

National Geothermal Data System Geochemical Data for Exploration

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ABSTRACT

The Nevada Bureau of Mines and Geology has been compiling data on geochemistry of geothermal resources in Nevada since 2002, and as part of the National Geothermal Data System (NGDS), the Bureau is checking data reliability, collecting data to fill gaps, and evaluating the data for use in exploration and better understanding of known geothermal systems. A key use of these data is the calculation of chemical geothermometers, which has long been a standard in early-stage exploration methods. This work shows that these calculations can provide useful insight into the presence of high temperature systems even when sampled water discharges at the surface are not thermally anomalous, or are minimally anomalous. All data and calculations are being cataloged for inclusion into the NGDS and for existing map services at the Nevada Bureau of Mines and Geology. These data and functions will be fully operational and publicly available by the time of this publication.

Introduction

The geothermal potential of Nevada thermal areas has long been known, and geochemical analyses have been obtained from water samples in many areas, attracting interest from potential developers. Thus, considerable hydrologic and geochemical data are available for numerous sites (data links noted below). There are numerous sites throughout the state that have the potential for utilization of geothermal resources, but have insufficient geochemical information publicly available to evaluate them. Various efforts over the last several years have begun to address these data deficiencies, and the progress made will be presented here.

As part of the National Geothermal Data System, and as part of the original mission of the Great Basin Center for Geothermal Energy (GBCGE, from 2000 to 2010), various datasets have been

compiled and evaluated and have been and are being posted on searchable catalogs via web services available to the public: see <http://www.geothermaldata.org/> and <http://www.stategeothermal-data.org/>. (Because the GBCGE changed its mission in 2010 to omit data serving and the public and industry outreach aspects of the Center and focus on academics, the Nevada Bureau of Mines and Geology assumed the data and outreach responsibilities under the continued leadership of the first author.)

One dataset that has been compiled by NBMG is the Great Basin Groundwater Geochemical database (GBGDB) at (<http://www.nbmgs.unr.edu/Geothermal/GeochemDatabase.html>), which contains approximately 50,000 records for thermal and non-thermal waters in the Great Basin. Data sources include data from GEOTHERM, WATSTORE-NWIS, internal Nevada Bureau of Mines and Geology datasets collected as part of GBCGE work funded prior to 2010 and numerous published sources that were entered into digital format. The purpose of this paper is to review progress made in the evaluation of this data set, note some of its limitations, and highlight some recent uses of the data. Initial descriptions and interpretations of these data were provided by Coolbaugh et al. (2003); Shevenell and Garside (2003); and Zehner et al. (2006).

Background

When this work was initiated in 2002, it was known that numerous thermal springs in Nevada had no corresponding geochemical data. From ≈ 2700 digitized springs from 7.5' quadrangles, there were 1030 thermal springs with no chemical analyses and/or temperature (Figure 1). Additional sites were identified through field work by various researchers at the GBCGE through early 2010. Figure 1 illustrates the location of power plants, direct use applications, and wells and springs (as of 2002) in the database in existence at that time noting locations of good data, and those lacking sufficient information to evaluate the sites for geothermal potential. The data used to construct this map were compiled into an Excel spreadsheet, obtained from several sources: Trexler et al. (1983), GEOTHERM, WATSTORE, Southern Methodist University (SMU) web site, GeoHeat Center

(2002), Garside (1994), Mariner (2004 - paper copies of lab analyses from the 1970s entered into spreadsheets), and Shevenell et al. (2000). As of 2003, the database contained approximately 20,000 records. Many of these sites had generally-complete major and trace element analyses, yet few had any stable isotope information, or chemical data from nearby cold waters from which mixing between deep-seated, high temperature thermal and shallower non-thermal waters could be evaluated. From the map (Figure 1) and the work of Garside (1994), 208 springs and 109 wells had sufficient chemical analyses to evaluate (preliminarily) an area's geothermal potential. Conversely, from the data in Figure 1, there were 88 areas (most with multiple springs, which accounts for the 1,030 sites noted in the Introduction as having no analyses') with no reliable chemical analyses. As in Figure 1, a large number of individual known springs and wells statewide that lacked even basic information (i.e., temperature or fluid geochemistry) for evaluating geothermal potential. Hence, a sampling campaign was undertaken in the summer of 2002 along with data compilation to improve the availability of basic geothermal exploration data for Nevada, specifically, the geochemistry of thermal and non-thermal waters.

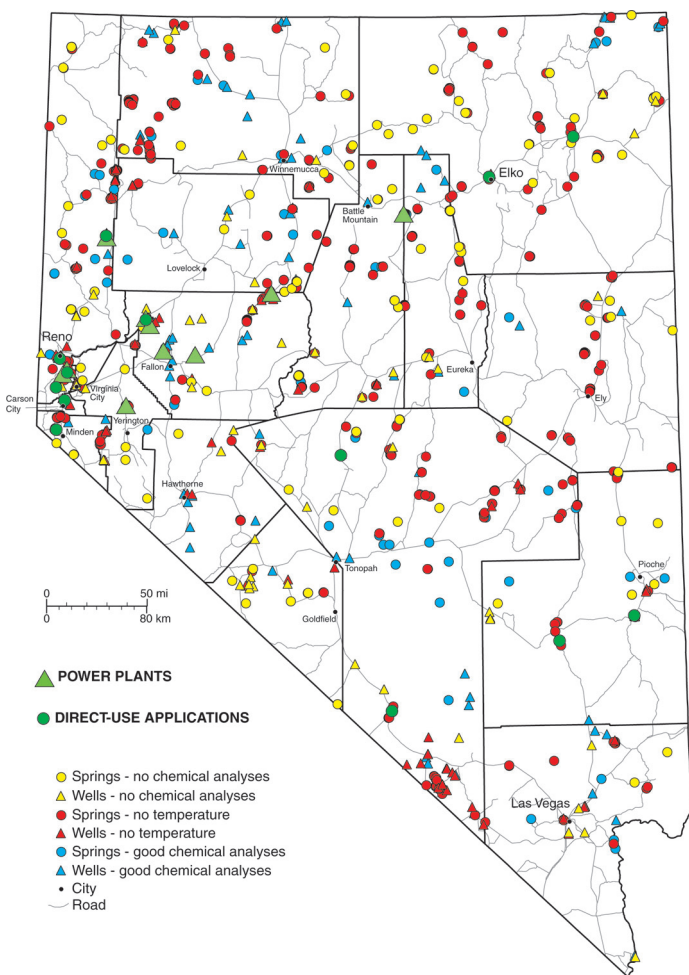


Figure 1. Location of thermal wells, springs, geothermal power plants, and direct-use applications in Nevada. Red and yellow sites have insufficient data from which to evaluate geothermal potential as of 2002. Figure is after Shevenell and Garside (2003).

