9 as of 1969.	Pisa 2 no. 1, p. 77, 578, 622, 698, SF. p. 820
<u>Matsukawa, Japan</u> : 12 wells, $T_{\max} 270^{\circ}\text{C}$; <u>Prod</u> : BR-2, MR-1, 2, 3, 5, 6 (no. 4 casing collapsed) <u>Strat</u> : 7 test holes; <u>Dry</u> : AR-1, BR-1.	Pisa 2 no. 1, p. 221, Pisa 2 no. 2, p. 1150, 1440, 1480, SF. p. 630.
<u>Momotombo, Nicaragua</u> : 7 wells, $T_{\max} 320^{\circ}\text{C}$; <u>Prod</u> : no. 2 + new drillings; <u>Marg</u> : no. 3; <u>Dry</u> : 3 wells.	Dominico - private communication

TABLE II (cont)

<u>Mt. Amiata, Italy:</u> $T_{\max}$ 177°C 60 wells	Pisa, 2 no. 1, p. 83, 425, SF. p. 820
<u>Mt. Home, Idaho:</u> 1 well, $T_{\max}$ 189°C; <u>Prod:</u> no. 1.	Overton
<u>Namafjall, Iceland:</u> 7 wells, $T_{\max}$ 280°C; <u>Prod:</u> no. 3, 4, 5, 6, 7; <u>Marg:</u> No. 1, 2; <u>Dry:</u> none.	Pisa 2 no. 1, p. 540, 925, Pisa 2 no. 2, p. 1646
<u>Niland, California:</u> 5 wells, $T_{\max}$ 322°C; <u>Prod:</u> Magma Max, 1, 4; <u>Inj:</u> M-2, 3; <u>WC:</u> Woolsey.	Overton
<u>Olkaria, Kenya:</u> 8 wells $T_{\max}$ 287°C <u>Prod:</u> no. 3, 4; <u>Dry:</u> 2 wells (status of other wells unknown).	SF. p. 7
<u>Onikobe, Japan:</u> data indicates 10 wells are producing	Pisa 2 no. 2, p. 1475, SF. p. 631
<u>Otake, Japan:</u> 11 wells, $T_{\max}$ 250°C; <u>Prod:</u> no. 0-1, 2, 3, 5, 6, 7, 8, 9, 10, T-1, T-2 (6, 7, 8, 9, 10 Prod. 1969) (0-7, 8, 9, 10 best wells); <u>Strat:</u> 7 holes; <u>Dry:</u> none.	Pisa 2 no. 1, p. 197, 209, Pisa 2 no. 2, p. 1458, SF. p. 674, 1643
<u>Pauzhetsk, Kamchatka:</u> 20 wells, $T_{\max}$ 200°C; <u>Prod:</u> R-2, 4, 10, 11, 12, 13, 14, 15, 16, 20; <u>Obs:</u> R-1, 5, 6, 7, 8, 18, 19, 21; <u>Strat:</u> P-1; <u>Dry:</u> 2 wells.	Pisa 2 no. 2, p. 1077, 1116, 1256, 1628, SF. p. 809
<u>Raft River, Idaho:</u> 3 wells, $T_{\max}$ 147°C <u>Prod:</u> RRGE-1, 2, 3 (stimulation required); <u>Dry:</u> none.	Overton
<u>Roosevelt Springs, Utah:</u> 6 wells, $T_{\max}$ 227°C <u>Prod:</u> 13-10, 12-35, 54-3 (3-1 casing collapse); <u>Dry:</u> 9-1, 80-32; <u>Strat:</u> OH-1, OH-2, 82-33	Overton

TABLE II (cont)

<p><u>Tauhara, New Zealand</u>: 15 wells, $T_{\max}$ 250°C.; (environmental delays); <u>Prod</u>: TH-1, 2, 3 + new drilling; <u>Obs</u>: TH-4.</p>	<p>Pisa 2 no. 1, p. 233, SF. p. 378</p>
<p><u>The Geysers, California</u>: 110 wells, $T_{\max}$ 285°C; <u>Prod</u>: 86 wells; <u>Inj</u>: 3 wells; ~7% dry holes.</p>	<p>Geotherm, Mar 75; Pisa 2 no. 2, p. 1552, SF. p. 1399, 1405</p>
<p><u>Travale, Italy</u>: 27 wells, $T_{\max}$ 277°C; <u>Prod</u>: TR-3, 4, 5, 6, 9, 12, 15, 16, 18, 19, 20, 21, S. Piero, S. Luigi, C-1, R-1, R-4, T-22; <u>Obs</u>: F-2, 3 bis, 8, 11, 13, 14, 17; <u>Dry</u>: R-2, 3 (R-3 not completed).</p>	<p>Pisa 2 no. 1, p. 587</p>
<p><u>Valles, New Mexico</u>: 16 wells, $T_{\max}$ >200°C; <u>Prod</u>: 9 wells; <u>Inj</u>: 3 wells; <u>Dry</u>: 4 wells.</p>	<p>on-site visit</p>
<p><u>Waiotapu, New Zealand</u>: 7 wells, $T_{\max}$ 295°C, low permeability; CaCO₃ sealing.</p>	<p>Pisa 2 no. 1, p. 234, 478; Pisa 2 no. 2, p. 1312, SF. p. 378, 2461</p>
<p><u>Wairakei, New Zealand</u>: 108 wells, $T_{\max}$ 270°C; <u>Prod</u>: 4-1, 2, 9, 14, 15, 18, 20, 21, 22, 24, 26, 26A, 27, 28, 29, 30, 31, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 50, 52, 53, 55, 56, 57, 59, 60, 61, 62, 63, 67, 68, 70, 71, 72, 73, 74, 75, 76, 78, 80, 81, 83, 86, 92, 108, 203, 216, 217 (62 prod. in 1969. 71 at various times); <u>Strat</u>: M-1, 2, 3, 4, 5, 6, 7; <u>Dry</u>: 33, 36, 223, 224; <u>WC</u>: TH-2; <u>Obs</u>: 205, 206, 207, 210, 212, 215, 218, 219, 220, 222 (data from numerous wells missing).</p>	<p>Pisa 2 no. 1, p. 232, Pisa 2 no. 2, p. 1331, 1355, 1426, SF. p. 40</p>

TABLE III
GEOLOGIC CATEGORIZATION OF GEOTHERMAL FIELDS AND AREAS

Geologic Category	Area or Field	Dry-Hole Fraction	Comments
i. Quaternary/Tertiary - sedimentary basins, intermontane Av < 5% dry	Brawley, California	0	
	Cerro Prieto, Mexico	0.03	
	East Mesa, California	0	
	Niland, California	0 or 0.2	No flow test on Woolsey well
ii. Quaternary/Tertiary extrusives - tuffs, basalts, breccia, flows Av 22% dry	Ahuachapan, El Salvador	0.22	
	Broadlands, New Zealand	0.29	
	Chandler, Arizona	1.0	Based on 2 wells
	Hatchobaru, Japan	---	
	Kawah, Java	0.25	
	Kawerau, New Zealand	0.13	
	La Bouillante, Guatemala	0.25	Tuffs, lavas
	Matsukawa, Japan	0.17	
	Mountain Home, Idaho	0	Based on 1 well
	Namafjall, Iceland	0	Quaternary - basalt
	Olkaria, Kenya	0.25	
	Onikobe, Japan	---	
	Otake, Japan	0	
	Pauzhetsk, USSR	0.1	
	Tauhara, New Zealand	---	
	Tiwi, Phillipines	---	Quaternary - andesites
	Valles, New Mexico	0.25	
	Wairakei, New Zealand	---	
	Waiotapu, New Zealand	---	
iii. Mesozoic and older metamorphics, sediments Av 27% dry	El Tatio, Chile	0.57	
	Kizildere, Turkey	0.19	
	Larderello, Italy	---	
	Momotombo, Nicaragua	0.43	
	Mt. Amiata, Italy	---	Quaternary - volcanics Mesozoic - sediments
	The Geysers, California	~ 0.07	
	Travale, Italy	0.07	0.2 for last 5 wells
iv. Intrusives, granite-like reservoirs	Roosevelt Springs, Utah	0.33	
i or iv.	Raft River, Idaho	0*	Fractures at basement contact, 3rd well in granite

*Stimulation required to achieve this.

TABLE IV
GEOTHERMAL FIELD SUBSURFACE CHARACTERISTICS

Geologic Category	Field	Location	Status	Mass Flow Rate/Well (Tons/h)	T (°C, Av/Max)	k (md)	Porosity (%)	Formation
i	Cerro Prieto	Mexico	Production	60 av	300/370	--	~ 25	Quaternary/Tertiary - sandstone
	East Mesa	California	Test	22.7-127	Range 117-202	6- 28	20-27	Quaternary/Tertiary - silt, sandstone
	Niland	California	Test	102-245	Range 238-322	50-170	27	Quaternary/Tertiary - sandstone
ii	Ahuachapan	El Salvador	Test	385 av	230/248	--	---	Quaternary - lava, tuff
	Broadlands	New Zealand	Production	40-254	255/307	0.3-170	2-36	Quaternary - tuff, rhyolite
	Chandler	Arizona	Inactive	0.6	170/178	0.1-0.4	5-22	Tuff (tight)
	Matsukawa	Japan	Production	5.8-65	220/270	up to 310	13	Miocene - tuff Quaternary - andesite
	Mountain Home	Idaho	Inactive	13.2	189 (1 well)	2.2	14	Quaternary - clay, siltstone
	Namafjall	Iceland	---	--	250/280	--	---	Quaternary - basalt
	Otake	Japan	Production	17-246	230/250	--	---	Quaternary/Pliocene - tuff, andesite
	Pauzhetsk	USSR	Production	52 av	185/200	269-440	---	Quaternary - andesite, rhyolite
	Valles	New Mexico	Standby	> 100	--/ > 200	--	---	Quaternary - tuff
	Wairakei	New Zealand	Production	135 av	230/270	--	---	Breccia, andesite
iii	El Tatio	Chile	Standby	--	230/262	--	---	Quaternary/Tertiary - rhyolite Mesozoic - sediments
	Kizildere	Turkey	Standby	529 Well No. 14	Range 158-204	108 best well	---	Marble, shist
	Larderello	Italy	Production	17.9 av 175 max	200/300	high	---	Mesozoic - flysch to quartzite
	The Geysers	California	Production	3.4-70	250/285	--	---	Mesozoic - greywacke, basalt
	Travale	Italy	Reworking	10 av	239/277	--	---	Mesozoic - flysch, dolomite
iv	Roosevelt Springs	Utah	Test	100-125	227 (1 well)	< 1 (well 9-1)	2	Granodiorite
i or iv	Raft River	Idaho	Test	180	146/147	25-165	17-30	Fractured metamorphics above Elba quartzite

Cerro Prieto). Consequently, hydraulic fracturing would be of negligible value, although chemical treatment might easily remove calcareous cement.

