Surface Indicators of Geothermal Activity at Salt Wells, Nevada, USA, Including Warm Ground, Borate Deposits, and Siliceous Alteration

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Blind systems, borates, sinter, Salt Wells, Eight Mile, exploration, playas, shallow temperature, warm

ABSTRACT

Surface indicators of geothermal activity are often present above blind or concealed geothermal systems in the Great Basin, but their expressions are sometimes subtle. When mapped in detail, these indicators yield valuable information on the location, structural controls, and potential subsurface reservoir temperatures of geothermal fluids. An example is provided by the Salt Wells geothermal system in Churchill County, Nevada, USA, where surface features define a 9-km-long area that matches the drill-defined extent of a large subsurface thermal anomaly. At higher elevations above the water table, these features include opalized sediments, siliceous sinter, and argillic alteration, and at lower elevations where water tables reach the surface in the playa environment, they include warm (geothermally heated) ground, ephemeral hot and warm springs/seeps, actively forming zones of opal and calcium carbonate-cemented sediments, and borate evaporite crusts. These features often mark the surface traces of active hydrothermal conduits (faults).

Where the water table is shallow at Salt Wells, warm ground can be mapped by measuring temperatures at a depth of 30 cm. This is best accomplished in the winter when background temperatures are low. Similarly, the sampling of ephemeral hot springs and seeps at Salt Wells is most easily accomplished during the wetter, cooler conditions of winter, because the springs dry up during the summer.

Large areas of playa at Salt Wells are fed by geothermal groundwater. By identifying individual upwelling zones, it is possible to obtain samples of relatively pristine geothermal fluids close to the surface that yield geothermometer estimates of reservoir temperatures similar to those from nearby geothermal wells. Because of a lack of associated springs and seeps, similar geothermal playas could easily exist elsewhere in the Great Basin and escape notice. Such playas might be identified in some cases by a distinctive salt crust composition that includes higher-than-normal concentrations of borate minerals.

Introduction

When examined closely, many blind geothermal systems of the Great Basin reveal surface clues of subsurface geothermal activity. Examples include opalized sediments at Desert Peak, (Benoit et al., 1982); sinter and silicified sediments at Humboldt House (Waibel, 2003); hydrothermal eruption craters at North Valley (Stewart and Roddy, 2002) and Rye Patch, Nevada; and advanced argillic alteration at Blue Mountain (Parr and Percival, 1991) and Empire, Nevada (Garside and Shilling, 1979). The existence of these surface indicators was not sufficiently known in many cases to attract the initial exploration interest that led to geothermal discovery in these areas. Instead, it was regional temperature gradient drilling; water well drilling, and oil and mineral exploration that first led to discoveries. Nevertheless, the distribution and trends of surface features provide valuable clues to the nature and structural controls of geothermal reservoirs at depth.

The Salt Wells geothermal system in Churchill County, Nevada has often been described as a blind geothermal system (e.g. Klein et al., 2004). It has a large, 12-km-long heat flow anomaly (Edmiston and Benoit, 1984), but it turns out that much it is overlain by surface geothermal indicators of various types. The diversity and extent of those indicators had not been recognized previously, and mapping methods were modified here in order to map them efficiently. Salt Wells provides an example of how such surface features can provide information on the structural controls of geothermal fluid flow. In addition, detailed mapping can lead to the identification of ephemeral hot springs and zones of hot groundwater upwelling in playas, which can be sampled to obtain estimates of geothermal reservoir temperatures. Techniques developed regarding how and when to best map these features can potentially be applied to other blind geothermal targets in the Great Basin.

Field Methods

An iPAQ pocket computer equipped with a global positioning system (GPS) was used for surface mapping; the equipment and procedures are described by Coolbaugh et al. (2004). The primary advantages of the iPAQ and GPS are the speed with which features can be digitally recorded for direct computer downloading, and the fact that the GPS unit allows accurate mapping of such features in non-distinctive terrain that makes accurate mapping with conventional methods difficult. Additional equipment used for mapping specific geothermal features is described below.