Additionally, many of the sites that did have available water chemistry data either had poor data or poor locations, both of which required reanalysis or checking by various methods. Because many locations were poor, it was unclear which spring could be attributed to which sample in many cases, or if a spring were sampled multiple times or nearby springs were sampled on different dates. Also, there were many duplicates in the combined dataset yet it often was not clear if the analyses were identical (many were, except for a few chemical constituents) or if the sample were from another location or date. Hence, considerable effort was required to increase the reliability of the data set in addressing these issues.

An example of one type of location error is illustrated in Figure 2, where it is clearly impossible to determine which of the springs in the area was sampled and represented by the historical data. This figure shows the locations of (1) the background USGS topographic map showing multiple spring locations, (2) the Robert Mariner (labeled Mariner) good chemical analyses from the 1970s, but located in the wrong section, (3) temperature measurement sites (cluster of green dots) based on a site visit in 2003, and (4) samples collected from springs during the 2002-2009 sampling campaign (BV samples), all projected to the same datum. Neither locations nor total numbers of springs match among the data sets. Clearly, it was not possible to correlate one set of data with another based on location, and hence temporal evaluations of individual springs cannot be made in many cases, except at sites with the measured GPS coordinates obtained for categories (3) and (4) from site visits conducted during the work presented here. Exact correlations to the 1970s Mariner data are not possible.

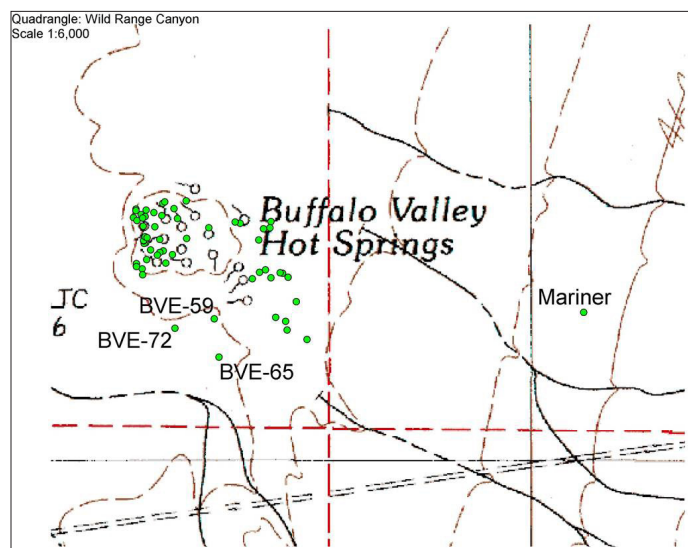


Figure 2. Location map of Buffalo valley showing the location of springs on the USGS 7.5' quadrangle and locations based on site visits. See text for discussion.

Methods

Given the known data gaps and location errors noted above, a sampling program was initiated in late 2002, which continued through 2009, at selected sites throughout Nevada (see Shevenell and Garside, 2003 site selection and preliminary results). Samples

were filtered through 0.45 μm papers with cations acidified to $\text{pH}=2$ with reagent grade HNO_3 . SiO_2 samples were diluted in the field (1:10) and flow rates of the discharging springs were estimated where possible. Conductivity and pH were measured in the field and collected waters were analyzed at the Nevada Bureau of Mines and Geology Geochemical laboratory. Selected sites were sampled for noble gases (not reported here), but no additional gas samples were collected given that most springs in Nevada do not issue visible gases. The Great Basin Groundwater Geochemical Database was then expanded with results of these 322 new water sample analyses, and with added water quality data from the USGS NWIS digital water chemistry database (National Water Information System), which increased the database to approximately 45,000 records.

Temperature and chemical analyses were compiled from a variety of sources (including the ones noted) over a ten year period, with additions and corrections to the existing analysis on-going until the present. Locations were corrected with field visits and GPS measurements, and comparison with aerial photography and digital topographic maps. Figures 3 and 4 show typical springs sampled and located as part of the 1,060 site visits made during

this time. Many site locations were corrected using USGS 7.5' quadrangle maps and the National Geographic software TOPO in areas with more distinct spring and well locations than noted in the example in Figure 2. Other locations were calculated from cadastral data in a permitted wells file maintained at the Nevada Bureau of Mines and Geology, accurate to the quarter-quarter section.

Results

Improvement of Data Availability

Results of the additional NWIS data compilation and field visits are illustrated in Figure 5, which shows a subset of the samples from the database with temperatures $>20^\circ\text{C}$, which is the temperature cut-off above which fluids are designated as thermal. Although 1,060 springs and wells were visited and data entered into the GBGDB, this map shows many thermal springs and wells still with poor or very poor water charge balances, or incomplete analyses that cannot be reliably used to estimate subsurface temperatures using traditional chemical (silica or cation)

