Geothermal Resources Council, TRANSACTIONS, Vol. 8, August 1984

CHARACTERISTICS OF BASIN AND RANGE GEOTHERMAL SYSTEMS WITH FLUID TEMPERATURES OF 150°C TO 200°C

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ABSTRACT

Six geothermal reservoirs with fluid temperatures over 200°C and ten geothermal systems with measured fluid temperatures of 150-200°C have been discovered in the northern Basin and Range Province of the USA. A comparison of these high and moderate-temperature systems shows considerable overlap in geographical distribution, geology, and physical properties. Our ability to distinguish between moderate and high-temperature systems using fluid chemistry has been limited by often inaccurate estimates based on shallow samples and by a bias in the NaKCa geothermometer which, in this province, overestimates fluid temperatures at economic drilling depths for both shallow and deep samples. The best indications of a possible high temperature reservoir near a moderate-temperature well appear to be silica base temperatures above 210°C for deep fluid entries and a high-temperature gradient in the bottom of the well.

INTRODUCTION

Exploration for high-temperature geothermal reservoirs in the northern Basin and Range geologic province of the western USA has resulted in the discovery of six reservoirs with confirmed fluid temperatures above 200°C and ten geothermal systems with fluid temperatures of 150°C to 200°C. In all of these areas there has been at least some fluid production. Deep drilling at 25 other geothermal prospects in this province has so far not resulted in announced discoveries of fluids with temperatures above 150°C. Benoit and Butler (1983) summarized available data for all of the high-temperature systems and four of the moderate temperature systems, three of which have temperatures above 200°C in non-producing zones.

The objectives of this paper are to (1) describe the moderate-temperature systems not included in Benoit and Butler (1983), (2) summarize and compare temperature and chemical data from all of the known moderate and high-temperature systems in this province, (3) comment on the accuracy of the two chemical geothermometers most commonly used to predict reservoir temperature. In this paper the term "high temperature system" refers to those systems which have produced fluid from zones with temperatures above 200°C. The term "moderate-temperature system" refers to systems where produced fluid has come from zones with temperatures between 150 and 200°C.

SUMMARIES OF MODERATE TEMPERATURE SYSTEMS

The ten moderate-temperature systems for which data are available are listed in Table 1. The reader should note that Long Valley has been divided into two areas on Table 1: the Casa Diablo area, which is currently undergoing development, and eastern Long Valley where wells drilled to date have not found temperatures above 150°C. The locations of all geothermal areas discussed in this paper are shown in Figure 1.

The reader is referred to Benoit and Butler (1983) for summary descriptions of the Long Valley, Humboldt House, Brady's, and Soda Lake geothermal systems. Exploration results at the six moderate temperature systems not covered by Benoit and Butler plus some supplementary data on the Soda Lake system are summarized below.

Soda Lake

Basin and Range structures, buried beneath the surficial cover of the Carson Desert, are important fluid conduits for the Soda Lake geothermal system. Drilling and seismic data have defined a narrow, NNE-trending graben which probably controls both fluid upwelling and the eruption of Quaternary basalts NNE and SSW of the field. Low-salinity Na-Cl waters, rich in CO_2, rise along graben-bounding faults and charge laterally flowing thermal aquifers in basin-filling sediments and in deeper Tertiary tuffaceous rocks. Flow in these aquifers in large part controls the broad, non-linear form of the shallow thermal anomaly at Soda Lake. Shallow temperature data indicate strong northward flow of thermal aquifers in alluvium, down the regional hydrologic gradient toward discharge at the Carson Sink. Flow directions in deeper Tertiary aquifers are as yet poorly understood, and may be independent of the shallow system.

To date, all production in the field (two wells) is from outflow zones. No wells penetrate hotter upwelling conduits which, based on consistent chemistry of deep produced fluids, should have temperatures near 220°C. Long-term testing of a

183°C aquifer in the 84-33 well yielded flow rates up to 136,000 kg/hr. Excellent reservoir continuity has been demonstrated by interference tests of the two producing wells which are 1.8 km apart.

Stillwater

The Stillwater thermal anomaly is 27 km east of, and stratigraphically similar to, the Soda Lake anomaly. However, structurally it is on trend with the Salt Wells anomaly 19 km to the south. Stillwater and Salt Wells are linked by an active fault system which partly controls hydrothermal circulation at both anomalies. At Stillwater, two centers of upwelling along this fault zone supply 156°C water to a 482 m deep sandstone aquifer, creating a shallow thermal anomaly with an area of about 62 sq km (E. Beuck, 1984 pers comm; Morgan, 1982). In 1964 this aquifer was successfully tested during the drilling of the first deep exploratory well, the Reynolds 1. However, when subsequent tests in volcanic formations below this aquifer found decreasing temperatures the well was abandoned.