Measurement of Shallow Temperature Anomalies

Shallow temperature measurements have proven effective in identifying thermal anomalies at many geothermal areas (Olmsted, 1977; LeSchack and Lewis, 1983; Trexler et al., 1982). Those surveys typically involve placing thermocouples at the bottom of 1 to 2-meter-deep auger holes, refilling them, and measuring the temperatures at a later time when re-equilibration has occurred. The tendency of thermal groundwater to migrate to the top of the water table suggested a modified approach at the Salt Wells playa where the water table is at or very near the surface, and it was decided to measure temperatures at the relatively shallow depth of 30 cm (12 in). This was accomplished by inserting a 30-cm (12-inch)-long, 1/8-inch-diameter thermocouple probe directly into the ground by hand. The small thermal mass of the device, in combination with water-saturated sediments, allowed temperature equilibration to occur within a minute or two, making it possible to record hundreds of measurements per day. Several thousand such measurements were made for this study, of which just over 1,000 were digitally mapped. This made it possible to greatly increase the spatial resolution of temperature measurements and better document the structural control of temperature anomalies.

A digital K-type thermocouple meter and probe was used for fieldwork. Instrument precision was affected primarily by ambient temperature fluctuations and was approximately +/-1 to 2°C. The vast majority of the temperature measurements were obtained in February 2005 when background temperatures at a 30-cm-depth were near a seasonal minimum. Background temperatures during the survey varied from 3 to 10°C, depending on location, compared with summer background temperatures that exceed 30°C at the same depth. The large majority of the survey was completed during a prolonged period of cloudy, wet weather. Several reference stations were revisited multiple times during the survey to monitor for possible progressive changes in subsurface temperatures and assess the effects of minor rain events. In all cases, ground temperatures in background and anomalous areas were remarkably stable (+/- 2°C).

A continuous 24-hour temperature test was made on-site in February 2006, using a 3-wire Pt-RTD (platinum resistance temperature device) with a precision of ~ 0.1°C. The 24-hour test demonstrated that temperatures at a 30 cm depth were essentially constant during the day (+/- 0.1°C) although temperatures did rise overnight by almost one degree in response to unseasonably warm, sunny weather the previous day.

Variations in near-surface temperatures can be caused by a number of non-geothermal factors, including changes in air temperature (as it affects instrument temperature compensation), soil moisture, near-surface groundwater flow, surface albedo, topographic slope orientation, and thermal inertia. The effects of all of these variables were qualitatively monitored during the survey. The threshold used to distinguish anomalies from background temperatures, 12°C, was higher than the range in background temperatures observed. A total of 286 readings were above the 12°C threshold, and 133 were ≥20°C. Thirty-two (32) measurements were ≥38°C (100°F), and the highest temperature measured at a 30 cm depth was 67.2°C (153°F). Interestingly, most areas of hot or warm ground did not occur in the immediate vicinity of hot springs or seeps. The relatively continuous nature of hot/warm ground yielded much valuable structural information compared to the more sporadically occurring springs and seeps.

Water Sampling Methods

Six hot springs/seeps and groundwaters were sampled and analyzed for major and trace elements at laboratories of the Nevada Bureau of Mines and Geology (NBMG), University of Nevada (UNR). Because of low flow rates at springs (samples SW1, 2, 3 and 5), a small amount of shovel work was used to promote open flow so that non-stagnant water could be sampled (Figure 1). At one dried-up hot seep (SW-4), water

Figure 1a. A portion of the southernmost hot spring at Salt Wells. A minor amount of shovel worked helped expose a clearly defined outflow zone of hot water at 54.4°C, which yielded a quartz (no steam loss, Fournier, 1977, 1981) geothermometer temperature of 183°C (Table 1, sample SW-3).

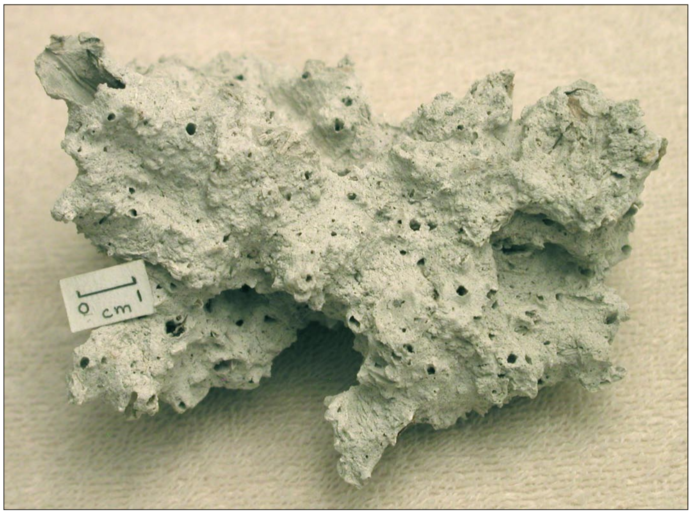

Figure 1b. Silicified root casts obtained from 60 cm below surface at location in Figure 1a.