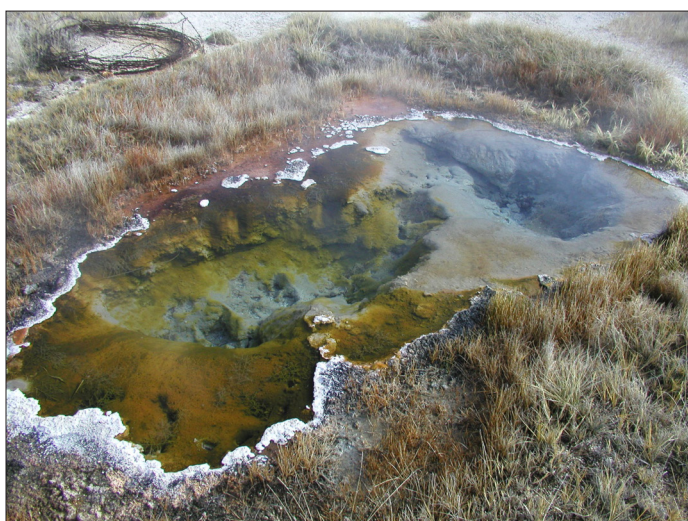


Figure 3. Photo of a typical spring sampled in Nevada (Sulphur Hot Springs, Ruby Mountains) during the 2002-2009 field sampling campaign (Photo by Mark Coolbaugh).



Figure 4. Photo of a typical spring sampled in Nevada (Buffalo Valley Hot Springs) during the 2002-2009 field sampling campaign.

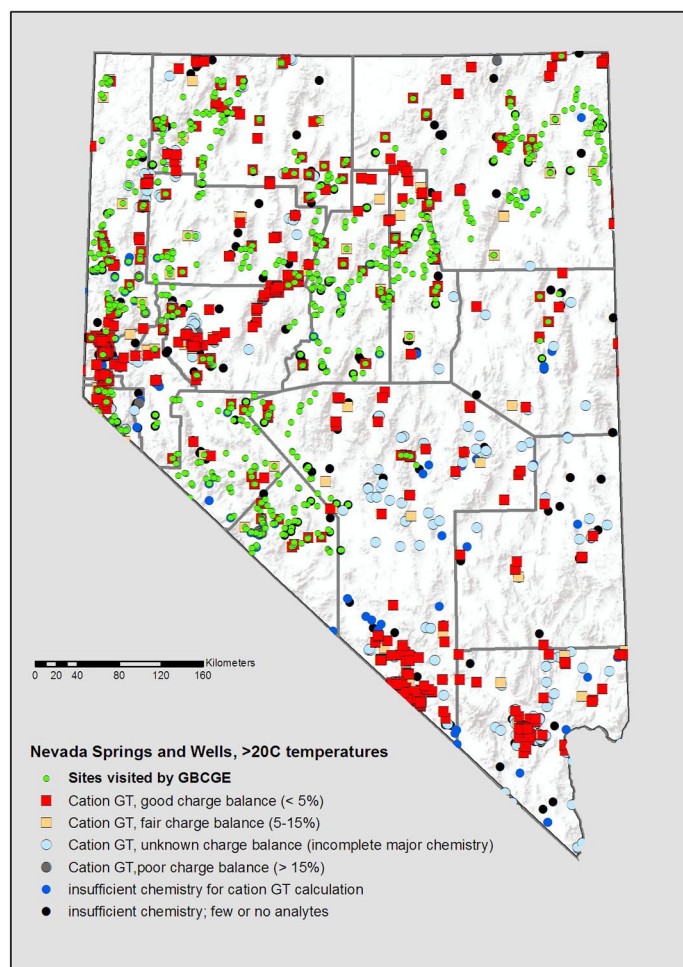


Figure 5. Map of Nevada showing locations of field visits (green dots) during which 322 water samples were collected (mostly with charge balances $<5\%$), and 1060 temperature measurements were obtained. The other symbols indicate the degree to which the remaining sites in the database have good to very poor charge balances.

geothermometers. Geothermometers with poor charge balances were nonetheless calculated and placed into the database, but their values are in question. However, no analysis was undertaken to

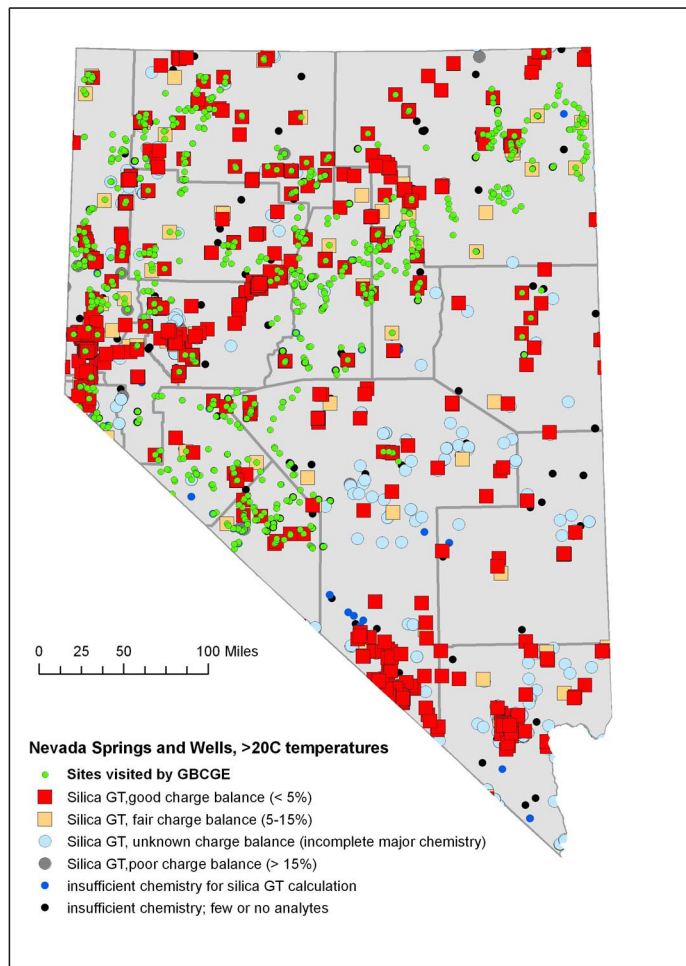


Figure 6. Locations of known geothermal areas based on data in the Great Basin Groundwater Database (GBGDB) showing deficiencies in the data for Nevada and charge balances relative to the ability to calculate silica geothermometers (GT) with the reported data.