From 1976 to 1982, Union Oil Company drilled three observation wells and two exploratory wells at Stillwater. The first exploratory well, the Debraga 2, was drilled 1.2 km north of and on structural trend with the Reynolds 1. A test through slotted liner of several zones in volcanic formations present from 731 m to a final depth of 2,110 m flowed 68,000 kg/hr. Geochemistry of the produced water indicated a maximum base temperature of 187°C (Union Oil, 1980?). The second Union exploratory well, the R. Weishaupt 1, was directionally drilled to a final vertical depth of 2,917 m at a position about 1.5 km west of the Reynolds 1. Temperatures in this well (Figure 2), which also bottomed in volcanic rocks, were slightly less than in previous wells at comparable depths and the well did not flow when tested (Ash, et al., 1982).

Salt Wells

The Salt Wells geothermal anomaly is located on the western margin of the Salt Wells basin 23 km southeast of Fallon, Nevada. The only surface indications of a major geothermal system at Salt Wells are sinter deposits left from hot springs reportedly active in the late 1800's and a cold spring of Na-Cl water which gives a NaKCa temperature of 207°C. The thermal anomaly extends from the community of Salt Wells south to the Cocoon Mountains, a distance of over 12 km. About half of the 46 sq km anomaly is underlain by aquifers at depths of less than 100 m with temperatures above 100°C resulting in a large anomalous heat flow of 54 MW (Blackwell, 1980, private report).

In 1980 Anadarko drilled a 2,591 m exploratory well in Simpson Pass where geological and geophysical studies indicated the potential for deep fracturing in a large horst block at the convergence of two active fault systems. After drilling through 670 m of volcanic rocks the well entered a quartz monzonite which persisted to final depth. Both formations are fractured and hydrothermally altered. While drilling with aerated water the well produced up to 76,000 kg/hr of water from fractures at 1,859 m and 2,057 m. The maximum temperature in this interval is 160°C (Figure 2). Deeper fractures at temperatures of up to 177°C were less productive. The water from these fractures had higher salinity and lower base temperatures than water from the shallow holes and probably came from a separate source (Geothermex, 1981, private report). High-resolution temperature logging of these fractures indicates no fluid movement under natural conditions.

Central Dixie Valley

In 1979 Thermal Power Company drilled a 2,750 m exploratory well at a location 19 km south of Sunedco's high-temperature geothermal discovery in Dixie Valley. The drilling history for this well, the Dixie Federal 45-14, notes a significant fluid entry occurred in the interval from 1,774 m to 1,789 m. Fluid was produced from this interval on a intermittent basis by air lift. Later temperature logging showed the temperature in this interval to be 176°C and the temperature at final depth to be 197°C (Figure 2). This system is probably not part of the system found by Sunedco based on distance and lower temperatures at depth.

Fish Lake Valley

Fish Lake Valley, located in southwestern Nevada 64 km east of Long Valley, is still in the early stages of exploration. An unsuccessful 2.8 km oil wildcat which logged a temperature of 159°C was later reentered by Magma Power Company and now produces a weak flow of 41°C water. No data have yet been published on the thermal anomaly, however Steam Reserves Corporation reports drilling a 600 m observation well which has a maximum temperature of 157°C at 135 m (Harry Olson, 1984, pers comm). High geochemical base temperatures for this prospect (Table 1) combined with the relatively high-temperature shallow aquifer found so far indicate potential for a high-temperature discovery. The first deep geothermal well at this prospect is scheduled to spud in April, 1984.

Borax Lake

Borax Lake is a hot spring pool located near the center of Pueblo Valley, a young rift valley in southeastern Oregon. The ten acre pool is perched on top of a mound about 6 m above the valley floor and appears to be fed entirely from a single large vent. A recent monitoring program has shown temperatures near the edge of the pool vary seasonally from 14°C to 36°C. Boiling springs occur along a fault extending from near the northwest corner of the pool to a point 1.2 km north of the pool. The U. S. Geological Survey (USGS, 1978) has estimated total hot spring discharge to be 3,500 lpm and has calculated an expected reservoir temperature of 191°C based partly on the SO_4-H_2O geothermometer.

Over 30 shallow temperature gradient holes have delineated a 31 sq km thermal anomaly centered about 1.6 km southwest of Borax Lake. An intermediate depth gradient hole drilled by Anadarko Production Company 1.8 km southwest of the lake was halted at a depth of 349 m after