Category (ii) fields generally have good permeability, and the dry-hole fraction is approximately 0.2. This results from the high porosity and fracturing present in the tuffs and breccia comprising many of these Tertiary or Quaternary extrusives. Tuffs, particularly, have low shear strength and fracture readily even though the compressive strength is high for the high void ratio. Most of the current geothermal fields fit into category (ii), including those in New Zealand, Japan, Iceland, and Kamchatka.

Category (iii) fields seem to rely mainly on fractures for fluid productions, since the primary porosity is generally less than 5% in metamorphics. Category (iii) fields are somewhat unpredictable and include The Geysers, Larderello, Travale, and Kizildere. Dry-hole fractions are approximately 0.25-0.3 in these fields. This category does exhibit high potential for stimulation, when extensive fracturing does not occur naturally near a well.

Category (iv), composed of igneous intrusives, is the prime candidate for hydraulic fracturing, because the primary porosity is of the order of 2%. In a broader sense this category probably includes categories (i) and (iii). That is, intrusives probably underlie both shallow sediments and metamorphics that produce steam. In category (iv), erosion of the cover allows the intrusives to be drilled at a shallow depth. This category has insufficient statistics for complete analysis and includes only Roosevelt Springs and possibly Raft River. Based on Roosevelt Springs, the dry hole fraction is 0.33.

V. WELL CHARACTERISTICS

Some individual well characteristics for U. S. geothermal areas are presented in Table V. Note that the permeabilities vary from a few tenths of a millidarcy to 170 millidarcys and the porosities vary from 2-30%. The superscript ^a in Table V refers to wells which are known to be available for stimulation experimentation. These data are tabulated to provide a convenient comparison of the most significant well characteristics for a range of U. S. sites being drilled for geothermal fluids which are interesting from a stimulation standpoint. None of these sites are commercially produced, although East Mesa and Roosevelt Springs are capable of producing steam without major engineering problems.

TABLE V
INDIVIDUAL U. S. GEOTHERMAL WELL CHARACTERISTICS

Site	Well No.	Depth (m)	T _{max} (°C)	Av. k (md)	Average Porosity (%)	Max Gradient (°C/km)	Rock Type	Total Dissolved Solids (ppm)	Comments
Chandler ^a (AZ)	PR - 1	2806	163	0.3	22	49	Tuff	26 700	
	PR - 2	3186	178	---	5	47	Tuff	29 700	
East Mesa (CA)	5 - 1	1834	117	6	27	51	Sandstone	2 450	2.7 ppm boron
	6 - 1	2448	202	--	--	73	Brawley Sandstone	1 850	
	6 - 2	1831	144	28	23	66	Sandstone	2 687	N10W Fault, 16.7 ppm boron
	8 - 1	1891	---	14	27	60	Sandstone	1 543	7.6 pH
	31 - 1	1899	138	--	20	61	Sandstone	2 005	Slickensides
Mountain Home (ID)	1	2932	189	2.2	14	61	Tuff	800	NW Fault
Niland (CA)	M - 1	777	271	50 - 75	27	355	Sandstone	191 515	6.0 pH
	M - 2	1331	322	--	--	258	Sandstone	---	Temp. inversion at 1143 m
	M - 3	951	308	73	27	312	Sandstone	211 165	Temp. inversion at 732 m
	M - 4	782	275	170	--	332	Sandstone	303 050	
	W - 1	732	238	--	--	291	Sandstone	179 790	Temp. inversion at 518 m
Raft River (ID)	RRGE-1	1526	146	33 av 165 max	30	90	Tuff	1 715	N65E Fault
	RRGE-2	1831	147	25	17	76	Tuff	1 852	7.4 pH, 0.25 ppm boron
Roosevelt Springs ^a (UT)	9 - 1	2100	227	< 1	2	103	Granodiorite	645 Spring	Spring now dry

Notes

^aAvailable for experimentation.

PR - Powers Ranch
M - Magma Max
W - Woolsey
RRGE - Raft River Geothermal Energy

A. Permeability

Because failure of geothermal wells to flow economically is due mainly to low-permeability formations in unfractured regions, a more detailed study of the use of permeability as a flow index is in order. Presented below is the usage common in the petroleum industry for flow toward a single borehole for the general configuration of a constant-thickness permeable reservoir. Darcy's law considers that fluid flows only under the action of a pressure gradient (dp/dx), and the flow velocity (v) in any horizontal plane for a one-dimensional system is given by:

$$v = - \frac{k}{\mu} \frac{dp}{dx}, \text{ where } \mu \text{ is the fluid viscosity.} \quad (1)$$

If the reservoir is tilted, the pressure (p) must be corrected to a constant datum by including the hydrostatic head term

$$p = p_{\text{static}} + \rho gh, \quad (2)$$

where ρ is the fluid density, g is the gravitational constant, and h is the height above the reference datum. For steady incompressible radial flow of a constant property fluid through a permeable reservoir, the volumetric flow rate (Q) is given by:

$$Q = \frac{2\pi k h_r \Delta p}{B_o \mu \ln(r_e/r_w)}, \quad (3)$$

where

- h_r = reservoir height
- k = formation permeability
- Q = reservoir volumetric flow rate into wellbore measured at surface conditions
- r_e = mean outer radius of the reservoir
- r_w = wellbore radius
- Δp = pressure drop along a datum from the outer edge of the reservoir to the wellbore
- μ = dynamic viscosity of the producing fluid
- B_o = temperature- and pressure-dependent correction factor to convert from surface volumetric flow rate to reservoir volumetric flow rate such that

$$Q_{\text{SURFACE}} B_o = Q_{\text{RESERVOIR}}$$

This reservoir model is depicted in Fig. 1.

Fig. 1.
Reservoir model for steady-state flow
permeability calculations.

The solution represented in Eq. (3) is analogous to the solution for the radial diffusion of heat in a cylindrical body with an impressed temperature difference. For a reservoir producing under steady-flow conditions, this equation can be used to calculate the flow permeability from field flow test data. Written in oil field units, Eq. (3) has the following form:

$$k = \frac{\mu Q B_o \ln (r_e/r_w)}{7.08 h_r \Delta p}, \quad (4)$$

with k in darcys, μ in centipoise, Q in barrels/day measured at surface conditions, h_r in ft, and Δp in psi. Although r_e is not generally known with precision (estimates of r_e become better as the number of production and exploratory holes in a field increases), $\ln (r_e/r_w)$ may be estimated as 10 without significant errors. For a 1-ft-diam wellbore (0.305 m), this requires a reservoir radius of 11 013 ft (3357 m). Should the reservoir radius be only 6680 ft (2036 m), $\ln (r_e/r_w)$ is 9.50, resulting in only a 5.0% error. Normally, boreholes are near 8 in. (0.203 m); this requires a 7341-ft or 2238-m reservoir to yield a $\ln (r_e/r_w)$ of 10. The reservoir radius can vary from 4453-12 100 ft (1357-3688 m) before errors of 5% are exceeded. For smaller reservoirs, a lower estimate of the logarithmic function can be used and this insensitivity will still prevail.

The utility of a steady-state solution is often limited, and the interpretation of well-flow test data must frequently be based on a time-dependent solution of the reservoir flow characteristics. To consider the general patterns of flow in porous media, the density (ρ) must be treated as a function of pressure (p) in the governing differential equation. In general, the equation then becomes nonlinear and methods for obtaining solutions are often based on simplifications of the exact nonlinear equation which lead to linear equations of the diffusivity type. If the fluid is a liquid of constant compressibility, it is possible to linearize the differential equation for unsteady flow, leading to an equation of state of the form

$$\frac{\partial \rho}{\partial t} = \beta_f \frac{\partial p}{\partial t}, \quad (5)$$

where β_f is the compressibility of the reservoir fluid. The governing differential equation is of the diffusion type, which in cylindrical coordinates has the form

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} = \frac{1}{a^2} \frac{\partial p}{\partial t}, \quad (6)$$

where $a^2 = k/\mu (\phi\beta_f + \beta_r)$, with ϕ being the porosity fraction and β_r the compressibility of the reservoir rock. For the geothermal reservoirs of interest to this study, β_r is small compared with $\phi\beta_f$, and hence a^2 can be taken as $k/\mu \phi \beta_f$, a measure of the diffusivity of the reservoir to flow. The reservoir is considered to be of infinite radial extent, has a thickness h_r , and constant formation permeability (k) and porosity fraction (ϕ). A single-phase liquid of dynamic viscosity (μ) flows radially through the reservoir to a producing well at a constant volumetric flow rate (Q). In the limit as the well radius approaches zero, $2\pi \lim (r \partial p / \partial r) = \mu Q B_o / k h_r$. The solution of Eq. (6) with these assumptions is:

$$\Delta p = \frac{\mu Q B_o}{4\pi k h_r} \int_{r^2/4a^2t}^{\infty} \frac{e^{-x}}{x} dx$$

$$\text{or} \quad \Delta p = \frac{\mu Q B_o}{4\pi k h_r} \cdot E_i(\lambda), \quad (7)$$

where $E_i(\lambda)$ is the exponential integral of argument $\lambda = r^2/4a^2t$.

This solution has its utility in its application to the analysis of well pressure transients during flow testing. If a pressure probe is located in the production zone of a well, it can be used to record pressure linearly with time during drawdown ($-\Delta p$ with constant flow rate) and during buildup after shut-in ($+\Delta p$ with no external flow). These data can then be plotted on a semilog graph of Δp vs $\log_{10} t$. An example of such a graph from a well in the Raft River geo-thermal area is illustrated in Fig. 2. Note that the data are in the form of two continuous linear segments. The presence of two different slopes would indicate that production was obtained from two different (horizontally displaced) zones, and the linear segments would suggest that a relation of the form

$$\Delta p = m \log_{10} t + b \quad (8)$$

is valid where m is the slope of the line, t is time, and b is a time-independent grouping. This expression for Δp implied from the field-flow data can be compared with the analytical expression for Δp in Eq. (7) obtained from the diffusion differential equation. The exponential integral can be approximated by its first two terms yielding:

$$E_i(\lambda) = -0.5772 - \ln \lambda + \dots$$

$$\text{or} \quad E_i(\lambda) = \ln \left(\frac{1}{1.781 \lambda} \right) = \ln \left(\frac{4 k t}{1.781 r^2 \mu \phi \beta_f} \right) \quad (9)$$

Equation (7) can therefore be written in the form

$$\Delta p = \frac{\mu Q B_o}{4\pi k h_r} \ln t + \frac{\mu Q B_o}{4\pi k h_r} \ln \left(\frac{4 k}{1.781 r^2 \mu \phi \beta_f} \right)$$

$$\text{or} \quad \Delta p = \frac{2.303 \mu Q B_o}{4\pi k h_r} \log_{10} t + \text{time invariant grouping.} \quad (10)$$

Comparing Eq. (10) with Eq. (8) leads to an expression for the formation permeability in terms of the slope of the Δp vs $\log_{10} t$ field data plot.

$$k = \frac{2.303 \mu Q B_o}{4\pi m h_r} .$$

line #1 ($m_1 = 4.7$ psi/cycle)

$$k = \frac{(0.19)(13\,714)}{(6.15)(4.7)(2316)}$$

$k = 0.0389$ darcys

line #2 ($m_2 = 11.2$ psi/cycle)

$$k = \frac{(0.19)(13\,714)}{(6.15)(11.2)(2316)}$$

$k = 0.0163$ darcys

Fig. 2.
Differential pressure vs $\log_{10} t$ for a Raft River geothermal well.