was obtained from a 40-cm-deep shovel hole that hit the water table at 20 cm and rapidly filled with hot water (46°C); a zone of fluid entry into the hole was visible in the turbid water and was sampled. Playa groundwater at the north end of the Salt Wells geothermal system (SW-6) was obtained from a 1.5 meter-deep-hole that was held open with plastic pipe and left standing for 2 hours. The hole was designed to intercept water from an upflow zone of hot groundwater that was initially recognized by an anomalous lack of evaporite crust at the surface and by a temperature of 67°C at a 30 cm depth. The temperature increased to 85°C at 1.5 meters.

GBCGE sample collection procedures, adapted from Arnorsson (2000), were used in collection of all samples. Samples were analyzed by standard induced coupled plasma (ICP) mass spectroscopy and emission and atomic absorption methods for cations, and ICP emission for anions.

Borate Crust Detection

The borate minerals tincalconite and borax were identified in the field with an Analytical Spectral Devices, Inc. Fieldspec® spectroradiometer, which also identified the sodium sulfate minerals mirabilite and thenardite, and common salt (NaCl). X-Ray diffraction was used to confirm the identity of a few samples. Kratt et al. (2006) provide more information on the use of field spectroradiometers and satellite imagery for detecting borate deposits associated with geothermal activity, including at Salt Wells.

Surface Geothermal Indicators

Surface indicators of geothermal activity at Salt Wells include silicified sediments and sinter, warm ground, ephemeral hot and warm springs/seeps, borate deposits, Quaternary faults, and advanced argillic alteration. The presence of warm ground and almost all of the ephemeral springs and seeps were previously unknown at Salt Wells, and the relationship of borate deposits with geothermal activity had not been documented. These features are briefly described below.

Silicified Sediments, Siliceous Sinter, and Argillic Alteration

The presence of sinter and silicification has long been recognized as an indicator of a current or fossil geothermal system. At Salt Wells, silicification was first noted by Morrison (1964) during his survey of Lake Lahontan, but he did not map it in detail nor did he describe the full extent of such alteration. Silicified rocks at Salt Wells include volcanic rocks, colluvium, sands, root casts and mud; also present are siliceous sinter and silicified algal casts on cobbles. These siliceous rocks have been described and mapped in detail by Coolbaugh et al. (2004). Almost all outcrops of silicified rocks occur above the playa where they have been exposed by erosion. Evidence that silicification of rocks and soils by thermal waters is continuing today in the subsurface is apparent by the presence of silicified mud, silicified root casts, and siliceous sinter associated with several of the higher temperature active thermal features in the playa (Figure 1b). In some places, calcium carbonate-cemented soil also occurs beneath areas of warm ground and hot springs and seeps.

Advanced argillic alteration occurs near the south end of a long, thermally active structure, at a point where the surface trace of the fault first climbs the lower slopes of the Bunejug Mountains (point "A", Figure 2). This alteration might have