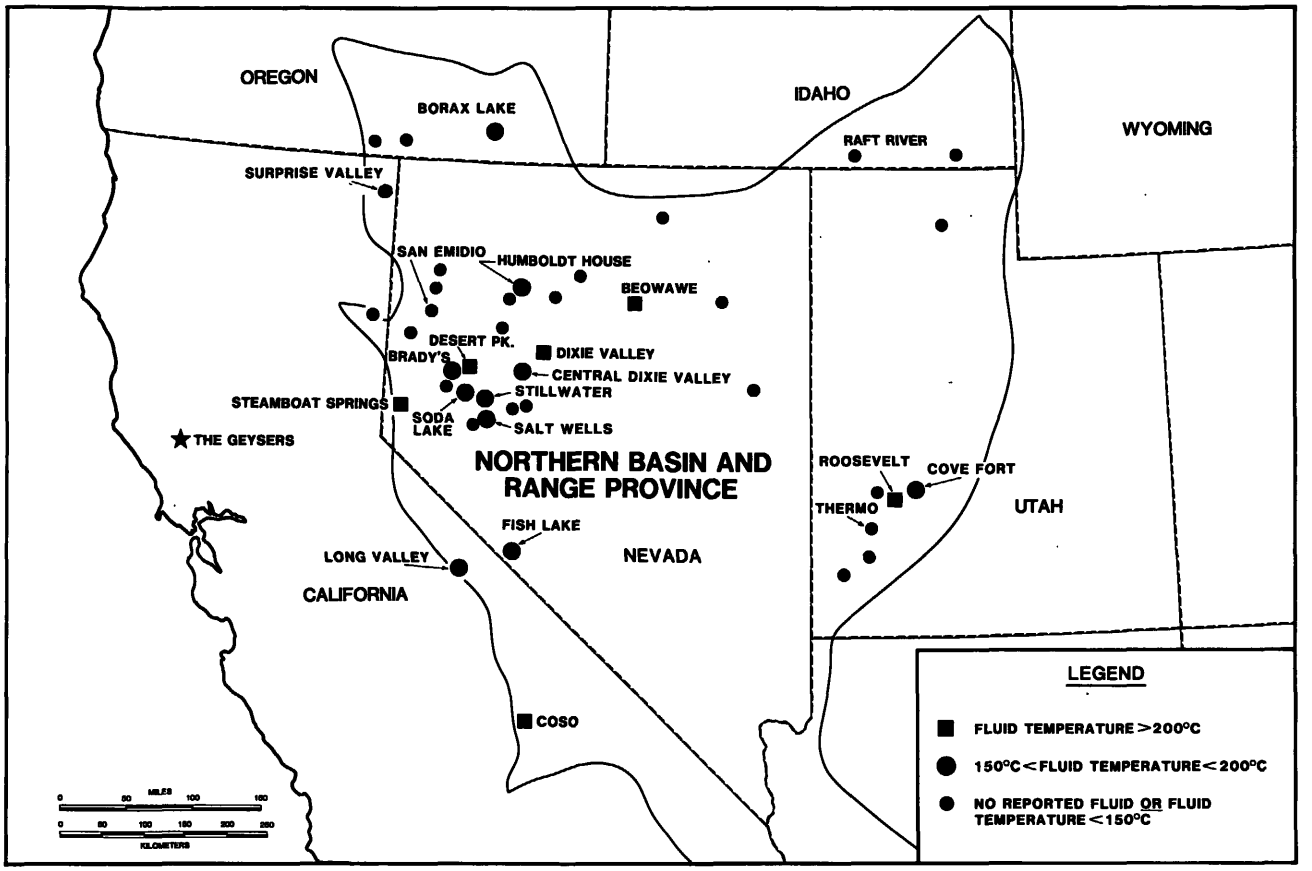

Figure 1. Map showing the location of drilled geothermal areas in the Northern Basin and Range Province (Modified from Edmiston, 1982).

Table 1. Measured temperatures and geochemical base temperatures of moderate and high-temperature geothermal systems in the Northern Basin and Range Province. Previously unpublished data are underlined.

GEOTHERMAL SYSTEM	QUAT. VOLC.	MAXIMUM MEASURED TEMPERATURES							GEOCHEMICAL BASE TEMPERATURE				WATER TYPE	
		FLUID ENTRY (C)	ANY POINT (C)	AT A REVERSAL TEMP (C)	AT A REVERSAL DEPTH (M)	BOTTOM OF DEEPEST TEMP (C)	BOTTOM OF DEEPEST DEPTH (M)	BOTTOM OF DEEPEST LOG GRAD. (C/KM)	SHALLOW SOURCE NaKCa (C)	SHALLOW SOURCE SiO2 (C)	DEEP SOURCE NaKCa (C)	DEEP SOURCE SiO2 (C)		FIG.4 NO.
ROOSEVELT	RHY	267	271			271	1862				297	263	Na-Cl	1
DIXIE VALLEY-NORTH		238	238								207	229	Na-Mixed	2
STEAMBOAT	RHY	228	228	177	277	228	929		207	201	259	252	Na-Cl	3
BEOWAWE		216	216			216	2911	4	200	220	251	239	Na-HCO3	4
COSO	RHY	213	213			213	405		238	161	234		Na-Cl	5
DESERT PEAK		208	213	148	110	213	2938	15			222	222	Na-Cl	6
SODA LAKE	BAS	184	204	166	250	204	2587	16			217	219	Na-Cl	7
HUMBOLDT HOUSE		182	205	111	107	193	2457	38	238	166	252	219	Na-Cl	8
LONG V.-CASA DIABLO	RHY	178	178	156	121	147	1846	18			238	219	Na-Mixed	9
SALT WELLS		177	181	142	106	181	2591	40	235	220	205		Na-Cl	10
DIXIE V.-CENTRAL		176	197			197	2749	12	144	145	194	216	Na-Cl	11
COVE FORT	BAS	169	178	171	762	178	2358	20			224	168	Na-Cl	12
FISH LAKE VALLEY		157	157	157	135	151	600	37			240	197	Na-Mixed	13
STILLWATER		156	177	156	482	177	2868	31	140	169	187	169	Na-Cl	14
BRADY		154	212	179	152	212	1543				157	167	Na-Cl	15
BORAX LAKE		153	160			160	614	166	176	165			Na-Mixed	16
RAFT RIVER		149	149			148	1798	5			182	158	Na-Cl	17
SAN EMIDIO		148	148	148	561	121	1613	0	207	183			Na-Cl	18
LONG VALLEY-EAST	RHY	147	147	110	305	147	1846	38	191	161			Na-Mixed	19
THERMO			171			171	2221		200	144			Na-Mixed	20
SURPRISE VALLEY			160			160	1167		174	160			Na-Mixed	21