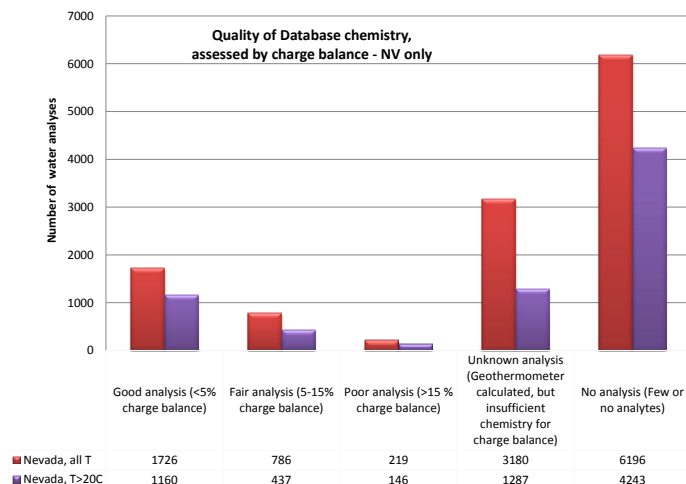


Figure 7. Plot showing data quality for water samples available in the GBGDB for Nevada thermal waters, and waters of all temperatures.

verify the degree to which a poor charge balance may translate to a poor geothermometer temperature estimate.

This map (Figure 5) shows the sites relative to calculated Na-K-Ca, Mg-corr (Fournier, 1981) geothermometers, and indicates insufficient chemistry at many of the thermal sites to conduct these calculations. As of July 2010, there were still 120 reported thermal sites (multiple springs) with poor charge balance and/or inadequate temperature data.

Similarly Figure 6, which presents available SiO₂ geothermometer calculations, reveals that many sites lack sufficient SiO₂ data for temperature estimations, but the map also shows many sites with adequate data to evaluate state-wide geothermometer estimates.

The quality of geochemical data, as measured by charge balance, is evaluated in the next series of figures. In Figure 7, two data sets are represented: (1) those with temperatures >20°C, and (2) all available data, which includes a large number of non-thermal (<20°C) wells and springs due to the inclusion of NWIS data into the database. The numbers of poorly documented entries is large in part because individual sites may have multiple entries, albeit, incomplete reported analyses. Many may only have reported locations, flow, temperature, isotope, or some other data deemed important in any specific study for which the sample was collected. The data collection objectives for samples included in NWIS vary widely, and primarily were not for the purpose of collecting complete water analyses for geothermometer calculations.

The data depicted in Figure 7, show that, in Nevada, 63% of the 2731 complete (many were incomplete) water analyses were “good” with charge balances of <5%. An additional 29% were “fair”, or between 5-15% off in charge balance, and 8% were “poor” with charge balances >15%. A similar break-down is found for water samples within the Great Basin perimeter (CA, AZ, OR, WY, UT, ID, excluding Nevada): out of 2296 complete analyses, 53% were good, 33% were fair, and 15% were poor. Thermal waters, excluding samples of <20°C, have an even more favorable rate of good/fair/poor charge balance proportions. For Nevada thermal waters, the 1743 complete analyses broke down into percentages of 67/25/8 for the good/fair/poor charge balance categories. Thermal waters in the Great Basin perimeter had good/fair/poor percentages of 55/34/11. Overall, a small fraction of complete analyses were poor in both Nevada and the Great Basin perimeter, ranging from 8-15% for all waters to 8-11% for thermal waters. It can be assumed that a similar proportion holds for “unknown” analyses, which have insufficient chemistry for charge balance calculations, and hence the large bars in Figure 7 for the unknown and no analysis categories. Data with unknown charge balance comprise roughly half of the analyzed samples, and are therefore included in a statewide survey of geothermometer data because only 8-15% of them can be expected to have poor analyses based on the results of the charge balances for the complete analyses. Many of these data are from the National Water Information System (NWIS), a USGS water data site, which frequently omits bicarbonate from the analytical suite, thus resulting in the large number (and percentage) of samples with poor charge balance. Additionally, Figure 7, and other similar ones that follow, include single analyses, and not single locations. Some specific locations may have been sampled and reported multiple times, thus increasing the total numbers depicted in Figure 7. Additionally, because

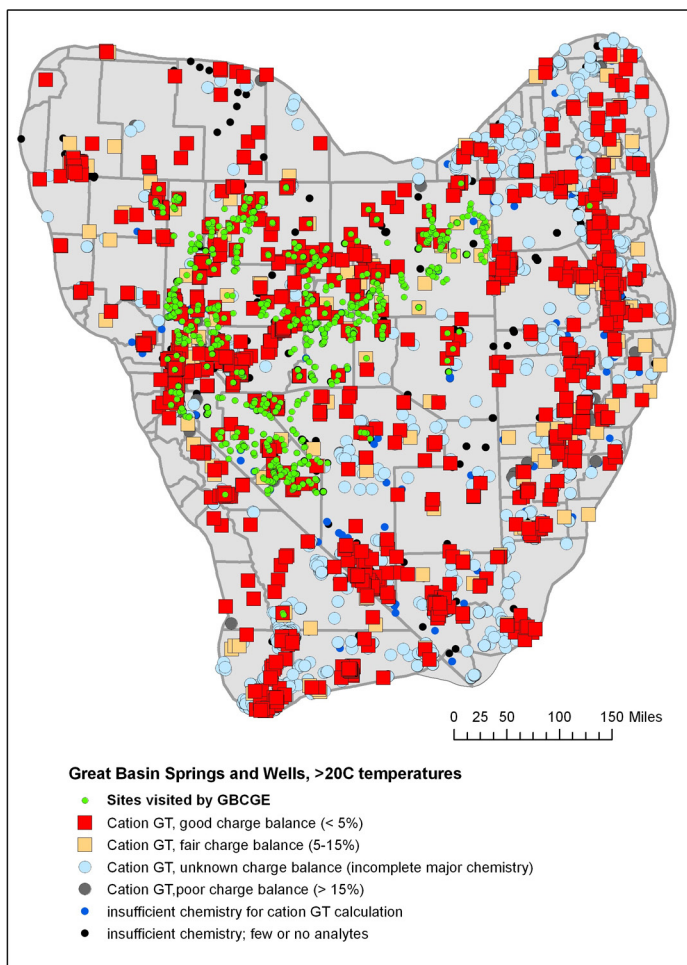


Figure 8. Map showing quality of geochemical data relative to the ability to calculate cation geothermometers throughout the Great Basin for springs and wells >20°C.

many of the “All T” sites with insufficient or few analyses are cold waters, additional, complete data from them would assist in future work evaluating geothermometer temperatures from cold springs (discussed below).