In oil field units, this expression has the form

$$k = \frac{\mu Q B_o}{6.15 m h_r}, \quad (11)$$

with k in darcys, μ in centipoise, Q in barrels/day, m in psi/log cycle and h_r in feet. Equations (4) and (11) were used to calculate permeabilities appearing in Table V. A sample calculation of this type is illustrated in Fig. 2 using the data of that figure for Raft River.

B. Geological Constraints on Permeability

From the data contained in Table III, a correlation is indicated between the dry-hole fraction and rock type and age. The ability of a well to flow determines whether or not it is abandoned when a sufficiently high-temperature producing fluid is available. Barring technical drilling or completion difficulties, the dry-hole fraction is related to the formation permeability and the occurrence of natural fracture systems. Although permeability cannot be equated directly with measurable rock parameters, there is a qualitative functional relationship with the following factors for unfractured sedimentary rocks:

- ⊗ Surface or uncompacted porosity of a given rock type, ϕ_0 .
- ⊗ Depth of occurrence, D .
- ⊗ Rock temperature above ambient, ΔT .
- ⊗ Time since burial or of a pertinent tectonic event, t .
- ⊗ A measure of the distribution of porosity in the rock expressed as exposed surface area per unit volume of rock, S_p , (L^2/L^3).

An appraisal of permeability may be made with an understanding of the function of these geologic parameters. As a rock is buried, the change in porosity that occurs due to the force of compaction depends upon the initial porosity present and the depth of burial. The higher temperatures present at depth accelerate the chemical reactions which cause additional cementing and growth of grains, further reducing the porosity. Since these chemical processes occur at particular rates, the extent of these changes will be influenced by the time since burial. In a qualitative fashion, the above relations can be expressed as

$$\phi/\phi_0 \sim e^{-C_1 \Delta T t}, \quad (12)$$

where C_1 is a constant with the appropriate dimensions. The Kozeny theory examines in detail the relation among permeability, porosity, and the specific internal surface area of the porous medium. A fundamental result of this theory is that the fluid flow through a rock is inversely proportional to the square of the specific internal surface area. The rock porosity is determined by the grain arrangement, and the grain surface encountered per unit of rock determines the fluid-grain interaction (which is a function of hydration of clays, coulombic attraction of ions to solid, and path length). A general form of the Kozeny equation is

$$k = C_2 \phi^n / T_o S_p^2, \quad (13)$$

where C_2 is a constant, T_o is the tortuosity of the flow path, and n is generally between 2-3, although considerable uncertainty over the correct porosity factor exists. Combining Eq. (13) with the qualitative relation (12) leads to

$$k \sim \frac{C_2 \phi_o^n e^{-C_1 D \Delta T \tau n}}{T_o S_p^2}. \quad (14)$$

Knowing the geologic material deposited, the reservoir depth, the geothermal gradient, the time of burial or of the tectonic event, and the rock grain arrangement allows a qualitative estimation of rock permeability to be made in the absence of dominant fracturing. The true formation flow permeability will depend on both the rock permeability and the additional permeability resulting from natural or artificially induced fractures. Although most stimulation techniques can alter the fracture permeability, little can be done to improve the basic rock permeability, except for selective chemical leaching in certain types of formations. A fundamental understanding of these two flow mechanisms is important in the interpretation of reservoir production and recharging characteristics.

Present day active tectonism produces wide-scale fracturing which is largely unpredictable, and it is precisely in geothermal areas where active tectonism frequently occurs. Large-scale vertical fractures produce high permeability, and even though the magnitude is unpredictable, the location of vertical fractures is correlative with shallow or surface phenomena. Linear arrangements of hot springs or mineralized seeps are first clues to wide-scale fracturing. If well

spacing is sufficiently dense, linear patterns in fluid chemistry or temperature may also serve as indicators. Consequently, some indication of the type and magnitude of permeability may be obtained from general geologic information.

VI. POSSIBILITIES FOR ARTIFICIAL STIMULATION

As indicated in Table III, the dry-hole fraction is greatest in intrusive rocks and in Mesozoic to Paleozoic metamorphics. These geologic categories include prime candidates for stimulation experiments. The Quaternary to late Tertiary sediments category is comprised of geothermal fields with very few dry holes and moderate formation permeabilities, and hence is not very interesting from a stimulation standpoint. In terms of providing commercial flow possibilities, the stimulation priority based on geologic categorization would be as follows, proceeding from highest to lowest:

Geologic Category

iv	Precambrian or younger rocks (<u>best</u>)
iii	Mesozoic or older metamorphic rocks
ii	Quaternary to late Tertiary extrusives
i	Quaternary to late Tertiary sediments
(<u>generally not recommended</u>)

Overlain on categories iii and iv should be indications of high-stress fields or active fracturing. The best indicators are active thermal springs and strong topographic relief (erosion unable to keep up with earth movement). Active surface faulting or fracturing is also a good clue to high stress. When unusual earth stresses exist, small additional hydraulic pressures may be sufficient to vertically fracture the formation. Horizontal fractures usually do not occur below 1000 m, although they may be present in regions of thrust faulting.

Stimulation by hydrochloric acid may be useful in regions of carbonate deposition. CaCO_3 could occur in any of the four geologic categories, but is not believed to be generally worthwhile for geothermal interest. Calcite decreases in solubility with increasing temperature and decreasing pressure. In some wells the increased solubility associated with a decreasing temperature is the dominant influence and the producing fluids leaving the geothermal reservoir tend to remain undersaturated in CaCO_3 . However, a rapid drop of pressure at the

wellbore produces scaling--as occurs at Kizildere, Turkey. Most reservoir plugging, by compounds precipitating from cooled water, is believed to be of the silica type. Silica (SiO_2) monotonically drops in solubility as temperature decreases.

VII. THE ROOSEVELT SPRINGS CASE

A. Geological Mapping and Appraisal

As a result of field work at Roosevelt Springs, pertinent data on the geology and fault structure of the area were collected along with the status of the drilled wells. Phillips Petroleum drilled three slim holes (OH-1,2,3) for the purpose of obtaining information on the Roosevelt Springs Known Geothermal Resource Area (KGRA). The location of these holes is shown on the map of the Roosevelt Springs KGRA unit (Fig. 3). The locations for these wells were determined using surface expressions of faulting as a guide. Siliceous sinter (Q_{hs}) and Precambrian metamorphic gneiss (P_{cm}) outline the N-S dome fault and a subsidiary northwest-trending fault. Hot springs emerged in arrays along these faults and deposited silica in mounds as the water cooled. No active thermal springs now exist in this area since silica has plugged all the flow exits. A north-south mound of sinter and uplifted gneisses mark the location of the main dome fault. The E-W Negro Mag fault running just north of well 54-3 is more difficult to identify at the surface, although some evidence of ancient terraces and ravines marks this supposed graben. The east boundary of the field is indistinct, and the north and south sides likely have decreasing temperatures as a dominant phenomenon because hot springs deposits decrease with distance from the main drilled area. The west boundary of the field is marked by the Dome fault and the subsidiary northwest-trending fault.

Wells 13-10, 12-35, and 54-3 are the principal producers as of June 1976, whereas well 3-1 had a casing collapse. Well 54-3 is used for demonstration purposes and is set up with a steam separator and water bleed line. A slight H_2S odor is apparent at 13-10 and 54-3, and cool water is bleeding at both. Water samples were collected for analysis from these wells.

Fig. 3.
Roosevelt Springs KGRA Unit showing well locations,
major faults, and geologic structure.

B. Prospect Well 9-1

Well 9-1 is on the west side of the Dome fault some 500 m from the apex of the uplift. A cross section of the tentative east-west structure through Roosevelt KGRA well 13-10 prepared by Phillips Petroleum is illustrated in Fig. 4. This cross section indicates that well 9-1 has penetrated the graben into the Precambrian gneisses but has not crossed the Dome fault (a normal down-thrown-to-east fault). A zone of fracturing or alteration is apparent on the well logs at 1768 m and may be sufficiently stressed for easy stimulation. Other indications of anomalies exist at 1240 m on the logs, and while drilling from 1089-1098 m, a water flow occurred. The maximum temperature recorded in this well was 227°C at the total depth of 2100 m in diorite. The porosity is generally less than 2% but may be as high as 5% in fractured regions. The permeability is expected to be less than 1 millidarcy, although no test information was recorded. The water salinity is estimated at a few thousand ppm by spontaneous potential indications, and is expected to be mainly of the sodium chloride-sodium sulfate variety.

It is concluded that prospect well 9-1 is located in a very advantageous position for experimentation, opposite the Roosevelt Springs field across the Dome fault which is expressed at the surface by a line of hot springs deposits. It is expected that hydraulically induced fractures extending to this Dome fault and other natural fractures will intersect a major source of hot water, at depths of about 1220 m or deeper. Scaling problems due to carbonates are expected to be insignificant, but some silica scaling may occur. The area is expected to be highly tectonically stressed and should not present any major problems for fracture propagation. Phillips Petroleum has partly developed the Roosevelt Springs geothermal area and has made known its intention to make dry hole 9-1 available for experimentation with hydraulic fracturing techniques. This well is therefore considered to be an excellent candidate for stimulation with particular emphasis placed on the following advantages:

- Well 9-1 is within 900 m of 13-10 (see Fig. 3), a proven producer of 200°C hot water.
- Indications of minor fractures and a small water flow in 9-1 were noted during drilling and logging.

Fig. 4.
Tentative east-west structure section through Roosevelt
KGRA well 13-10 prepared by Phillips Petroleum.

- The area is highly stressed due to uplift and thermal forces, and should fracture readily.
- Well 9-1 is already cased and prepared for workover.
- The Roosevelt Springs area is in geologic category iv, deemed the most desirable for stimulation experimentation.
- The combination of very low rock permeability, low to moderate dissolved solids and moderate formation depth are all favorable for stimulation experiments.

VIII. OTHER POTENTIAL STIMULATION SITES

A. The Geysers

The Geysers geothermal area, located in the Mayacmas Mountains of northern California, is currently the world's largest producer of electrical energy from a geothermal source. Along with Larderello and the Monte Amiata areas of Italy, it represents one of the few areas known to be composed of a vapor-dominated hydrothermal system.¹ A review of the geology and structural control of the geothermal resource at The Geysers has been presented by McLaughlin and Stanley² who note; "the field is a few kilometers south of Clear Lake basin, a center of major Quaternary volcanism, and a few kilometers northwest of Mount Saint Helena, the locus of late Tertiary volcanism. Available subsurface data indicate that steam production in The Geysers region is largely from fracture zones in Franciscan graywacke. Given the presence of suitable reservoir rocks at any of several structural levels, the structural conditions determining the presence of steam would appear to depend upon: (1) the presence of channel ways such as faults, fractures, or bedding planes that allow percolation of meteoric water to some depth and provide an adequate but not excessive supply of water to the system, (2) the presence of structural traps for steam accumulation, and (3) a potent heat source."