encountering pressures in excess of hydrostatic in a fractured basalt flow. The section above the basalt, which was found at a depth of 335 m consists of claystone, clay and sand. Temperature at 349 m was estimated to be 153°C. A second intermediate hole drilled by Union Oil Company about midway between the Anadarko hole and Borax Lake did not encounter the basalt and reached a depth of 620 m where a temperature of 160°C was recorded. A seismic reflection survey conducted for Anadarko indicates both holes were drilled on a horst block near the center of the basin with apparent vertical relief of up to 579 m. A 1.8 km exploratory well planned by Anadarko in 1982 was postponed due to an announced lack of demand for additional electric power in the northwest U. S. and concerns about the regulatory policies of state agencies.

Cove Fort

The Cove Fort geothermal reservoir is located in southwestern Utah about 24 km northeast of the Roosevelt geothermal field. Cove Fort is the only reservoir included in this paper which occurs mostly in carbonate rocks and the only reservoir located in the vicinity of a major center of Recent basaltic volcanism. Lateral flow of thermal water in the carbonates at depths of 300 to 600 m results in a shallow thermal anomaly covering an area of 390 sq km, the largest known anomaly in the western U. S. outside Yellowstone Park. We estimate a total anomalous heat flow for this anomaly of at least 92 MW.

Between 1975 and 1979, Union Oil Company drilled four exploratory geothermal wells at Cove Fort and Hunt Energy operated one exploratory well. Data from the Union wells are summarized by Glenn and Ross (1982). The hottest well drilled by Union was CFSU 42-7 which had a temperature of 179°C near its final depth of 2,400 m. A flow test of this well yielded 22,000 kg/hr at a low wellhead pressure. The silica geothermometer for the produced fluid closely agrees with the measured temperature in the test interval of 169°C (Maassen, 1978). However, the NaKCa geothermometer indicates a base temperature of 224°C.

In October 1983, a geothermal well being drilled by Mother Earth Energy only 365 m from the CFSU 42-7 had a dry steam blowout while drilling at 356 m (GRC Bulletin, February, 1984). Initial reports placed the wellhead temperature at about 200°C at a flow rate of 114,000 kg/hr and pressure of 36 ata. The blowing well was eventually plugged and Mother Earth is now reported to have drilled a successful development well at Cove Fort. The maximum temperatures shown for Cove Fort in Table 1 are based on the Union wells due to uncertainty concerning the temperature of the recent discovery.

Other Areas

Data from four geothermal systems which come close to satisfying the criteria of fluid entry temperatures above 150°C are also included in Table 1. These systems are: Raft River, Idaho; Surprise Valley, California; San Emidio Desert, Nevada; and Thermo, Utah. At Raft River the U. S. Department of Energy and other public agencies drilled a prospect with a geochemical base temperature of 150°C to demonstrate the feasibility of low-temperature power generation. The first exploratory well, RRGE-1, found a 141°C reservoir at a depth of 1,520 m. Subsequent wells extended the reservoir temperature to 149°C. The average geochemical base temperatures for samples from three wells are: NaKCa-182°C and silica-158°C (Spencer, 1980). A comprehensive review of all data on Raft River has been published by Dolenc et al. (1981).

At Surprise Valley a temperature of 160°C has been reported for the Magma Power Company-Phipps No. 2 well, one of four widely spaced deep wells in the area (Duffield and Fournier, 1974). At Thermo Hot Springs, Republic Geothermal Inc. drilled a dry hole with a maximum temperature of 171°C at a final depth of 2,221 m (G. Huttrer, 1984, pers comm). At the San Emidio prospect a temperature gradient hole drilled by Phillips Petroleum Company had a temperature maximum of 148°C at 549 m followed by a slight reversal in temperature gradient. No fluid production has been reported at Surprise Valley, Thermo or San Emidio.