Great Basin Data Availability and Quality

The following figures illustrate the data availability as of late 2010, although only limited geochemical data gathering occurred since that time due to the completion of funded projects. Afterwards, considerable location checking was conducted as part of preparing the data for inclusion into the NGDS. Figure 8 illustrates quality of geochemical data throughout the Great Basin for springs and wells >20°C, extracted from the approximately 50,000 record database.

As can be seen from Figure 8, there are a great many known thermal sites (springs or wells >20°C) in the Great Basin, many of which have adequate chemical analyses to make basic geothermal assessments, yet a considerable number of locations (light blue, dark blue, gray and black dots) still have insufficient information to make these basic geothermal assessments.

Figure 9 shows the current state of quality of water chemistry analyses and illustrates that 89.8% of the available analyses for the Great Basin (GB) do not have sufficient chemistry to compute a charge balance or have few analytes from which to calculate reliable geothermometer temperatures. For the Nevada samples, 84.9% do not have data to calculate reliable chemical geothermometers. When considering only samples with temperatures >20°C, 9% of the GB samples have chemical analyses suitable for geothermometer calculation, whereas 13.6% of the Nevada analyses are suitable. Many sites were likely sampled for environmental considerations such as NO₃, and waters from these areas may not provide any useful geothermal information, even if they were re-sampled. Hence, although the GBGDB is quite large at nearly 50,000 records, most records (i.e., 14,636 unknown analyses and 20,242 no analyses) are not suitable for reliable geothermometer calculations, but records have many other useful data for other types of evaluations such as locations and temperatures. As noted, many of the lower temperature samples were collected for purposes other than geothermal evaluations and likely would not be useful even with complete analyses.

Figure 10 shows the quality of water chemistry analyses for temperatures >20°C. Although there are far more available records with some level of chemical analysis for the Great Basin perimeter states, Nevada has more good water quality analyses, in large part due to the sampling campaign conducted between 2002 and 2009, as wells as due to the large number of agricultural wells in Utah with which comparisons of datasets are made. There are approximately 7,300 analyses available from waters >20°C in Nevada, and 13,500 for the GB perimeter states, 22% and 9.1% that are of good quality, respectively, for use in geothermal investigations. Geothermal assessments in the future would benefit from a program to selectively sample some of these waters that do not fall into the 22% and 9.1% categories noted.

Exploration – Evaluation of Cold Waters

Geothermometers were calculated for all waters with sufficient water chemistry and are reported at <http://www.nbmng.unr.edu/Geothermal/GeochemDatabase.html>. However, in so doing, it

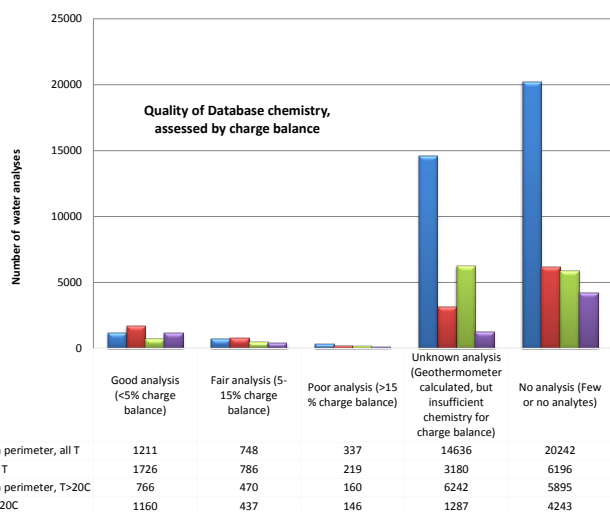


Figure 9. Bar graph showing quality of separate chemical analyses (many samples from the same source occur in some locations) for samples in Nevada and the Great Basin for water temperatures >20°C and also for all available analyses at all temperatures. These are available data as of summer 2010, with entries, although much fewer, on-going.

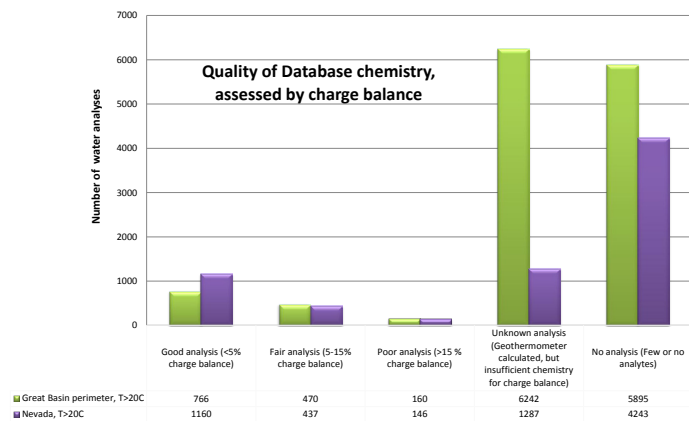


Figure 10. Quality of water analyses for samples collected at temperatures >20°C.

was found that many of the sites with temperatures <20°C also had anomalous geothermometer temperatures (Zehner et al, 2006). Zehner et al. (2006) note that some cold spring geochemistries correlate well with 150°C geothermal resources. During various exploration activities and research, several sites from cold springs or wells having elevated geothermometer temperatures were found to be the cooled portion of a geothermal system by later drilling, and these appear in Table 1.