Although they are not very abundant, dry-steam geothermal fields are particularly important because of their efficient production of electricity. Ewing³ has pointed out that both Larderello and The Geysers dry-steam fields have experienced a decline in steam pressure from producing wells through the years. At The Geysers, the turbine exhaust condensate is reinjected into the reservoir,

and it appears logical that the injection of surface waters into the thermal system should retard depletion. Ewing states that "it is difficult to estimate how effective the stimulation of dry-steam systems might be, but it is reasonable to assume that a geothermal well ... may be amenable to stimulation by techniques similar to those in use for gas and oil wells." At The Geysers, drilling site preparation costs are high because of the rough terrain and inaccessible location. This has led to the practice of drilling multiple deviated wells from a common site. Experience at The Geysers has indicated that five wells can be drilled from a common location and one well may be dry even though it is only 30-40 m from a commercial producer⁴ [the definition of a dry hole at The Geysers differs from normal convention; if a well produces < 50 000 lb of steam per hour (22 700 kg/hr), it is not considered to be commercial]. Stimulation attempts using hydraulic fracturing have not been successful, as the formation just keeps accepting fluid without a sufficient pressure rise to even attempt propping the natural or induced fractures. It is felt that two fracture entries into a well-bore make a successful well at The Geysers although these entries may be as large as 5-6 mm in width.⁴ In at least some of these stimulation experiments, the conditions for successful hydraulic fracturing of the producing formation have been far from ideal. In wells with only partial casing, attempts were made to pressurize long segments of the uncased well. Fluid loss could be occurring in formations other than those in the steam-producing region where the stimulation is desired. In view of the potential difficulties associated with stimulation entirely by hydraulic fracturing methods, examination of the use of chemical explosives is justified in the brittle, highly stressed rocks present at The Geysers.

B. Larderello

The Larderello geothermal reservoir, made up of carbonate formations, has been intensively explored and exploited by wells drilled down to about 2000 m. The National Electric Agency of Italy (ENEL) recently started a program to explore the deeper horizons of the crystalline basement underlying the known reservoir, with the goal of producing geothermal fluids of higher energy content. The crystalline basement is a schistose-quartzitic complex which, at depths of 4000-5000 m, is expected to be hot (about 300°C) but to have low permeability. Due to the expected low permeability of the crystalline basement rock, it will probably be useful for energy production only if wells penetrating it can be

stimulated successfully, or if stimulation techniques can be used to connect such wells to the bottom of the natural steam reservoir through the basement complex, or if artificial circulation systems are created within the basement complex.

The specific objectives of this program are:

- If possible, to stimulate production of natural geothermal fluids from the basement complex by applying appropriate stimulation techniques.
- Otherwise, to attempt by extension of these techniques to connect the well to the bottom of the natural geothermal reservoir, where a superheated brine is presumed to exist. This connection might be used either to superheat the existing fluid or to permit injection of new fluid to recharge the reservoir above it.
- Alternatively, or if the above attempts are unsuccessful, to apply the Los Alamos Hot Dry Rock concept to create an artificial system for forced circulation of water through the basement complex to extract natural heat from it.

Similarities between Larderello and The Geysers should lead to an interesting international exchange on stimulation techniques appropriate to geologic category iii, vapor-dominated geothermal fields.

C. Stimulation Success Ranking

In determining the overall stimulation success ranking, two other geothermal areas were considered in some detail. These are Mt. Home, ID and Chandler, AZ. Pertinent data for these sites are presented in Table VI, which also includes the data for Roosevelt Springs (discussed in Sec. VII of this report) for comparison purposes. The lower producing fluid temperature (and associated lower geothermal gradient) at the Chandler, AZ site are detrimental characteristics from the standpoint of the stimulation study in question. The very high total-dissolved-solids content at Chandler (26 700 ppm) must also be taken into account. These dissolved solids could be responsible for substantial reductions in the permeability of the system upon production at commercially useful mass flow rates. Mountain Home therefore has the advantage of higher producing fluid temperatures, higher geothermal gradient, much lower total-dissolved-solids content, and the potential for higher sustained permeability after stimulation when compared with the Chandler site. In view of the comparable depths and geologic categories, the

sole advantage of the Chandler site would appear to be its higher porosity and associated potential for larger available fluid volume. From the data in Table VI note that Roosevelt Springs has a higher producing fluid temperature, higher geothermal gradient, lower total-dissolved-solids content, and shallower depth than either Mountain Home or Chandler site. In addition, Roosevelt Springs has an available "dry hole" located within 900 m of an excellent geothermal energy producer and has some indications of natural fractures at depth.

TABLE VI
GEOHERMAL WELL STIMULATION DATA

<u>Roosevelt Springs, Utah</u>	<u>Mountain Home, Idaho</u>	<u>Chandler, Arizona</u>
Moderate - high temperature fluid (227°C)	Moderate temperature fluid (189°C)	Low - moderate temperature fluid (163°C)
Geologic category iv	Geologic category ii	Geologic category ii
High geothermal gradient (103°C/km)	Moderate geothermal gradient (61°C/km)	Moderate geothermal gradient (49°C/km)
Low dissolved solids (645 ppm)	Low dissolved solids (800 ppm)	High dissolved solids (26 700 ppm)
Permeability < 1 md	Permeability 2.2 md	Permeability 0.3 md
Depth 2099 m	Depth 2932 m	Depth 2806 m
Porosity 2%	Porosity 14%	Porosity 22%
Located within 900 m of a producing geothermal well	NW fault	

On the basis of the data collected, analyzed, and presented in this report, the overall stimulation success ranking contained in Table VII was determined. The selection of Roosevelt Springs as the first priority for stimulation by hydraulic fracturing techniques was motivated by the many favorable thermal, geological, and reservoir properties of this geothermal area and prospect well 9-1 in particular (see Secs. VII-A and B for details). This geologic category iv well is available for experimentation, is located within 900 m of an excellent geothermal producer, has some indications of natural fractures at depth, and as indicated by the data in Tables V and VI is associated with a geothermal area of

TABLE VII
RANKING OF GEOTHERMAL SITES FOR ARTIFICIAL STIMULATION

Site	Success Ranking	Representative Temperature (°C)	Representative Permeability (md)	Geologic Category	Total Dissolved Solids (ppm)	Remarks
Roosevelt Springs, Utah	1	227	< 1	iv	645	Stimulation by hydraulic fracturing
The Geysers, California	2	250 - 285	--	iii	< 1% noncondensable gases in steam	Stimulation by chemical explosive fracturing
Mountain Home, Idaho	3	189	2.2	ii	800	Moderate stimulation potential
Chandler, Arizona	4	163	0.3	ii	26 700	Moderate stimulation potential

Raft River, Idaho	5	146	33	i or iv	1 715	Insufficient data avail- able for complete analysis

East Mesa, California	-	202	6 - 28	i	1 850	Not recommended for stimulation
Niland, California	-	322	> 50	i	> 180 000	Not recommended for stimulation

very desirable characteristics. The selection of The Geysers as the second priority was principally based on the suitability of wells in this field for stimulation by chemical explosive fracturing techniques. The brittle, highly stressed rocks in The Geysers field should be amenable to explosive fracturing, and the existence of noncommercial wells located within 30-40 m of excellent steam producers confirms the proximity of these wells to the reservoir (see Sec. VIII-A for details). Application of some of the explosive fracturing methods discussed in Appendix A to geothermal well stimulation could be attempted at this geologic category iii site. A comparison of the data for Mt. Home and Chandler (both geologic category ii sites) with Roosevelt Springs (see Table VI) led to the selection of Mt. Home as the third priority with Chandler following as the fourth priority. Raft River is listed as a possible stimulation site, but sufficient data were not available for an accurate assessment of this area. One well at Raft River was stimulated by directional drilling and the attempt was successful. Stimulation experiments are not recommended at the geologic category i sites of East Mesa and Niland, CA. The geographic location of these seven sites is shown on the map in Fig. 5.

IX. CONCLUSIONS

Statistics from numerous geothermal fields around the world which have been flow tested and have temperatures greater than 150°C indicate that the associated reservoirs can be grouped into four general geologic categories:

- i. Quaternary to late Tertiary sediments (water-deposited rocks with age less than 2×10^7 years). These fields have almost no dry holes, because either warm or hot water is almost always producible in young sediments.
- ii. Quaternary to late Tertiary extrusives (igneous rocks which have flowed onto the earth's surface with age less than 2×10^7 years). These fields have approximately 20% dry holes due mainly to low-porosity rhyolites and lack of fractures in some wells.
- iii. Mesozoic or older metamorphic rocks (highly compressed and heated rocks with age at least 7×10^7 years). These fields depend mainly on fractures because the undisturbed rock has low porosity and approximately 25-30% of the holes are dry.

Fig. 5.
 Locations of U. S. geothermal areas studied for stimulation experiments.

- iv. Precambrian or younger rocks (with uplift age of 1×10^6 years or more). These fields depend entirely upon high-stress fracturing because intrusive rocks have porosities of the order of 2% or less. Data in this category are limited to Roosevelt Springs, where 33% of the wells were dry and producers must be near faulting or high-shear zones.

Dry holes for reservoir stimulation purposes are defined as wells producing little or no fluids as a result of insufficient flow permeability in the formation. These holes can be characterized as existing where large quantities of hot fluids are available but where flow paths are restricted and the permeability is of the order of a few millidarcys or less. Reservoir stimulation is defined as the creation of permeable paths by artificial techniques such as hydraulic fracturing, chemical explosive fracturing, propellant-induced fracturing, or selective chemical leaching.

Knowing the geologic material deposited, the reservoir depth, the geothermal gradient, the time of burial or of the tectonic event, and the rock grain arrangement allows a qualitative estimation of rock permeability to be made in the absence of dominant fracturing. The true formation flow permeability will depend on both the rock permeability and the additional permeability resulting from natural or artificially induced fractures. Fracturing depends principally upon shear stress distribution and rock strength, and these are largely unpredictable in magnitude. The location of highly fractured subsurface rock is possible with geophysical techniques, whereas fracture extent or size is not. Artificial stimulation increases in practical importance as permeability decreases; consequently reservoir categories iv and iii are the prime candidates for investigation. Roosevelt Springs well 9-1 is selected as the prime candidate for stimulation by hydraulic fracturing with particular emphasis placed on the following advantages:

- Well 9-1 is within 900 m of a proven producer of 200°C hot water.
- Indications of minor fractures and a small water flow in 9-1 were noted during drilling and logging.
- The area is highly stressed due to uplift and thermal forces and should fracture readily.