SUMMARY OF MEASURED TEMPERATURES

A summary of the characteristics of a geothermal discovery should include data on temperatures, pressures, flow rates, estimated reservoir volume, depletion rates, and fluid chemistry. However, since these data are available for only a few of the systems in Table 1, we will emphasize those parameters which are most often available and are of greatest concern in the early stages of exploration: measured temperatures in wellbores and geochemical base temperatures for fluids produced from wells. The most important temperature data from a geothermal well are the temperatures of significant fluid entries. Other significant data include deep bottomhole temperatures and the depth and temperature of reversals in temperature gradient. Available data on these parameters are summarized in Table 1. While space does not permit citing the source of each number appearing in Table 1, previously unpublished data are highlighted by underlining.

The data in Table 1 exhibit several significant trends. The first two columns under the heading of "MAXIMUM MEASURED TEMPERATURES" indicate all of the high-temperature systems and half of the moderate-temperature systems have maximum measured fluid entry temperature within 10°C of the maximum temperature recorded at any point. A comparison of these columns with the column headed "QUAT. VOLC.", under which areas with Quaternary rhyolitic and basaltic volcanism are indicated, shows there are exceptions to the correlation between high reservoir temperatures and Quaternary rhyolitic volcanism in this province. Relatively low temperatures occur in wells drilled to date in the Long Valley caldera while high-temperatures have been found at Dixie Valley and Beowawe, two areas with no obvious volcanic heat source.

Moving to the columns pertaining to temperature

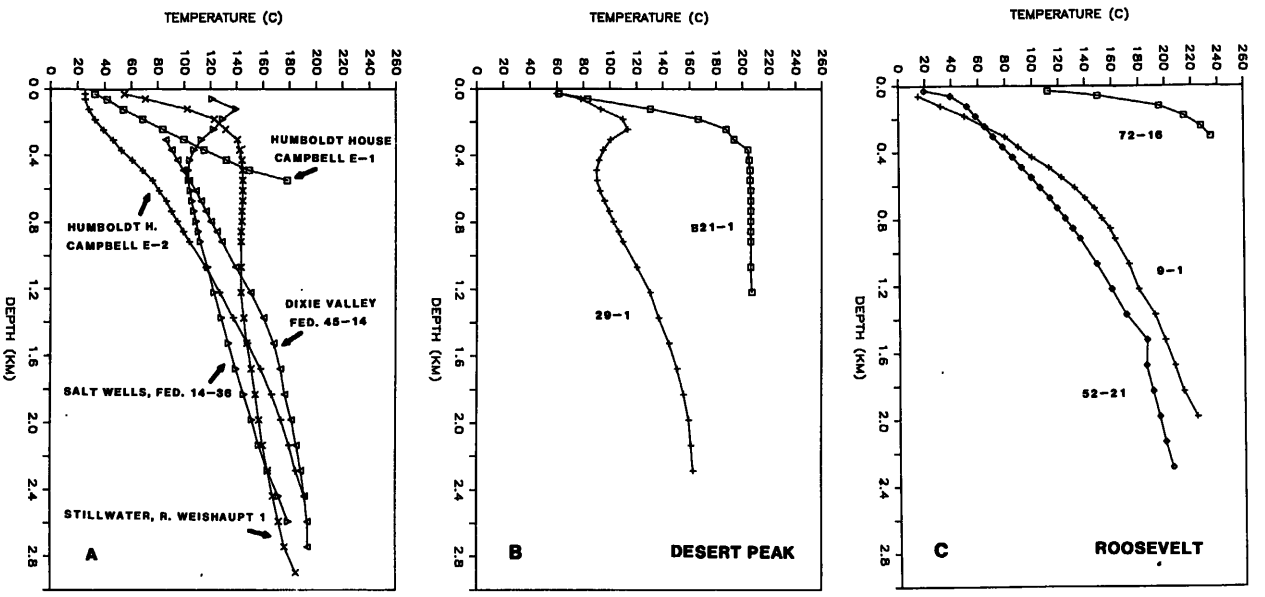

Figure 2: (a) Temperature logs from four moderate temperature systems. (b) Temperature logs from the Desert Peak high-temperature geothermal field. (c) Temperature logs from the Roosevelt high-temperature geothermal field.

reversals we see reversals at depths of less than 300 m are a common feature of Basin and Range systems. Most of these reversals occur in thin, nearly horizontal aquifers which are not suitable for development as reservoirs for power generation. These aquifers provide large targets during the reconnaissance phase of exploration, much like hydrothermal alteration haloes around ore deposits. However, they eventually increase exploration costs by requiring the use of deep temperature gradient holes to gather data pertaining to reservoirs which may underlie these shallow zones.

The columns pertaining to temperatures at depth indicate temperatures measured at depths of more than 2.3 km are usually not much higher than the maximum temperature of fluid entries or, sometimes, even the temperature of shallow reversals in near surface aquifers. Excluding Borax Lake and Fish Lake Valley, where there has been only shallow drilling, temperatures and temperature gradients measured at depth in the systems having moderate-temperature fluids are remarkably uniform. Only two areas, Humboldt House and Salt Wells, have gradients at depth which are near the upper range of Basin and Range background values. Allowing for the normal temperature dependance of thermal conductivity, the gradient of 40 C/km in quartz monzonite at Salt Wells implies a heat flow of about 104 mW/m^2. The gradient of 38 C/km in quartzite at Humboldt House implies a heat flow of about 142 mW/m^2.