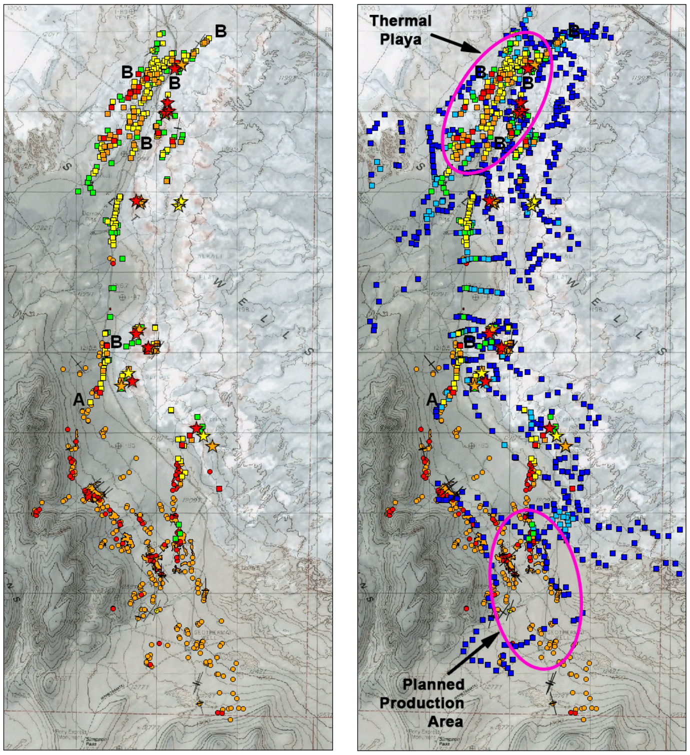

Figure 2. Map of surface geothermal indicators at Salt Wells without (a) and with (b) background temperatures. Red and orange circles and polygons = siliceous rocks; Squares = warm ground, dark blue <10°C, light blue 10-12°C, green 12-15°C, yellow 15-25°C, orange 25-37°C, red ≥37°C; Stars = springs and seeps, yellow 20-25°C, orange 25-37°C, red ≥37°C. A = area of advanced argillic alteration, B = borate deposits. Black strike symbols indicate strike of siliceous and/or carbonate veins or fault scarps. Background squares = 1 km. North is up.

formed from steam condensate derived from boiling fluids flowing along the fault. No shallow temperature anomalies were detected however, suggesting that fumarolic activity, if formerly present, is no longer active.

Table 1. Chemical analyses for springs, groundwaters, and thermal waters from geothermal wells, Salt Wells, Nevada. Samples are arranged in the table in order of north to south. Samples SW-1-6 were analyzed at Nevada Bureau of Mines and Geology as part of this study. "Geo well" analyses are from Anadarko geothermal wells and are provided courtesy of Amp Resources, LLC. References for geothermometer equations are: quartz (no steam loss) and chalcedony (Fournier, 1977; Fournier, 1981); and Na-K-Ca-Mg (Fournier and Truesdell, 1973; Fournier and Potter, 1979). Ave Temp = average of quartz and Na-K-Ca-Mg geothermometers.

Sample		SW-2	SW-6	SW-1	SW-5	SW-4	SW-3	14-25	14-36 7	14-36 10
Area		north end	north end	north end	central	south end	south end	south end	south end	south end
Description		seep	playa grwtr	seep	Borax Spr	grwtr	spring	geo well	geo well	geo well
UTM_Nad 27	East	364,220	363,667	364,134	363,738	363,891	364,489	364,448	364,404	364,404
UTM_Nad 27	North	4,357,548	4,357,234	4,357,128	4,355,906	4,354,070	4,353,068	4,351,951	4,350,328	4,350,328
Temp	°C	66.4	75.6	54.2	81.6	46.0	54.4	hot	hot	hot
HCO3-	mg/L	201	183	222	178	221	204	206		
B	mg/L	10.4	13.2	9.8	9.0	14.2	13.5	8.1		
F-	mg/L	5.3	5.8	6.0	5.9	6.0	5.9	8.5		
Cl-	mg/L	1090	1250	1210	1170	1460	1400	1300		
NO3-2	mg/L	0	0	0	0	0	0	0.2		
SO4-2	mg/L	243	260	249	243	329	286	300		
Ca	mg/L	41.3	36.8	47.3	33.6	46.9	34.7	18.0	32.5	23.2
Fe	mg/L	0.107	0.003	0.200	0.117	0.026	0.204	0.800		
K	mg/L	68.7	83.0	75.0	78.9	102.0	85.3	67.0	66.4	75.7
Li	mg/L	1.80	2.00	1.79	1.84	2.29	2.00	2.00	2.38	2.27
Mg	mg/L	2.3	1.7	3.9	1.3	2.7	2.6	2.1	1.6	0.2
Mn	mg/L	0.167	0.127	0.081	0.098	0.529	0.147	< 0.100		
Na	mg/L	841	931	914	866	1080	1030	1000	954	921
SiO2	mg/L	236	293	165	201	200	209	260	196	319
Charge	Sum Cat	40.85	44.88	44.61	41.74	52.48	49.22	46.57		
Charge	Sum An	39.40	43.98	43.28	41.31	51.98	49.11	46.76		
Charge	Balance	1.04	1.02	1.03	1.01	1.01	1.00	1.00		
Geothermom	Quartz	191.4	207.6	167.3	180.3	180.1	183.1	198.6	178.6	214.2
Geothermom	Chalced	172.1	191.2	144.4	159.2	159.0	162.5	180.5	157.3	198.9
Geothermom	T_NaKCaMg	174.9	190.3	161.6	194.9	186.3	176.8	165.7	177.9	193.3
Geothermom	T_SiO2	191.4	207.6	167.3	180.3	180.1	183.1	198.6	178.6	214.2
Qtz-NaKCaMg	Ave_Temp	183.1	198.9	164.5	187.6	183.2	180.0	182.1	178.2	203.7