- Well 9-1 is already cased and prepared for workover.
- The Roosevelt Springs area is in geologic category iv, deemed the most desirable for stimulation experimentation.
- The combination of very low rock permeability, low to moderate dissolved solids, and moderate formation depth are all favorable for stimulation experiments.

The brittle, highly stressed rocks in The Geysers field should be amenable to chemical explosive fracturing, and the existence of noncommercial wells located within 30-40 m of excellent steam producers confirms the proximity of these wells to the reservoir. The Geysers (geologic category iii) is therefore selected as the second priority stimulation site with the emphasis on explosive fracturing. Mt. Home, ID and Chandler, AZ are selected next although these category ii areas are less desirable for stimulation from the formation geology standpoint.

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APPENDIX A

WELL STIMULATION BY HYDRAULIC FRACTURING AND CHEMICAL EXPLOSIVE FRACTURING

The technique of hydraulic fracturing, in which fluid pressure is applied to a limited region of a wellbore at pressures high enough to part the formation, was first applied to a natural gas well in 1947. Since that time, it has become a standard technique for improving communication between a wellbore and the surrounding reservoir rock. It is particularly useful in competent reservoir rock of low permeability, or if natural flow channels in the rock near the wellbore have been plugged by drilling fluids, hydrating clays, or long-term geochemical changes such as silica or calcite introductions.

Because a geothermal reservoir consists of fluid in a rock matrix, from which the fluid must be extracted, hydraulic fracturing should be useful for improving the yield of fluid from the reservoir. The heat energy in a geothermal system is always preponderantly in the rock, rather than in the fluid, which acts mainly as a heat transfer medium to bring the geothermal energy to the surface. A geothermal reservoir may be uneconomic because of failure to deliver steam or hot water at a high enough rate due to low natural permeability, or because the well is not resupplied rapidly enough with water by natural

permeation processes, and the well becomes depleted. Hydraulic fractures in producing, injecting, and dry wells can alleviate both of these problems, and make efficient geothermal energy extraction possible from many marginal reservoirs and noncommercially flowing dry holes. The hot dry rock geothermal program, in which fluid is circulated through a hydraulic fracture in very impermeable rock, is a limiting case of such stimulation.

If a geothermal well is adequately cased down into the producing region, hydraulic fractures can be produced by pressurizing this casing from the surface. If the well is not cased into the producing region, and it is necessary to use open-hole packers to isolate the region in which the fracture is to be produced, then packers must be developed which can simultaneously withstand the high temperatures of geothermal reservoirs and the high pressures associated with hydraulic fracturing. With this exception, the hydraulic fracturing technique is readily applicable to geothermal wells.

A relatively common use of explosives in hydrocarbon recovery processes involves detonating a charge in the wellbore adjacent to the producing zone. This technique, known as wellbore springing, can result in a cavity radius of the order of a few times the original drilled borehole radius. This method can be particularly effective for well completions as an alternative to underreaming in difficult formations, and to reestablish fracture communications (fractures that have become plugged with mineral deposits) with a wellbore. As pointed out by Austin and Leonard,^{1A} "the advantage of explosives is that only a light service rig is needed and the probability of entrapping major 'junk,' debris, or equipment in the hole is minimal. Furthermore, the shock and vibration damage to the well perimeter due to springing the hole can of itself significantly enhance production rates." The above statements apply to new production wells, flow-altered production wells, and also to injection wells to allow economical reinjection of geothermal fluids to utilize more of the available energy in the formation. Increases in formation permeability produced by explosive fracturing can result from the following mechanisms:

- The formation of new fracture systems.
- The extension of existing major fractures and microfractures.
- Physical destruction of grain-to-grain bonding in the formation rock.
- The removal or displacement of physical blockages in flow channels.

Another technique that sees widespread use in oil fields (for well completion) and is directly applicable to geothermal well stimulation involves the use of conical shaped charges to produce small-diameter perforations in the formation. As an alternative to wellbore springing, the effective wellbore diameter is increased by the additional flow area provided by the multiple perforations at nominal right angles to the borehole axis. Although the flow enhancement provided by these perforations is limited to within a few wellbore radii of the hole, the method is useful when the formation immediately surrounding the well has been plugged by precipitates or hydrating clays. An extension of this technique is under development at the Los Alamos Scientific Laboratory (LASL) in connection with research to develop fossil energy extraction processes for tight, very low permeability shale formations. A major LASL program, funded under weapons responsibilities, concerns the development of explosively formed metallic jets or slugs designed to penetrate large distances of high-density material in a single shot. It is anticipated that these devices could be used to increase the permeability of tight gas-bearing shales (or low-permeability geothermal formations) without the necessity of creating large-scale fractures, or to provide the flow channels between distant fractures and the wellbore. These rock-penetrating jets also have the potential to provide shot holes for the controlled emplacement of liquid or slurry explosives, although the jet path alone will serve to increase the formation permeability.

Austin and Leonard^{1A} point out that "the detonation of an explosive charge in a borehole results in two distinct and recognizable zones in the host rocks: a close-in zone, where the rock fabric is destroyed by crushing, compaction, and phase changes; and a distant zone, where fracturing and grain-bond failure occur." Consideration must obviously be given to both zones because both zones must be traversed by a geothermal fluid to reach the wellbore. The importance of these two zones is illustrated in Ref. 1A for the case of close-in failure in porous rock resulting in pore-space collapse. When this collapse is extensive and the damaged zone is symmetric and not intersected by radial fractures, the collapsed zone can remain intact in a metastable and highly stressed state. Very low permeabilities can exist in this zone so that the result of a symmetric blast can be a loss of production even though extensive formation fracturing has occurred in the near field. This may explain why some explosive stimulation experiments in gas wells have resulted in decreased production. The use of conical

shaped charges or explosively driven metallic jets to penetrate this crushed zone and communicate with the distant fractures may alleviate this problem.

A study on the effectiveness of explosive-stimulation methods must take into account the particular reservoir rocks within the geothermal formation. Goldsmith and Austin^{2A} and Goldsmith et al.^{3A} investigated the effects of stress-wave passage on grain structure in igneous rocks typical of those found at a number of potential geothermal deposits in eastern California. Their results reflect the dependence of fracturing success on the particular rock formation encountered. For a borehole in mixed granite rocks and dikes, explosive fracturing of dikes would be difficult if not impossible beyond the close-in zone. In a zone of mixed leucogranite and diorite, extensive fracturing and grain damage could be accomplished by repeated explosions in the diorite zones. Both Young's modulus and ultimate strength in the coarse-grained igneous rocks were shown to decrease after repeated shocks. Also, in studies with diorite, Austin and Pringle^{4A} concluded that a medium-to-coarse-grained intrusive rock such as diorite will yield abundant fractures when explosively loaded. In attempting to predict the effectiveness of an explosive stimulation program, therefore, some knowledge of the shock response properties of the reservoir rocks is required.

Motivated by the current need to extract hydrocarbon resources in situ from very tight formations, more advanced concepts in explosive stimulation are being developed and tested. These include slurry or gel explosives which can be injected into natural or hydraulically induced fractures and successfully detonated in very thin layers. Combined techniques such as explosive fracturing followed by a chemical leaching process to further increase permeability are used in the Sol Frac extraction of heavy oil from a fractured formation. A significant feature of the in situ fracturing problem is to provide a method to tailor the pulse shape of the stress wave to optimally fracture a specific formation. The fact that fracturing research is in progress using quasistatic loadings (hydraulic-fracturing) and extremely high rate loadings (chemical explosives), the addition of intermediate loadings through the use of propellants seems like a natural addition to complete the research program. Propellants may also possess the potentially significant advantage of being able to control the pressure history in a wellbore to that required for efficient fracture formation and extension. In addition, the lower strain rates associated with propellant

fracturing will minimize the pulverized zone around the borehole, allowing the propellant gases to penetrate this region and work on the far field more effectively.

These advanced concepts have the potential for enhancing the explosive stimulation of a variety of geothermal reservoirs. Special problems that must be addressed for geothermal applications include the following:

- High-temperature stability of explosives.
- Reactions with geothermal fluids resulting in sensitization or desensitization of the explosive.
- Disposal of unused explosive in the well or fracture system.
- High cost of special explosives.

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APPENDIX B

TABULATION OF GEOTHERMAL RESERVOIR DATA FORMS

Detailed data forms for many of the geothermal reservoirs investigated in this study are presented in this appendix. Specific well data from the following areas are included:

Ahuachapan, El Salvador
Broadlands, New Zealand
Cerro Prieto, Mexico
Chandler, AZ
East Mesa, CA
Kizildere, Turkey
Larderello, Italy
Matsukawa, Japan
Mt. Home, ID
Niland, CA
Otake, Japan
Pauzhetsk, U.S.S.R.
Roosevelt Springs, UT
Waiotapu, New Zealand
Wairakei, New Zealand

Company/field	Ahuachapan, El Salvador		
Well Name	#4	#1	#22
Total Depth	640 m	1205 m	659 m
T _{max} , °C	234	232	
Casing	12-1/4" @ 640 m	8-1/2" @ 1205 m	8-1/2" @ 659 m
Surface Elevation	812 m		
	<u>HYDROGEOCHEMICAL</u>		
Spring Temperature			(data from un-numbered drillhole) 220° C
SiO ₂ , (ppm)/pH	650/-		456/7.02
Na/K, ppm	6100/1060 = 5.75		5025/905 = 5.55
Ca/Mg, ppm	440/0.1 = 4400		354/23.4 = 15.1
Cl/SO ₄ , ppm	11,100/29 = 383		8730/28 = 312
HCO ₃ /CO ₃ , ppm	30/-		49/-
TDS, ppm			15,703
Other Chemicals (ppm)	170B 12 MW Production (est. life of water ~ 6 yr)	7.5 MW Production	1.5F, 131B 7 MW Production