One of the most difficult problems faced by a geothermal developer is determining when an unsuccessful exploratory well has adequately tested a prospect. All of the available data on the prospect are considered in making such a determination. However, the decision often hinges on an interpretation of the hydrologic system based largely on the temperature log. Just how difficult this problem can become when the well has encountered temperatures above 150°C is illustrated in Figure 2.

Figure 2a depicts five temperature logs from four moderate-temperature systems: Humboldt House, Salt Wells, Central Dixie Valley, and Stillwater. Although the logs show a wide range of behavior at shallow depths, temperatures in the four deep wells converge below 1.8 km and indicate a uniform temperature of about 190°C at 2.8 km. The only productive well shown in Figure 2a is the Campbell E-1, the discovery well at Humboldt House, which produced 363,000 kg/hr of fluid with a maximum subsurface temperature of 183°C (Benoit and Butler, 1983). The Campbell E-2 is a dry hole subsequently drilled 2.3 km from the discovery well.

Do temperature profiles such as the four deep wells shown in Figure 2a indicate the absence of a nearby reservoir with temperatures above 200°C? Figure 2b shows two temperature logs from Desert Peak. The log labeled 29-1 is from the first exploratory well at Desert Peak, a dry hole. The log labeled B21-1 is from the discovery well which was drilled 2.5 km from the dry hole. At the Roosevelt field (Figure 2C) a similar relationship exists between two dry holes (52-21 and 9-1) and a productive well (72-16) located nearly midway between the dry holes. Profiles such as those in the 72-16 well at Roosevelt and the B21-1 well at Desert Peak are usually found near major centers of fluid upwelling. Geologic maps showing the locations of most of the holes in Figure 2 appear in Benoit and Butler (1983).

The mean temperatures and related standard

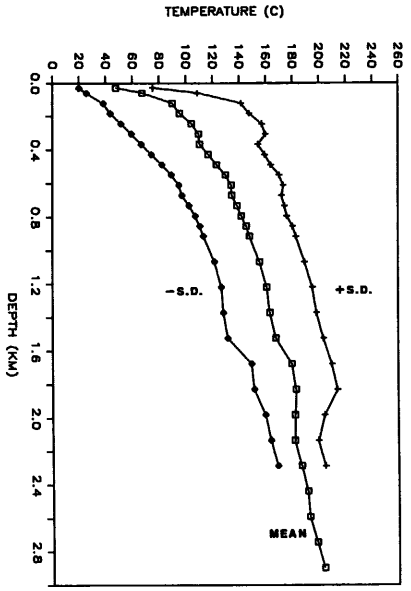

Figure 3: Statistics for 23 temperature logs at moderate and high-temperature systems.

deviations for 23 wells located at some of the high and moderate-temperate systems are graphically presented in Figure 3. The high temperature systems represented in Figure 3 are Roosevelt, Beowawe, and Desert Peak. Figure 3 shows the average well at a geothermal system with fluid temperatures above 150°C reaches 150°C at a depth of 1.0 km, below which the gradient declines to 25°C/km. Wells exceeding the upper standard deviation (about one well in six) reach temperatures above 200°C at depths of less than 1.4 km and tend to become isothermal at greater depth. The most distinguishing feature of dry holes drilled near high-temperature discoveries is that they tend to have above average temperature gradients at depths greater than 1.5 km.

GEOCHEMISTRY

The geochemical data used in preparing Table 1 came from a variety of sources and generally represents single chemical analyses, a few of which are of questionable quality. Also, comprehensive geochemical interpretations are available for only a few of these systems. Consequently, the chemical data are of acceptable quality for gross chemical characterizations but individual geochemical predicted temperatures may be in error. Therefore the silica and NaKCa geothermometers will be subjected only to statistical treatment, thus minimizing the effects of individual poor quality samples or analyses. Available SO_4-H_2O data have been discussed by Mariner et al. (1983).

Water Types

Thermal waters in the northern Basin and Range province vary widely in both amount and composition of dissolved constituents. Almost all the major water types have been documented and found to occur in restricted geographical regions (Mariner et al., 1983). The most important of these thermal water types is the Na-Cl water which is concentrated in the major topographic depressions near the east and west margins of the province. High chloride concentrations are an indication of extensive water-rock interaction with long flow paths and deep circulation where elevated temperatures can be encountered. Therefore, it is not coincidental that there is an excellent spatial correlation between known high-temperature geothermal reservoirs in the northern Basin and Range Province and outcrops of thermal Na-Cl water.

Ratios of the major cations and anions are shown on Figure 4. Na and K constitute more than 80% of the cations (in equivalents) for most systems and more than 95% of the cations for high-temperature systems. Only the water from Roosevelt contains more than 10% K. The anions show more variation but there is a clear dominance of Cl. Of the 16 systems with fluid entries greater than 150°C on Table 1, only 5 have less than 67% Cl. Beowawe is the only high-temperature HCO_3 water in the province. No high-temperature sulfate waters are known. The range in salinity is from 900 to 7000 mg/l and there are no clear correlations between temperature and either salinity or percent Cl.