Table 1. Examples of cold springs with elevated geothermometer temperatures in Nevada, with measured downhole temperatures from geothermal exploration wells in the area noted where available.

Spring	Temperatures (°C)		
	Measured	Geothermometer ¹	Drilled
North End Buffalo Valley	12	121	--
North Side Teels Marsh	13	155	97 ²
Rock Spring; Salt Wells	13.5	121	140
Eagle Spring; S of Desert Peak	17	142	218
Cold Spring Fish Lake Valley	18.3	149	157
Rhodes Marsh	21.6	159	--
Warm spr-Smoke Creek Desert	22.1	136	--
1 mile W/NW of Eagle Salt Works	13.3	109	--

¹ Average Na-K-Ca (Mg-corr) and Quartz (Fournier, 1981)

² See Zehner et al, 2012, this volume.

Table 1 shows areas with anomalous geothermometer temperatures calculated from cold springs, four of which are located near geothermal systems with measured downhole temperatures of 140°C to 218°C. While the calculated temperatures from cold spring chemistry do not directly match the measured temperatures because they do not directly tap the high temperature reservoir, they do provide an indication of elevated reservoir temperatures in the area. Two sites had geothermometer temperatures approaching the subsurface temperatures (Rock Spring and Warm spring in Smoke Creek Desert), suggesting the sampled cold waters there may have a greater component of unchanged reservoir fluid in their mixtures. Additional research and geochemical modeling

is required to evaluate mechanisms to result in these elevated geothermometer temperatures from cold fluids, but the empirical evidence suggests these data may be useful in locating blind geothermal systems.

Historically, the use of geothermometers has been restricted to hot springs or hot well waters, because at lower temperatures, the geothermometer temperature estimates become less reliable. However, we have investigated the application of geothermometers to cold and warm springs from the compiled databases. Although we have confirmed that at lower temperatures, the geothermometer estimates are in fact less reliable (see Table 1), and often underestimate the geothermal potential (see Figure 11), cold and warm springs located near (a few km) geothermal systems still frequently yield anomalously high geothermometer temperatures compared to springs more distantly located from geothermal activity.

Figure 11 shows geothermometer calculations for five areas with known potential, two of which (Desert Peak and Salt Wells) have measured temperatures of 218°C and 189°C, respectively, from drilling and production. The geothermometer temperature plotted in Figure 11 is the average of the Na-K-Ca, Mg-corr geothermometer (Fournier, 1981) and one of two SiO₂ geothermometers. If Na-K-Ca, Mg-corr >100°C, then the quartz no steam loss (Fournier 1977; Fournier, 1981) value is used in the average. If Na-K-Ca, Mg-corr <100°C, then the chalcedony geothermometer (Fournier, 1981) value is used in the average.

Several springs from <20°C to up to 80°C are plotted and have calculated geothermometers that trend toward and approach the measured temperatures at these sites (red and green symbols). For this reason, geothermometer estimates from cold springs can sometimes be a valuable exploration tool even if the temperature estimates cannot be taken literally. Figure 11 shows that there is a trend toward the drilled reservoir temperature at two sites evaluated (Desert Peak and Salt Wells), with the hotter samples providing temperature estimates closer to those in the reservoir, but the lower temperature samples also indicating a likely high temperature source fluid. Additional work is required to deter-

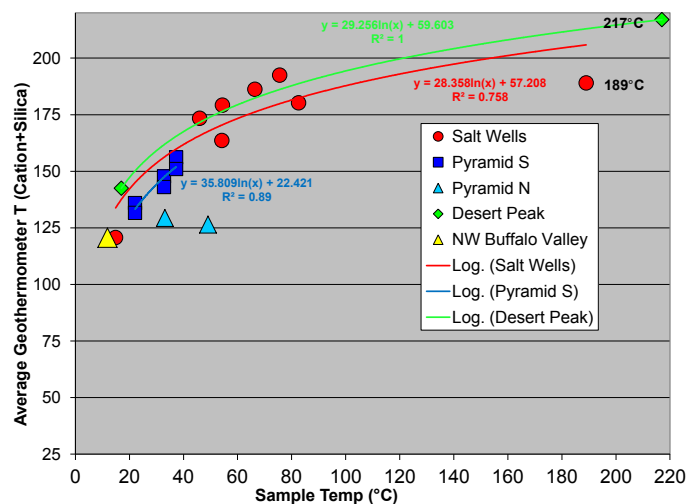


Figure 11. Plot of geothermometer temperatures (see text for explanation) of cold springs from five known geothermal areas in Nevada showing trend toward reservoir temperatures for Desert Peak and Salt Wells measured temperatures.

mine the conditions under which cold waters can be used in geothermometer temperature calculations, and the GBGDB data are used to determine locations of possible anomalous temperature expected from geothermometer calculations from analyses of cold waters. Although the regression equations are based on a small data set here, the R2 values are fairly good, which warrants additional investigation of these types of data in estimating reservoir temperatures.

Figures 12 and 13 show additional locations in Nevada of the cold springs with anomalous geothermometer temperatures for the Na-K-Ca, Mg-corr and chalcedony geothermometers (Fournier, 1981). Geothermometers used in both plots were calculated using data with good and fair charge balances, or those with poor charge balance, but which were poor because HCO_3 was not reported for the analysis. For the latter, it was assumed that the cation and SiO_2 values were good because one wouldn't expect a good charge balance in the case where HCO_3 is omitted from the analysis. Figure 12 shows locations of waters $<25^\circ\text{C}$ (to include some lower temperature warm waters) at discharge, with calculated cation (Na-K-Ca, Mg-corr) geothermometer temperatures exceeding 100°C , whereas Figure 13 shows cold locations with SiO_2 (chalcedony) geothermometer temperatures $>100^\circ\text{C}$. As documented in several studies in Nevada in recent years, chalcedony may not reveal the

actual reservoir temperature, but it has been reliable for estimating a conservative (not over-estimate) temperature of the resources investigated (unpublished work and Shevenell and DeRocher, 2005). Note that there are clusters of anomalous geothermometer temperatures in both maps around Reno and Fallon that are not currently known to be associated with geothermal activity, but still require further investigation. Nevertheless, there are clearly a considerable number of sites with anomalous geothermometer temperatures from cold waters without proximal geothermal activity that bear continued investigation to determine if they are suitable for additional geothermal exploration and development of currently blind geothermal systems.