Company/field	Broadlands, New Zealand		
Well Name	#3	#9	#7
Total Depth		-3480 ft/-1061 m	-2730 ft/-832 m
T _{max}		289°C	279°C
G _t , °C/km	460	440	438
<u>GEOLOGICAL</u>			
Sedim. Base		-1200.0 ft/Waiora formation	
Metam. Base			-2050 ft/Broadlands rhyolite
Surface faults	NE(Ohaki, Broadlands)	Well 200 ft SE of Ohaki fault fed by Ohaki fault	Brecciated & fissured
Fracturing	Production from faults & fractures	Production from Rautowiri	Production from Broadlands rhyolite
Geol. features	Greywacke basement dips down to West Ohaki rhyolite cap.	Mid-Waiora siltstone cap	
Surface Deposit	Pumice, tuff, alluvium. Waigra main aquifer, dips 0-5°. Rautowiri secondary aquifer.		
<u>HYDROGEOCHEMICAL</u>			
Source		Well #2(near #9)	Well #10(near #7)
H ₂ S		1 ppm	2 ppm
SiO ₂ (ppm)/pH	338/7.0	848/8.5	695/8.9
Na/K, ppm	860/82 = 10.5	1075/222.5 = 4.8	890/150 = 5.9
Ca/Mg, ppm	2.6/0.48 = 5.4	2.9/0.08 = 36	2.1/0.1 = 21
Cl/SO ₄ , ppm	1060/100 = 10.6	844/3.5 = 241	1262/6.0 = 210
HCO ₃ /CO ₃ , ppm	680/-	137/-	562/-
TDS, ppm	2462	3030	3032
Other Chemicals (ppm)		6.4 Br, 11.4 Li, 1.6 NH ₃	Produces dry steam
<u>THERMAL</u>			
Spring T, Depth	260°C @ 500 m	256°C @ 500 m	235°C @ 500 m
<u>HYDROLOGICAL</u>			
Elevation	1000 ft/305 m	1000 ft/305 m	1000 ft/305 m
Spring Flow	Ohaki pool 12,000 cc/sec	Total springs 20,000 cc/sec	
Well P, D	1210 psi -2000 ft 870 psi -1000 ft G _p = 0.34 psi/ft	1230 psi -2000 ft 850 psi -1000 ft G _p = 0.38 psi/ft	1430 psi -2000 ft 1100 psi -1000 ft G _p = 0.32 psi/ft
<u>ROCK PARAMETERS</u>			
Density ϕ, frac.	1.7-2.2 gm/cc wet	2.0-2.4 gm/cc wet	2.4-2.67 gm/cc wet
Average Porosity	18-36%	15-36%	2-16%, 9% ave.
Reservoir rock	Water laid <u>TUFF</u> , Waiora	Ash flow, <u>BRECCIA</u> , Rautowiri	Broadlands <u>RHYOLITE</u>
Flow rate, ton/hr	202; 600 BTU/lb enthalpy	68; 544 BTU/lb enthalpy	40; 988 BTU/lb enthalpy
Peculiarities			High silicification, Wells 7, 10 & 14 separate from Ohaki G _t area (Pressure higher)
	G _p $\frac{1210\text{psi}}{3000\text{ft}}$ ~0.4 psi/ft	G _p $\frac{1230}{3000}$ ~0.41 psi/ft	G _p $\frac{1430}{3000}$ ~0.48 psi/ft

Company/field	Cerro Prieto, Mexico			
Well Name	M-8	M-3	M-31	M-39
				388°C hottest well 8600 deepest well
	<u>HYDROGEOCHEMICAL</u>			
Source	1310 mwell, 355°C			
SiO ₂ (ppm)/pH	1420/-		480/8.3	592/8.5
Na/K, ppm	11,200/3420 = 3.3	5610/1040 = 5.39	4982/1117 = 4.46	5940/895 = 6.64
Ca/Mg, ppm	720/11 = 65.5	320/-	370/0.96 = 385	480/1.32 = 364
Cl/SO ₄ , ppm	21,600/0	9694/-	9650/20 = >483	11,080/<20 = >554
HCO ₃ /CO ₃ , ppm	1180/-		105.6/0	535/0
TDS, ppm		17,000	16,691	19,003
Other Chemicals(ppm)	2 As, 31 Li, 26 Br, 37 B	0.88 F (2302 psi @ 1975 m)	1.4F, 38 NH ₄ , 5.0 Ba 12 wells prod. ~ 700 ton/hr total	1.8 F, 13 NH ₄ , 3.0 Ba (1000 psi shut in pressure)

Company/field	GKI/Chandler, Arizona	
Well Name	Power Ranch #1	Power Ranch #2
Mud Type	Water	Water
Total Depth	9207 ft/2807 m	10,454 ft/3187 m
T _{max}	325°F @ 9065 ft (162.8°C)	352°F (177.8°C)
Gt, °C/km	49.2	47.4
Casing	9-5/8" @ 1648 m	13-3/8" @ 823 m, 7" Liner @ 3119 m
Bit at TD	8-3/4"	8-1/2"
Tests	Logs, T, Drill Stem Test, Prod.	Logs, T
	<u>GEOLOGICAL</u>	
Sedim. Base	5410 ft/1649 m	4760 ft/1451 m
Metam. Base		10,250 ft/3125 m
Surface faults	Recent 40m x 1m wide N25°E 5 miles South of well, 10 m deep.	
Geol. features	Basin & Range lowlands P _e intrusions, Lake bed.	Quaternary/Tertiary Basin & Range lowlands, Central Ariz., Salt River Valley.
Surface Deposit	Lake sand and clay to 1000 ft, Quaternary/Tertiary	
	<u>HYDROGEOCHEMICAL</u>	
Depth, Date	> 1494 m. 7/9/73	
H ₂ S, Boron(ppm)	120 B, < 30 H ₂ S	
SiO ₂ , (ppm)/pH	50/7.4	
Na/K, ppm	1980/300 = 6.6	
Ca/Mg, ppm	2900/14 = 207	
Cl/SO ₄ , ppm	2640/1080 = 2.44	
HCO ₃ /CO ₃ , ppm	41/0	
TDS, ppm	26,700	29,700
Other Chemicals(ppm)	4.8 F, 24 Li	
	<u>HYDROLOGICAL</u>	
Precipitation	8 in. 20.3 cm	8 in. 20.3 cm
Elevation	1338 ft 408 m	1336 ft 407 m
Mean surface T.	80°F/27°C	80°F/27°C
Water table	400 ft	
Well P, D	3893 psi @ 9180 ft (pressure bomb)	
	<u>ROCK PARAMETERS</u>	
Salinity, ppm	27,300 by SP	3650 by SP
Prod. interval	7830-9207 ft	
Sonic porosity, ϕ_a	0.22	0.13
Average Porosity		0.05 (TRW measured)
Reservoir rock	Volcanic	Volcanic
Flow rate	150 gal/min	150 gal/min (max)
Permeability, md	0.16 - 0.4 core (0.3 test)	0.16 - 0.4 core
Peculiarities	Est. 850 ton/hr initially (Blew 207°F mist while air assisted.)	Water different from #1, #2 is North of #1.

Company/field	U.S. Bureau of Reclamation/East Mesa, California			
Well Name	Well 5-1		Well 6-1	
Mud Type, wt.	8.5 pH, 1.12 SG		Lignite, Gel/1.09 SG	
Total Depth	6016 ft/1834 m		8030 ft/2450 m	
T _{max} (time)	242°F (7 hr)		255°F (drilling)	
Casing	13-3/8" @ 617 m		9-5/8" @ 7292 m	
Bit at TD	10-5/8"		8-1/2"	
Tests			Logs, Flow, P, T	
G _t , equilibrium			396°F-8030 ft, 73.2°C/km	
<u>GEOLOGICAL</u>				
Surface faults	N10°W, active		N10°W, active	
Geol. features	Sands and siltstones		Brawley formations, Quaternary	
Surface Deposit	Lake bed		Lake Coahuila deposit (Ancient Salton Sea)	
<u>HYDROGEOCHEMICAL</u>				
Depth, Date	1300 m 4/25/74	1710 m 4/30/74	1694 m 7/17/72	1870 m 8/15/72
Source	(Well)	(Well)	(Reservoir fluid)	(Reservoir fluid)
Boron(ppm)	2.7 B	3.0 B		
SiO ₂ , (ppm)/pH	123/7	142/7.5	185/-	290/-
Na/K, ppm	830/152 = 5.46	620/100 = 6.2	511/44 = 11.6	3689/391 = 9.4
Ca/Mg, ppm	52/3 = 17.3	59/4 = 14.8	38/1 = 38	237/4 = 59.3
Cl/SO ₄ , ppm	809/203 = 4	433/275 = 1.6	428/370 = 1.16	5457/269 = 20.3
HCO ₃ /CO ₃ , ppm	767/0	595/0	379/0	812/0
TDS, ppm	2450	2035	1850	12,620
<u>HYDROLOGICAL</u>				
Precipitation	3 in. 7.6 cm		3 in. 7.6 cm	
Elevation			36 ft 11 m	
Mean surface T.	73°F 22.8°C		73°F 22.8°C	
Well Flow			2 l/sec	
Water table			30 ft 9.2 m	
Well P, D			28 psi, 0 ft 1887 psi shut-in pressure @ 4474 ft	
<u>ROCK PARAMETERS</u>				
Salinity, ppm	2950, Log		5800, Log	
Prod. interval	1000 ft 305 m			
Sonic porosity, ϕ_a	0.29			
Density ϕ , frac.	0.27			
Neutron ϕ , frac.	0.24			
Average Porosity	0.27			
Reservoir rock	Sand and siltstone		Sand and siltstone	
Flow rate, ton/hr	55.6		22.7 (100 GPM)	
Permeability, md	6			
Peculiarities	Holtville airport Total column ave. 700 has buckle by com- md in shallow water pression in runway. well.			

Company/field	U.S. Bureau of Reclamation, East Mesa, California		
Well Name	Well 6-2	Well 8-1	Well 31-1
Mud Type, wt.	Clay base	1.12 SG	1.09 SG
Total Depth	6008 ft/1850 m	6205 ft/1892 m	6230 ft/1899 m
T _{max} , time	2480F (4 hr)		2500F (8 hr)
Casing	11-3/4" @ 306 m	13-3/8" @ 1000 m	13-3/8" @ 309 m
Bit at TD	10-5/8"	10-5/8"	10-5/8"
Tests	Logs	Logs, Flow, T	
G _t , equilibrium	66.4°C/km	60.1°C/km	60.8°C/km
Surface faults	<u>GEOLOGICAL</u>		
Fracturing	N10°W, active	N10°W, active	30° dip S50°W fault at 5500; normal 10° dip S60°W
Surface Deposit	Lake bed	Lake bed sands	
	<u>HYDROGEOCHEMICAL</u>		
Depth, Date	4/30/74	1715 m 8/6/73	1652 m 5/22/74
Source	(Well, cooling coil)	(Drill stem test)	(Reservoir fluid)
Boron(ppm)	15.5 B		2.0 B
SiO ₂ (ppm)/pH	192/-	195/7.2	151/7.6
Na/K, ppm	726/85 = 8.54	981/65.3 = 15.0	449/40 = 11.2
Ca/Mg, ppm	3.5/0.5 = 7.0	40/-	41/4 = 10.3
Cl/SO ₄ , ppm	679/152 = 4.47	770/206 = 3.74	380/249 = 1.53
HCO ₃ /CO ₃ , ppm	660/-	1248/-	375/0
TDS, ppm	2470	2830	1543
Other Chemicals (ppm)	0.45 F	17 NH ₄	4.5 F
	<u>HYDROLOGICAL</u>		
Precipitation	3 in 7.6 cm	3 in. 7.6 cm	3 in. 7.6 cm
Elevation	24 ft 7.3 m	50 ft 15.2 m	35 ft 10.7 m
Mean surface T.	73°F 22.8°C	73°F 22.8°C	73°F 22.8°C
Well Flow	9.5 l/sec		
Water table	30 ft 9.2 m		
Well P, D	12 psi, 0 ft		
	2664 psi, 5515-5625 ft		
	<u>ROCK PARAMETERS</u>		
Salinity, ppm		3800 Log	2200 Log
Prod. interval	654 ft 199 m	1050 ft 320 m	755 ft 230 m
Sonic porosity, ϕ_a	0.24	0.31	0.39
Density ϕ , frac.	0.25	0.24	0.27
Neutron ϕ , frac.	0.21	0.27	0.30
Average Porosity	0.23	0.27	0.29
Reservoir rock	Sand & siltstone	Sand & siltstone	Sand & siltstone
Flow rate, ton/hr	34.2 @ psi surface pressure	97.6	127
Permeability, md	28 (calc)	14	
Peculiarities			Slickensides in cuttings