Not all thermal chloride waters originate in high temperature geothermal systems. Deep drilling near several chloride thermal springs not mentioned in this paper has thus far produced temperatures less than 150°C.

Geothermometry

Geothermometry results for northern Basin and Range geothermal systems have been discussed by Mariner et al. (1983) using analyses from thermal springs or shallow wells. Mariner noted that geothermometers from these shallow sources tend to exceed temperatures in deep wells by 14°C. The geothermometry discussion here relies to a much greater extent on deep production well data.

Predicted silica and NaKCa temperatures for shallow and deep samples are plotted against maximum fluid temperatures in Figure 5. To provide a basis for comparing the results from deep samples with the more scattered results from shallow samples, lines with fixed slopes of 45° have been fit to both data sets.

The silica temperatures for the shallow samples show a high degree of scatter but are generally lower than for the deep samples. This presumably is a result of the relatively rapid reequilibration of silica as the fluid cools on its path to the surface. The shallow source line is only 2°C high but this number has little meaning due to the scatter. The deep source samples have much less scatter and the best fit 45° line is about 18°C above the fluid entry temperature. Most of the high-temperature samples fall below the line while most of the moderate-temperature samples are above the line.

The NaKCa temperatures show many of the same characteristics. The shallow source samples, which

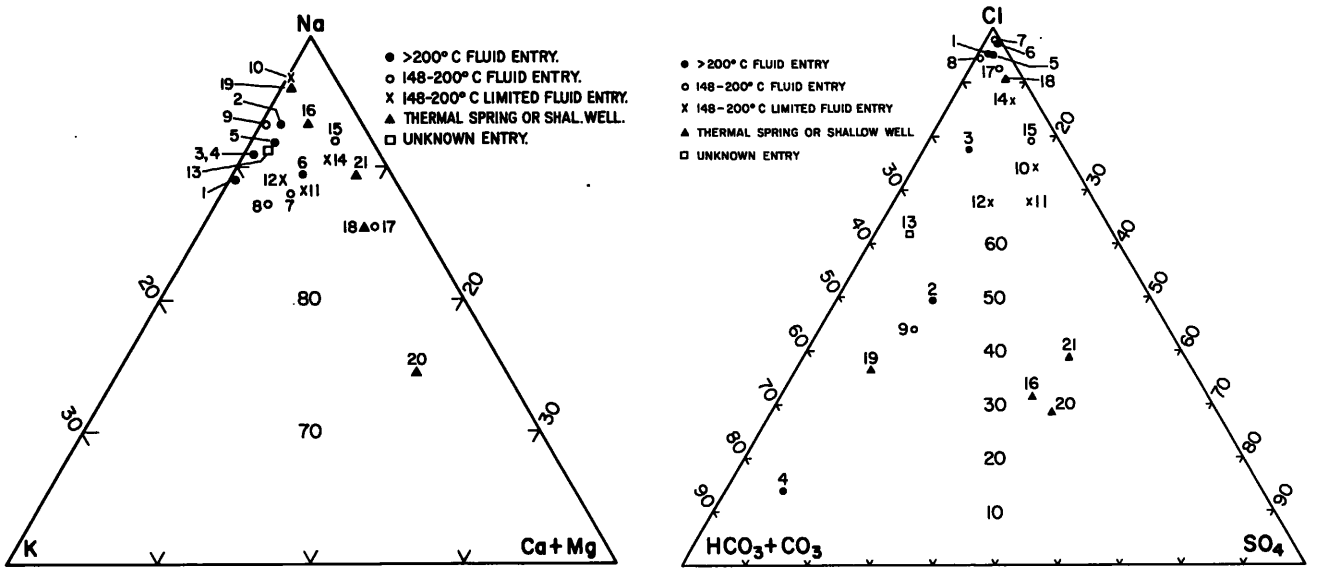

Figure 4: (a) Tri-linear plot of major cations. (b) Tri-linear plot of major anions.