Warm Ground

Warm ground at Salt Wells, as defined by shallow (30 cm) temperature anomalies, is largely but not entirely restricted to water-saturated playas. There are a wide and seemingly contradictory variety of surface clues that the ground might be warm. They include thicker than normal vegetation, such as salt grass and reeds, an anomalous lack of vegetation, anomalous winter growth of vegetation, the presence of shallow depressions, the presence of small rises or hills, small fault scarps, relatively thick evaporite crusts, or, frequently, an anomalous lack of such crusts. The only reliable way of identifying warm ground is by measuring its temperature below the surface.

One of the more distinctive and common clues to warm ground is the presence of 1 to 6-meter-diameter, smooth patches of slightly depressed playa mud, with little or no evaporite crusts, surrounded by playa with thicker, more uneven evaporite crusts (Figure 3). These smooth patches are sometimes much warmer than surrounding playa, and a sample of hot groundwater from beneath one of them was found to be virtually identical to geothermal waters sampled elsewhere at Salt Wells.

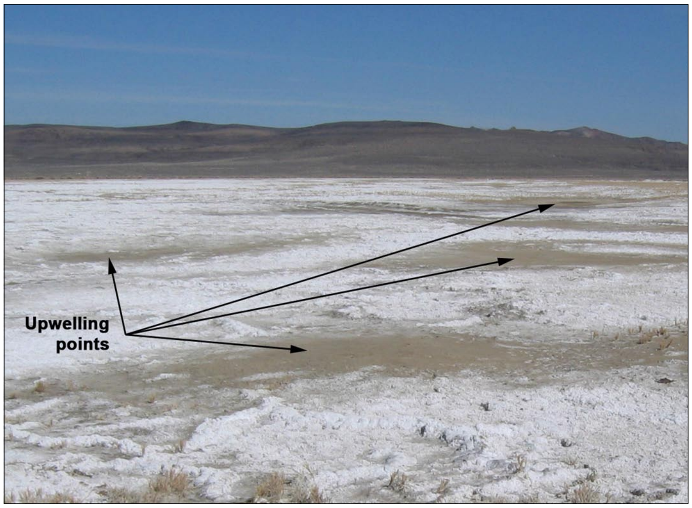

Figure 3. A playa fed by geothermal waters on the north end of the Salt Wells geothermal system. Upwelling columns of thermal water can be identified at the surface by a lack of evaporite mineral crusts immediately above the individual upwelling points. No thermal springs or seeps are present on this 65 hectare (160 acre) playa.

The interpretation of geothermometer results on playa groundwater depends on an understanding of how these warm spots form. They are believed to represent zones of buoyant upwelling thermal fluids that are significantly undersaturated in salt minerals (Table 1, sample SW-6). Because of their temperature and low salt content, these initial fluids are less dense and more buoyant than surrounding groundwater, and they rapidly work their way to the playa surface. Because of their initial undersaturation, these waters are capable of re-dissolving any pre-existing salt minerals as they make their first approach to the surface. Salt crusts do not initially form at the surface and springs do not form either, but instead the fluids spread laterally away from the initial upwelling point to make room for more upwelling fluid. Eventually, as this groundwater continues to flow laterally away from the upwelling point, continued evaporation results in saturation in one or more evaporite minerals, and surface mineral crusts begin to form. This upflow model explains why relatively pristine groundwater can be obtained from the near-surface central portion of the initial upwelling zones.