Company/field	MTS/Kizildere, Turkey	
Well Name	Well XIV	Gen'l Field
Mud Type, wt	6-9 pH; 1.3 SG	
Total Depth	1960 ft/598 m	
T _{max} , °C	203.5	
Casing	13-3/8" @ 135.4 m	
Bit at TD	9-5/8" @ 454.8 m	
Tests	T, P, shale log, chemistry	
G _t , equilibrium	344.9°C/km	
	<u>GEOLOGICAL</u>	
Sedim. Base	1476 ft/450 m	
Surface faults	Normal; EW graben	
Fracturing	Fractures detected at 600 m depth	in metamorphics
Geol. features	Caprock 259-265 m	
Surface Deposit	Pliocene and valley fill silt & sand (Miocene 313 m, Metamorphic 450 m, Marble 454 m)	
	<u>HYDROGEOCHEMICAL</u>	
Depth	531 m	Surface
Spring T, R		4 springs, 2-2.5 m, T _{max} = 100°C
Boron(ppm)	32.2B	30-35B
SiO ₂ ,(ppm)/pH	275/8.9	
Na/K, ppm	1000/123 = 8.13	1230/156 = 7.88
Ca/Mg, ppm	2/.5 = 4	6.8/3.65 = 1.86
Cl/SO ₄ , ppm	90/500 = 0.18	84.7/1408 = 0.06
HCO ₃ /CO ₃ , ppm	1910/-	1479/912 = 1.62
TDS, ppm	3957	5280
	<u>THERMAL</u>	
Area Sampled		8 km ²
No. hot springs		4 sampled
Max. spring temp.		100°C
	<u>HYDROLOGICAL</u>	
Precipitation	21.3 in. 54.13 cm	21.3 in. 54.13 cm
Elevation	1050 ft 320 m	
Mean surface T.	60.4°F/15.8°C	60.4°F 15.8°C
Water table	338 ft 103 m	
Spring Flow		16,500 cc/sec
Well P,D	870.6 psi @ 4428 ft G _p = 0.353 psi/ft	G _p 0.3-0.4 psi/ft, shut in
	<u>ROCK PARAMETERS</u>	
Salinity, ppm	3960	4430 (average)
Prod. interval	485 ft 148 m	inflow @ 200 & 250 m depths
Reservoir rock	Schist & Marble	
Fractures	Dominant	
Flow rate, ton/hr	496 water at 9 atm (529 total)	1086 for field, (3-6 wells)
Permeability, md	108, (minimum)	
Peculiarities	Best Kizildere well	

Company/field	ENEL/Larderello, Italy		
Well Name	Well #140	Experimental Well	Well #21 (Travale Field)
Total Depth	440 m	1097 m	919 m
Tmax,	228°C	236°C	239°C
Sedim. Base Geol. features Surface Deposit	<u>GEOLOGICAL</u>		
		355 m	
		Flysch to 310 m, Dolomite to 355 m, Phylites & Quartzite to total depth.	Gravity high, flysch cover Pliocene
	Neogene		
Depth Source Na/K, ppm	<u>HYDROGEOCHEMICAL</u>		
		750 m	
		Condensed steam 0.5/0.3 = 1.7	
Elevation Well P, D	<u>HYDROLOGICAL</u>		
	390 m	435 m	491 m
	90 psi @ surface	100 psi @ surface	
Salinity, ppm Reservoir rock	<u>ROCK PARAMETERS</u>		
			850 initially Dolomite & Anhydrite

Company/field	Nihon/Matsukawa, Japan
Well Name	Well MR-1
Total Depth	945 m
	<u>GEOLOGICAL</u>
Surface faults	NW & NE
Geol. features	Moramori Volcanic Debris
	<u>HYDROGEOCHEMICAL</u>
SiO ₂ (ppm)/pH	599.5/4.9
Na/K, ppm	263.5/143.5 = 1.84
Ca/Mg, ppm	22.9/8.7 = 2.63
Cl/SO ₄ , ppm	12.4/1780 = 0.007
HCO ₃ /CO ₃ , ppm	36.6/-
TDS	3843 mg/l
Other Chemicals(ppm)	248 HBO ₂ , 826 H ₂ SiO ₃
	<u>THERMAL</u>
No. hot springs	13
Max. spring temp.	70°C
	<u>ROCK PARAMETERS</u>
Average Porosity	~ 13%
Reservoir Rock	Tamagawa welded tuff (Miocene) & Yamatsuda sediment
Flow rate, ton/hr	70 initial, 15 with interference from well #5
Permeability, md	(Liquid reservoir) 15
Peculiarities	Caldera, 2 dry holes, AR-1, BR-1 intermittently flowed (330 & 425 m total depth).

Company/field	Gulf/Mt. Home, Idaho	
Well Name	Bostic 1-A	El Paso Station 11 Well
Location	12 miles SE Mt. Home	
Mud Type, wt.	Fresh gel, 8.9 lb/gal, 9 pH, CA++	
Total Depth	9620 ft/2933 m	1906 ft/581.1 m
T _{max} , (time)	348°F (10 hr)	112°F
Casing	10-3/4" @ 324 m	
Bit at TD	8-3/4 "	
Tests	Logs, drill stem test	
G _t , equilibrium	60.8 °C/km	
<u>GEOLOGICAL</u>		
Sedim. Base	8140 ft/2482 m	
Surface faults	NW trend at surface	
	Dipping 70-80°SW down to South	
Geol. features	Silt, clay, diatomite	Clay, silt, sand
Surface Deposit	Q _{bs} : Bruneau Formation/Idaho Group-basalt & stream deposits-Pleistocene. (Above Glenns Ferry stream deposit-Plio-Pleistocene.) Glenns Ferry subarea, just South of Hot Springs.	
<u>HYDROGEOCHEMICAL</u>		
Source T, R, Ω m	1.05 Ωmat 51°F	18.9 Ωmat 112°F
pH		8.3
Na/K, ppm		147.4/4.3 = 34.3
Ca/Mg, ppm		5.21/0.73 = 7.1
Cl/SO ₄ , ppm		27.3/43.23 = 0.63
HCO ₃ /CO ₃ , ppm		220.3/67.2 = 3.3
TDS, ppm	800	515.7
Other Chemicals	Encountered Gypsum at 5226 ft	22.9 Sodium Absorption Ratio
<u>THERMAL</u>		
Area Sampled	Hot Springs Creek 1-1/2 miles to West Hot Spring 9 miles to NNW of well	
Max. spring temp.	152°C South edge of Mt. Bennett Hills water well 380°C at 213 m 59°C well, 3 miles North	44.4°C, 581 m
<u>HYDROLOGICAL</u>		
Precipitation	(Glenn's Ferry Well) 8.7 in./22.1 cm	(Cold Well)
Elevation	3175 ft/968 m	
Mean surface T.	53.2°F/11.8°C	
Well Flow	305 l/sec cold well	0.44 l/sec
Water table	2774 ft/846 m	400 ft/122.0 m
Spring Flow		All springs, 35,290 cc/sec
<u>ROCK PARAMETERS</u>		
Prod. interval	579 ft/177 m	
Sonic porosity, φ _a	0.15	
Density φ, frac.	0.14	
Average Porosity	0.14	
Reservoir rock	Volcanic tuff	Silt, sand, clay (Glenn's Ferry)
Flow rate, ton/hr	13.2 at 115 psia well head	
Permeability, md	kh = 390, 2.2 md	
Peculiarities	Produced water cut mud (Q _{bs} = Quaternary Bruneau Sand)	100 ft/mile water table gradient (to South). Only Q _{bs} has good permeability in cold wells (deeper formation poor).

Company/field		Imperial Magma/Niland, California		
Well Name	Magma max #1	Magma max #2	Magma max #3	
Total Depth	2550 ft/777 m	4368 ft/1332 m	3120 ft/951 m	
T _{max} , (time)	140.6°C (2 hr)	164.4°C (7 hr)	168.9°C (5 hr)	
Casing	13-3/8" @ 1060 ft 8-5/8" liner	13-3/8" @ 1009 ft 9-5/8" @ 4350 ft	13-3/8" @ 1032 ft 9-5/8" @ 3076 ft	
Tests	Logs, drill stem test, Production	Logs, Water input	Logs, Water input	
G ₊ , equilibrium	355°C/km	258°C/km	312°C/km	
<u>GEOLOGICAL</u>				
Sedim. Base	950 m	850 m	850 m	
Surface faults	San Jacinto & Imperial fault			
Fracturing	Transverse to San Jacinto fault.			
Geol. features	Red Hill volcanic trend runs N40°E (16,000-55,000 yr old.) Pleistocene sands. Pliocene 1200 ft. Miocene 1700 ft.	High-angle fault ~3000 ft deep. Pleistocene to 1300 ft Obsidian, Scoria, Pumice at S.E. end of sea-Red Hill	Pleistocene to 1200 ft Pliocene to 1700 ft	
<u>HYDROGEOCHEMICAL</u>				
Depth, Date	277-690 m 4/30/72	4/30/72	4/30/72	
Source	Liquid sample (production)	Magma #1 steam sample	Magma #1 liquid	
Boron(ppm)	<0.08 B	0.08 B	<0.08 B	
SiO ₂ (ppm)/pH	8/6.0	6/8.0	8/6.0	
Na/K, ppm	44,450/8930 = 4.98	756/158 = 4.78	46,600/11,000 = 4.24	
Ca/Mg, ppm	20,890/572 = 36.5	119.3/9.2 = 13	24,646.6/546.9 = 45.1	
Cl/SO ₄ , ppm	116,091/-	1849.6/0.4 = 4624	127,820/-	
HCO ₃ /CO ₃ , ppm	100/-	140.3/-	96.4/-	
TDS, ppm	191,515		211,165	
Other Chemicals (ppm)	80 Fe, 400 NH ₄ , Steam has 17.7% CO ₂ , 0.58% N ₂ , 0.25% CH ₄	200 NH ₄ 1.0023 S.G. (Injection Well)	70 Fe, 400 NH ₄ 1.151 S.G. (Injection Well)	
<u>HYDROLOGICAL</u>				
Precipitation	3 in. 7.6 cm	3 in. 7.6 cm	3 in. 7.6 cm	
Elevation	-225 ft -68.6 m	-227 ft -69.2 m	-226 ft -68.9 m	
Well Flow	50 l/sec			
Water table	20 ft from surface			
Well P, D	833 psi, 1924 ft G _p = 0.440 psi/ft	1875 psi, 4340 ft	1251 psi, 2924 ft	
<u>ROCK PARAMETERS</u>				
Salinity, ppm	190,000			
Prod. interval	Perforated 1732-2264 ft	Perforated 3784-4360 ft	Perforated 2618-3076 ft	
Density ϕ, frac.	0.3 approx		0.26	
Neutron ϕ, frac.	0.24 approx		0.29	
Average Porosity	0.27		0.27	
Reservoir rock	Sandstone		Sandstone	
Flow rate, ton/hr	245 @ 160 psig. (377°F)	136 @ 200 psig	102 @ 325 psig	
Permeability, md	50-75		73	
Peculiarities	SP shows 17,500 ppm NaCl	Calcite streaks @ 3970 ft Temp. inversion @ 3750 ft SP shows 44,000 ppm NaCl	Calcite streaks @ 3620, 3640, 3841 ft SP shows 47,500 ppm NaCl Temp. inversion at 2400 ft	