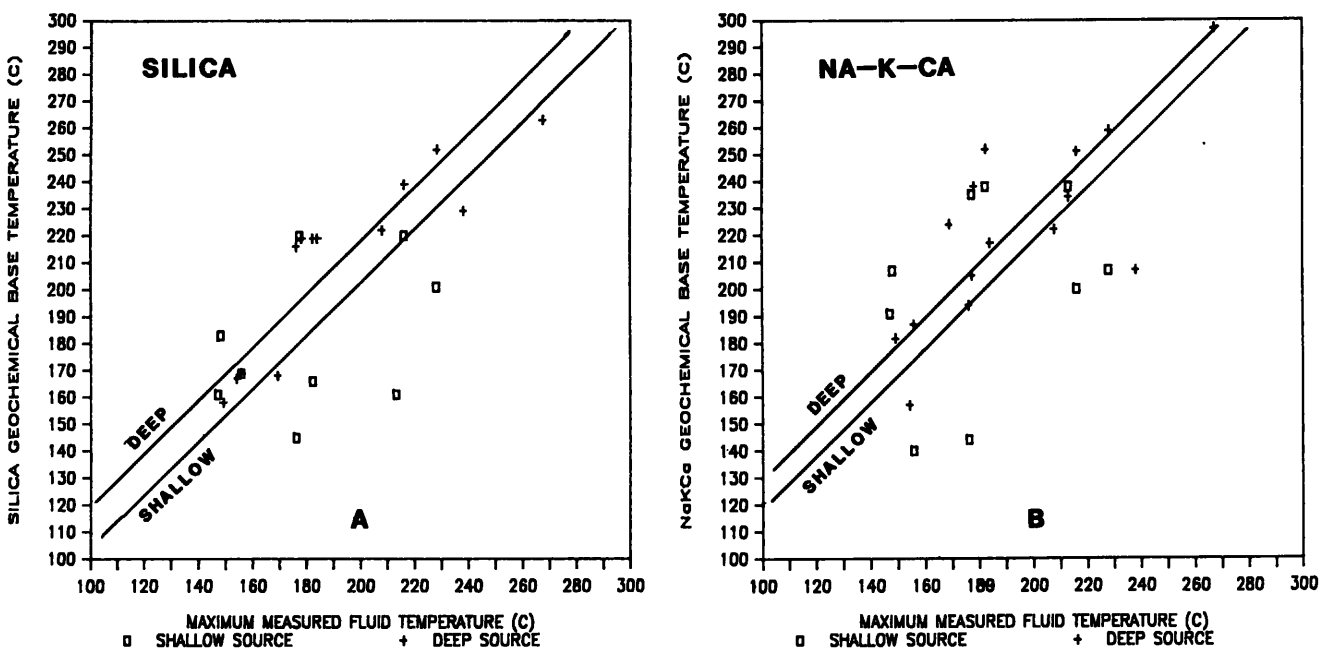

Figure 5: Silica base temperatures (a) and NaKCa base temperatures (b) vs. maximum measured fluid temperatures.

average 17°C high relative to actual fluid temperature, again show more scatter and predict lower temperatures than the deep source samples. The best fit 45° line through the deep source NaKCa data, which show more scatter than the deep source silica data, is 29°C high. Up to 5 or 10°C of this 29°C can probably be attributed to carbonate scale formation in the wellbore prior to sample collection. This is particularly true for waters with less than 10 or 20 mg/l of Ca, of which there are several represented on Table 1. Only one of the high-temperature systems (North Dixie Valley) falls more than 14°C below the best fit line for deep NaKCa samples indicating a more uniform bias than that found for deep silica samples. At lower temperatures the bias is seen at Raft River where there appears to be little likelihood of finding the 182°C fluids indicated by the NaKCa data.

CONCLUSIONS

Most of the moderate and high temperature geothermal systems found in this province to date occur in its northwest quarter, in proximity to hot springs of Na-Cl water, or along its western boundary in association with major centers of Quaternary rhyolitic volcanism. By comparison, only two systems with fluid temperatures above 150°C have been found in a smaller area with these features along the eastern margin of the province in southwestern Utah. Three of the six high temperature fields occur near centers of Quaternary rhyolitic volcanism; however, lower temperatures found in wells drilled in the eastern end of Long Valley Caldera indicate drilling in these areas also has its risks.

The most surprising phenomena noted in this study is that the two commonly used geothermometers, silica and NaKCa, give base temperature estimates for fluid samples produced from deep wells which are too high by an average of 18°C and 29°C respectively. In addition, the NaKCa geothermometer for hot spring and shallow well samples overestimates the temperature of fluid entries in nearby deep wells by an average of 17°C. Many explanations for these phenomena are possible. However, the explorationist should note these statistics pertain to using these techniques the way they have generally been used in commercial exploration: to predict reservoir temperatures at economic drilling depths.

The data presented in this paper together with data presented in Benoit and Butler (1983) indicate a considerable overlap in the properties of moderate and high-temperature systems in this province. Even allowing for a possible bias in the NaKCa geothermometer, it is likely this similarity is partly due to some of the moderate temperature systems containing undiscovered fluids with temperatures slightly over 200°C.

Distinguishing between wells drilled in moderate-temperature systems and moderate-temperature wells drilled on the flanks of high-temperature systems is one of the most difficult problems in geothermal exploration. It appears the most favorable indications of a nearby high-temperature reservoir are silica base temperatures of over 210°C for deep fluid entries and a significant positive gradient over most of the deep portion of the well. In this province, long, near-isothermal intervals of 150-175°C in deep well logs do not appear to be favorable indications of nearby higher temperature reservoirs.

ACKNOWLEDGEMENTS

We acknowledge the assistance and support of Anadarko Production Company and Phillips Petroleum Company for allowing publication of this paper and releasing previously unpublished data for our use. We are also indebted to Erik Layman, Chevron Resources Company, and Robert W. Butler, Chevron USA, for assisting us with data collection and contributing the section on Soda Lake.

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