One playa of 65-hectare (160 acre) size on the north end of the Salt Wells geothermal system consists almost entirely of warm ground and is fed by thermal groundwater, but no thermal springs are present (Figure 2, 3). Much of this playa has been mined for its borate minerals.

Ephemeral Hot Springs, Warm Springs, and Seeps

Twenty (20) hot and warm springs and seeps were found in eight main groups (Figure 2) over a distance of 5 km. The nine hottest springs and seeps had temperatures ranging from 39.1°C to 81.6°C, averaging 55.7°C. At the time of the temperature survey in February 2005, the playa had received significant amounts of recent rain and snow, and many cold springs were present with temperatures tightly clustered around 5-7°C. The highest temperature spring (Figure 4) appears to correspond both in location and temperature to Borax Spring, first mentioned by Russell (1885), but more recently not locatable by Trexler et al. (1981), or by the present authors in the summer of 2002. A likely explanation for the on-again, off-again observations is the fact that all of the Salt Wells springs and seeps are ephemeral. They all dried up during the summer of 2005 (although shallow temperature anomalies remained), and most of them reappeared again during the winter of 2006. Their ephemeral nature is believed due to a higher water table in the winter when precipitation rates are higher, and when evaporation and evapotransporation from vegetation are lower compared to summer. Even though flow rates from the springs and seeps are generally less than 1 liter/minute, they yield chemistries and geothermometer estimates of reservoir temperatures similar to those from geothermal well samples at Salt Wells (Table 1).

Figure 4. Borax Hot Spring, February, 2005 (81.6°C).

Borates

Salt Wells was one of the first places in Nevada mined for borate minerals (Papke, 1976). An estimated 23 tons (Garrett, 1998) were produced during the 1870s from approximately 400 acres of ulexite (Garrett, 1998) and borax-bearing playa. With the help of a spectroradiometer, the three main borax works (Figure 5) and most of the 400 acres of borate playa described in the literature have been relocated (Figure 2). The borate occurrences at Salt Wells occur along or adjacent to thermally active structures, and there seems little doubt that upwelling geothermal fluids are the carriers of boron, even though those fluids contain only 9-14 ppm B (Table 1). Salt Wells is one of a number of active geothermal systems in the Great Basin with subjacent borate deposits (Coolbaugh et al., 2006), and a strong correlation between Quaternary borate deposits and geothermal activity exists in the Great Basin. Coolbaugh et al. (2006) discuss this relationship in greater detail, and Kratt et al. (2006) describe methods of detecting borate deposits using ASTER satellite imagery.

Although the distribution of playa evaporate minerals has not been mapped in detail, a rough zoning is apparent in the greater Salt Wells basin that includes Eight Mile Flat on the northwest and Four Mile Flat on the southeast. All borax production has come from the higher elevation, extreme northwestern margin of the basin in the immediate vicinity of thermal springs and groundwaters. Sulfate evaporates, including mirabilite, are more widespread in occurrence, while sodium chloride is most concentrated at the lower elevation southeast end of the basin at Four Mile Flat. This crude evaporite-mineral zonation serves as a geothermal exploration vector of sorts, with borates occurring proximal to evaporating thermal springs and seeps. The precipitation and fixation of borates proximal to springs may be facilitated at Salt Wells by the presence of calcium, which allows the less-soluble ulexite to form, and by a rapid decrease in temperature, which facilitates precipitation of borax, whose solubility in water is strongly temperature dependent. In contrast, the high solubility of sodium chloride in cold water makes it susceptible to re-dissolution during rain-

Figure 5. a) Hummocky ground at the southernmost of three borax mining and processing operations. Temperatures at this locality are as high as 73°C one meter below surface. b) Specimen of fairly pure surface borate crust from locality a) above (see arrow), turned upside down, revealing fibers of borax underneath fine-grained tincalconite. Tincalconite forms at the surface from the dehydration of borax.

storms, with subsequent transportation by ephemeral streams to the lowest-elevation portion of the playa.