Company/field	Imperial Magma/Niland, California		
Well Name	Magma max #4	Woolsey/Salton Sea	Fish Hot Springs (Westside Salton Sea)
Total Depth	2567 ft/782 m	2400 ft/731 m	
T _{max} , (time)	276°F (2 hr)		
Casing	8-5/8" @ 516 ft	13-3/8" @ 1084 ft	
Bit at TD		7-7/8"	
Tests		Logs, T	
G _t , equilibrium	331.8°C/km	291.2°C/km	
GEOLOGICAL			
Geol. features	Pleistocene to 1200 ft; Pliocene to 1700 ft	Pleistocene to 1020 ft; Pliocene to 1500 ft	
HYDROGEOCHEMICAL			
Source		Magma DST #1, Well #1 2632-2656 ft	
SiO ₂ (ppm)/pH	/5.5	1210/5.6	
Na/K, ppm	54,000/23,800 = 2.27	31,000/8200 = 3.78	
Ca/Mg, ppm	40,000/100 = 400	15,515/40 = 388	
Cl/SO ₄ , ppm	184,000/10 = 18,400	91,000/-	
TDS, ppm	303,050(Lacking Si & HCO ₃)	179,790 mg/l @ 140°C	
Other Chemicals	320 Li, 100 Rb, 20 Cs, 200 Br, 498 B	198 Fe, 164 Mn S.G. = 1.16	
HYDROLOGICAL			
Precipitation	3 in. 7.6 cm	3 in. 7.6 cm	
Well Flow			10-100 gpm
Spring Flow			Fish Spring 280 gpm
Well P, D	1051 psi, 2450 ft	968 psi, 2259 ft 1059 psi, 2340 ft	
ROCK PARAMETERS			
Prod. interval	Perforated 2376- 2518	Perforated 1866- 2375	
Peculiarities	Well taking 500 gpm @ 200 psi. (Observation well)	Inversion of T at 1700 ft (2 maxima in T log.)	

Company/field		Northern Kyushu Electric Co./Otake, Japan			
Well Name	Well T-2	Well #7	Well #8	Well #9	Well #10
Total Depth	900 m	350 m	346 m	550 m	600 m
T _{max} ,	206°C	160°C at 230 m	196°C at 270 m	92°C, TD	92°C at 150 m
G _t , °C/km	212	628	668		
Casing	4" @ 442 m			8-5/8" @ 250 m	8-5/8" @ 250 m
Bit at TD	2-1/2"	8"	8"	7-5/8"	7-5/8"
<u>GEOLOGICAL</u>					
Surface faults	NW			NW, main	
Geol. features	0-300 m Kaolinized, 300-500 m Kaolinized & silicified, 500-700 m Fractures in silici- fied Pleistocene Kujyu (overlying Mio- cene Kusu) Andesites	Surface Deposit - Honda pumice flow	Surface Deposit - Alluvium	Basement: Miocene Kusu Hohi formation - Volcanic, Hu (Pleistocene)	Surface Deposit - Alluvium
<u>HYDROGEOCHEMICAL</u>					
SiO ₂ , (ppm)/pH		525/8.0		668/6.7	612/8.0
Na/K, ppm		920/100 = 9.2		940/110 = 8.55	1060/140 = 7.57
Ca/Mg, ppm		17.2/6.0 = 2.87		20.7/10 = 2.07	31.2/7.8 = 4.0
Cl/SO ₄ , ppm		1760/96 = 18.3		1630/145 = 11.2	1720/95 = 18.1
TDS, ppm		3530		3810	4030
<u>HYDROLOGICAL</u>					
Elevation	1030 m			960 m	990 m
Mean surface T.		60°F 15.6°C	60°F 15.6°C		
<u>ROCK PARAMETERS</u>					
Reservoir rock	Andesite, Tuff breccia			Andesite, Tuff breccia	
Fractures				NW & EW	
Flow rate, ton/hr	19 steam, 33 water(52)	53 steam, 193 water(246)	17 (steam only)	90, (29 steam)	165, (30 steam)
Peculiarities	Cavity at 559 m		No. 8 communicates with No. 10 well		

Company/field	Pauzhetsk, USSR	
Well Name	Well R-13, Kamchatka	General Field
Total Depth	400 m	
T _{max} ,	200°C	
G _t , °C/km		500-700
Geol. features	<u>GEOLOGICAL</u> Near Kambalny Range & Pauzhetka River, Alluvium to lower Holocene pumice.	
Depth, Date	<u>HYDROGEOCHEMICAL</u> Surface 10/57	
Spring T	Paryaschy boiling spring	3/61 well #4/195°C
pH	8.1	8.2
Na/K mg/ℓ	1010/74 = 13.7	986/105 = 9.4
Ca/Mg, mg/ℓ	60/8 = 7.5	52/3.5 = 14.9
Cl/SO ₄ , mg/ℓ	1667/76 = 22	1633/78 = 21.3
HCO ₃ /CO ₃ , mg/ℓ	41/0.9 = 46	4/22 = 0.18
TDS	3279 mg/ℓ	3448 mg/ℓ
Other Chemicals(mg/ℓ)	216 H ₂ SiO ₃ 3 Br, 0.4 NH ₄	393 H ₂ SiO ₃ , 0.6 NH ₄
Spring Flow	<u>HYDROLOGICAL</u> Post Production 600 cc/sec (Paryaschy) Pre-Production 10,000 cc/sec	
Salinity, ppm	<u>ROCK PARAMETERS</u> ~ 3500	
Reservoir rock	Tuff, Pleistocene above Pliocene sandstone	
Flow rate, ton/hr	63 initially	522 initially (10 wells)
Permeability, md	1/2 - 10 md laboratory 260-440 flow test	470 m ² /day transmissivity
Peculiarities	T _{max} = 193°C @ 230 m in R-1	

Company/field	Phillips/Roosevelt Springs, Utah	
Well Name	Well 9-1	Beaver County Hot Spring
Mud Type, wt	water, 8.4 lb/gal	
Total Depth	6885 ft/2099 m	
T _{max} , (time)	377°F (14-1/2 hr)	
Casing	15-1/2", 1280 m	
Bit at TD	8-1/2"	
Tests	logs, T, mud log	
G _t , equilibrium	102.6°C/km	
	<u>GEOLOGICAL</u>	
Sedim. Base	710 ft 216.5 m	
Fracturing	N20E @ 3600 & 5800 ft	
Geol. features	Granodiorite batholith	Mineral Mts., granite & metamorphic rocks to east. Age: 9.2 x 10 ⁶ yr (intrusion)
Surface deposit	Escalante Valley. Quaternary sands, Well 9-1 2900 feet from Prod. well (250,000 lb/hr) warm spring 3 miles away.	
	<u>HYDROGEOCHEMICAL</u>	
Spring T		190°F (1908), 185°F (1950), 131°F (1957)
H ₂ S		H ₂ S odor
Ca/Mg, ppm		31/10 = 3.1
Cl/SO ₄ , ppm		87/90 = 0.97
HCO ₃ /CO ₃ , ppm		30/0
TDS, ppm		645(1908)7040(1950)7800(1957)
	<u>HYDROLOGICAL</u>	
Precipitation	13 in. 33 cm	(Milford area)
Elevation	5828 ft 1777 m	4.85 in. 12 cm
Mean surface T.	52°F 11.1°C	
Well flow	115 l/sec from hot well to east	
Spring flow		Hot, 630 cc/sec
	<u>ROCK PARAMETERS</u>	
Salinity, ppm	22,000 by SP	(Milford area)
Prod. interval	Open hole	530 ppm from springs, (569 from wells)
Sonic porosity, ϕ_a	0.05 in fractures	
Density ϕ , frac.	0.019 in fractures	
Average porosity	0.02	
Reservoir rock	Granodiorite	
Fractures	in flow @ 3572-3604 ft	
Permeability, md	< 1	
Peculiarities	No flow on test possible fault at 5800 ft altered zone at 4070 ft	Wells have decreasing TDS with depth. Spring now dry.

Company/field	Government/Waiotapu, New Zealand		
Well Name	#20	#6	#7
	<u>HYDROGEOCHEMICAL</u>		
Depth	Surface		
SiO ₂ (ppm)/pH	380/8.6	620/8.9	600/8.8
Na/K, ppm	450/22 = 20.5	860/155 = 5.55	790/90 = 8.8
Ca/Mg, ppm	9/0.08 = 112	10/0.06 = 167	10/0.05 = 200
Cl/SO ₄ , ppm	688/93 = 7.40	1450/52 = 27.9	1310/36 = 36.4
TDS, ppm	1683	3224	2970

Company/field	Government/Wairaiiki, New Zealand	
Well Name	General Field	Well #36
Total Depth		2006 ft/612 m
T _{max} ,		146°C @ 1300 ft
	<u>GEOLOGICAL</u>	
Surface faults	SW-NE	
Geol. features	Huka Falls siltstone cap	
Surface Deposit	Pumice & Breccia	
	<u>HYDROGEOCHEMICAL</u>	
	Production Well #20 (202°C)	Production Well #44
H ₂ S, Boron(ppm)	0, 26 B	28.8 B
SiO ₂ (ppm)/pH	640/8.4	640/8.6
Na/K, ppm	1300/220 = 5.91	1320/225 = 5.87
Ca/Mg, ppm	18/0.04 = 450	17/0.03 = 567
Cl/SO ₄ , ppm	22.5/35 = 0.64	2260/36 = 62.8
TDS, ppm	4576	4653
Other Chemicals(ppm)		14.2 Li, 8.3 F, 6 Br, 4.8 As, 0.3 I, 0.15 NH ₃
	<u>HYDROLOGICAL</u>	
Water Table	surface	
Well P, D	882 psi -900 ft	882 psi -900 ft
	<u>ROCK PARAMETERS</u>	
Reservoir rock	Waiora Breccia	
Flow rate, ton/hr	8850 max from 62 wells	