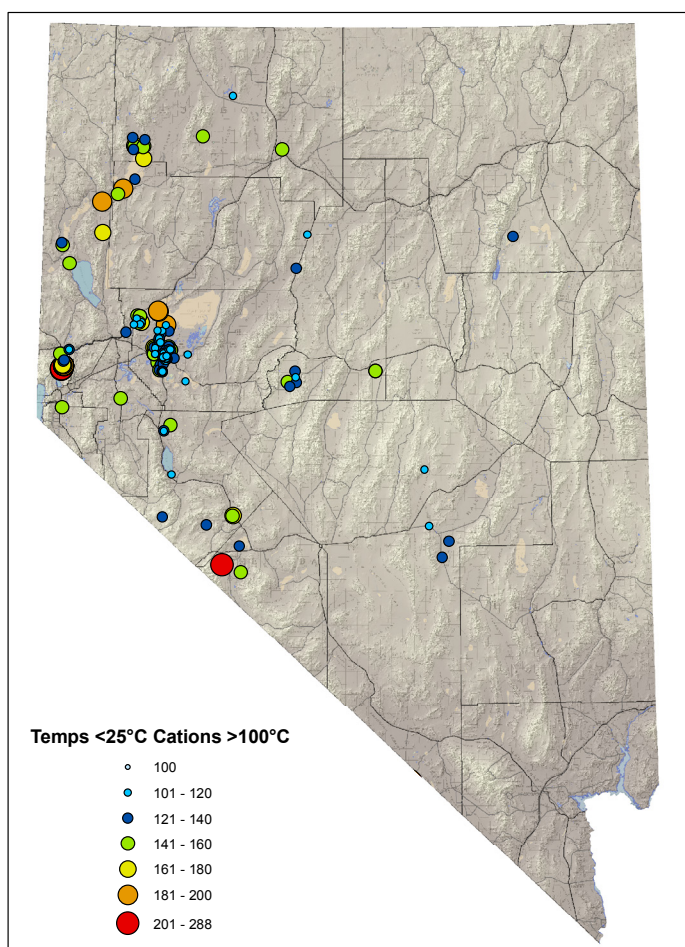


Figure 12. Map of Nevada showing calculated Na-K-Ca, Mg-corr geothermometer temperatures above 100°C obtained from the chemistry of cold and marginally warm springs and wells.

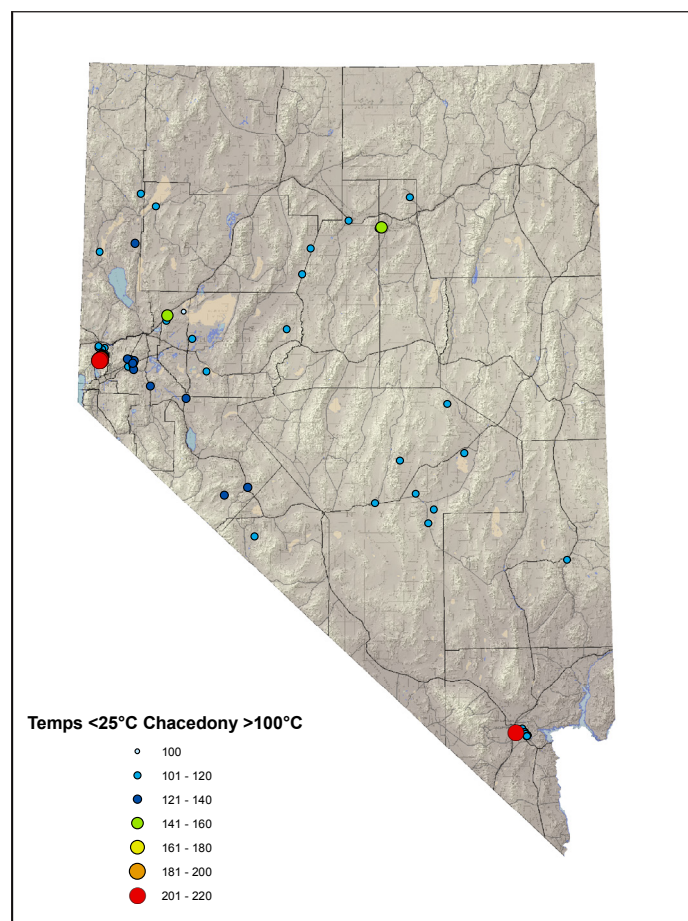


Figure 13. Map of Nevada showing calculated chalcedony geothermometer temperatures above 100°C obtained from the chemistry of cold, and marginally warm springs and wells.

There are 224 additional sites in the Nevada in the GBGDB with discharge temperatures $<20^\circ\text{C}$ and chalcedony *and* Na-K-Ca, Mg-corr $>50^\circ\text{C}$; most have not been drilled (see Figure 14 where these sites are plotted on a map of Nevada). In summary, this promising exploration tool should not be ignored in the Great Basin states.