Quaternary Fault Scarps

A number of Quaternary fault scarps cut the playa sediments and have recently been mapped by Faulds et al. (2005). Fault offsets are on the order of 30 cm to several meters, and small sinkholes have developed in places. Many linear and curvilinear structures are evident on aerial photographs and satellite imagery, and some of these coincide with areas of warm ground. Ongoing work in the area by UNR is aimed at defining possible controls imposed by this fault system on the geothermal system.

Results and Discussion

A series of northwest and north to northeast-striking structures or faults are delineated by surface geothermal features (Figure 2). Some of these structures show evidence of Quaternary movement. In general, these structures are marked by outcrops of silicified sediments at higher elevations above the water table towards the south, and by warm ground and hot springs at lower elevations near or at the water table to the north. The fact that two long north to north-northeast striking structures can be traced northward semi-continuously from areas of siliceous alteration into areas of warm ground provides confirmation that the siliceous outcrops are defining structures that still control geothermal fluid flow.

Amp Resources, LLC (recently acquired by Raser Technologies, Inc.) is planning to build a geothermal power plant near the south end of siliceous outcrops (Figure 2) where water temperatures in geothermal exploration wells drilled by Anadarko in the 1970s and 1980s were highest. Natural leakage of thermal groundwater from this area flowing northward in bedrock, but following a hydrologic gradient sub-parallel to topographic slope, could be feeding hot springs and heating warm ground further to the north. The presence of semi-continuous thermal activity along a 6-km-long, north to northeast-striking structure in the central and northern portions of the Salt Wells area (Figure 2) suggests that such northward flowing geothermal fluids could conceivably be responsible for the hot springs, thermal anomalies, and borate deposits found on the extreme northern end of the Salt Wells system. Alternatively, geothermal fluids might be ascending from depth intermittently all along the main north to northeast-striking structure.

In any case, the northernmost cluster of warm ground and hot springs has an unusually broad 2-km-long and 1-km-wide surface expression, and most of the thermal features in this area appear to follow a series of acutely intersecting northeast and north-northeast striking structures. The northern thermal area may very well represent near-surface outflow from a geothermal reservoir that is physically separate from the geothermal area(s) further to the south.

Subtle differences in the chemistry of thermal waters from the southern and northern areas (Table 1) hint at possible differences in reservoir characteristics or flow paths, but the differences are not considered sufficiently significant to be definitive without further sampling. Geothermometer temperatures calculated from springs and groundwater from the northern area are very similar to those from the southern springs and wells, averaging near 180°C.

Conclusions

Some geothermal systems that have been considered blind or concealed at the surface reveal a variety of surface indicators of geothermal activity when more closely scrutinized. Those indicators, which at Salt Wells include silicified sediments, sinter, warm ground, ephemeral springs and seeps, borate evaporates, Quaternary fault scarps, and advance argillic alteration, provide clues to the location, structural controls, and temperatures of the underlying geothermal reservoir. Of course, these geothermal indicators must be interpreted cautiously because geothermal waters sometimes travel a significant lateral distance from their deeper reservoirs before reaching the surface.

Where the water table is shallow at Salt Wells, warm ground can be mapped by measuring temperatures at a depth of 30 cm. This is best accomplished in the winter when background temperatures are low. Similarly, the sampling of ephemeral hot springs and seeps at Salt Wells is only accomplished during the wetter, cooler conditions of winter, because the springs dry up during the summer.

Large areas of playa at Salt Wells are fed by geothermal groundwater. Individual upwellings of thermal water can be identified from patterns of surface evaporate dissolution and precipitation (Figure 3; these patterns are not resolvable at the scale of Figure 2). With the help of a temperature probe, upwelling zones can be pinpointed and relatively pristine geothermal fluids can be obtained that yield geothermometer estimates of reservoir temperatures similar to those from nearby geothermal wells (e.g., 180°C).

Playas fed by geothermal waters could easily exist elsewhere in the Great Basin and escape notice when hot springs are not present. As documented for Salt Wells, such playas might be identified by a distinctive salt crust composition that includes higher-than-normal concentrations of borate minerals. Remote sensing and field spectral measurements have the capability of identifying some of these mineral compositions (Kratt et al., 2006). Shallow temperature probing in playas may also help locate additional blind geothermal systems.

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