NGDS and Map Services

All of these data along with numerous other data sets are being cataloged and incorporated into the National Geothermal

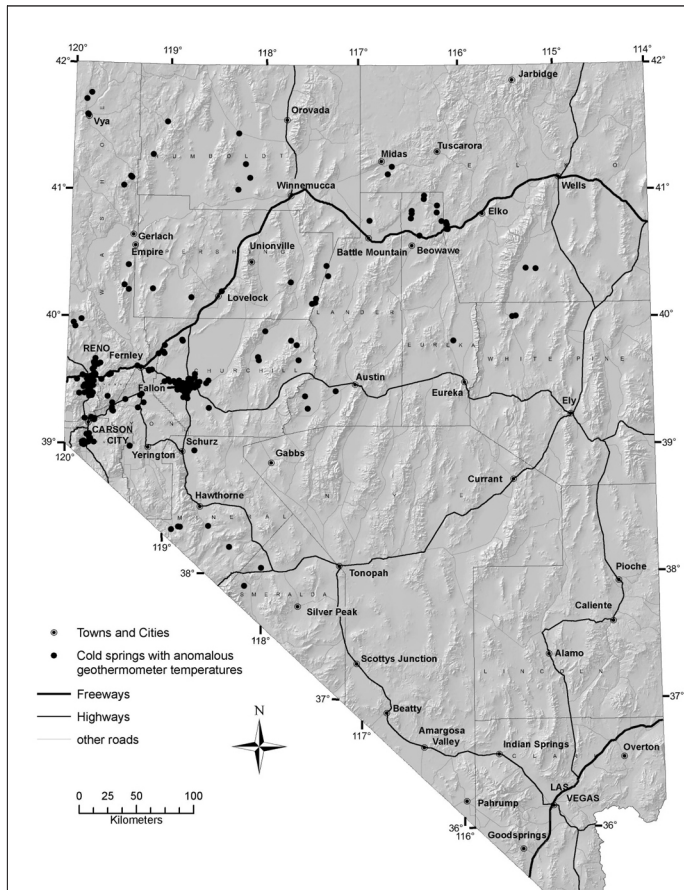


Figure 14. Cold Springs (<20°C) with geothermometer temperature (chalcedony and Na-K-Ca, Mg-corr) >50°C.

Data System to help future exploration and development efforts for geothermal power generation in the US. These data sets from across the country are populating the data catalogs at <http://www.geothermaldata.org/> and <http://www.stategeothermaldata.org/> with data contributions on-going and planned to continue through 2013. Some of the basic examples in the previous section demonstrate the use of these large datasets in future investigations and geothermal exploration and development efforts. Many other uses are also possible, and research is being conducted on the geochemical and other NGDS dataset currently being compiled.

Map services have been developed for many geothermal data sets for the Great Basin, and Nevada in particular, and datasets can currently be viewed or downloaded at <http://gisweb.unr.edu/geothermal/> where there are over 100 data sets available with many being updated by NBMG. Map services allow the ArcGIS user to directly use any geothermal data layers at NBMG in their own projects without the need to download data that may change as we update our databases. As we update and change databases, the map service identified in your ArcMap project will always point to the most up-to-date data layers at NBMG. These new services also allow individual users to generate interactive maps by request in real time. The geochemistry database is currently being converted into a map service to augment the current services. This service will include an overhauled NBMG Map 161 (Penfield et al., 2010; formerly interactive map 141; Shevenell and Garside, 2005) that

will allow querying of geochemical data by areas in Nevada or in its entirety, download of spring and well photographs, localized maps, updated text describing the geothermal areas (based on many years of field studies and literature reviews), geochemistry, and extensively verified locations of hot and warm springs and wells in the state.

Summary and Observations

Geochemical sampling of thermal and non-thermal waters was conducted in Nevada to fill in data gaps, support other exploration projects, conduct exploration and assessment (e.g., geothermometer calculations), and improve the database of historical data. Playas and cold springs were sampled to help locate blind geothermal systems. In one case (Salt Wells), a playa was sampled at a depth of 2 m from an auger hole that reached water with temperatures of 84.8°C. The average Na-K-Ca, Mg-corr and quartz geothermometer from this sample indicated a reservoir temperature of 192°C, indicating diffuse playa discharge areas may be another relatively new method of locating hidden geothermal systems in arid environments.

This work expanded and enhanced the present knowledge of Nevada's geothermal resources by providing new water chemistry information on known geothermal areas for which there was previously little or no information that was publicly available. These newly sampled (between 2002 and 2009) waters, along with the compiled database being prepared for the National Geothermal Data System, allow delineation of new, or poorly understood, geothermal areas in Nevada that may be developed for electrical power generation or direct use applications. Geochemical indicators of fluid flow paths and results from the stable isotope analyses (^{13}C , $\delta^{18}\text{O}$, δD , and $\delta^{34}\text{S}$), also compiled in the GBGDB can be used as natural tracers in the individual groundwaters, which will allow users to begin to identify distinct and different origins and evolutions of the various waters when used in conjunction with the evaluation of the inorganic chemical variations in the systems. Results from the ^3H and ^{14}C will allow evaluation of differences in mean residence times of the various fluids at selected sites. From the compiled and sampled $\delta^{18}\text{O}$, δD and radiogenic isotope results, an initial assessment of the timing and location of recharge to selected aquifer systems can be gleaned.

In conjunction with estimated geothermometer temperatures, possible mixing relationships have been plotted (to be posted to NGDS in 2012) and mixing can be computed using stable isotope data and selected major and trace element data (e.g., B, Cl, Li, Br) for each site or region to provide a preliminary assessment of likely reservoir temperatures from which the mixed spring waters originated. The results of the geochemical analysis and evaluation can be used to assess the hydrologic relationships between the thermal and the non-thermal waters, and relationships relative to fault locations can be illustrated on maps constructed with the use of GIS techniques and available through map services currently at NBMG, and soon to be available through the NGDS. These geothermal map services using these geochemical data, and numerous other datasets, can be accessed on-line for direct, interactive use, or accessed via link to the map service from ArcMap, as well as being available for direct downloads (<http://www.nbmng.unr.edu/Geothermal/InteractiveMaps.html>).

Some summary comments on geochemical work, database construction and geothermometer estimates in Nevada over the past 10 years include:

- Cation and silica geothermometers rarely agree in NV.
- When both data sets are available and clearly duplicate analyses (unlike the BV example of Figure 2, the geochemistry of sampled waters from these studies are generally quite similar to those obtained by Robert Mariner for the same spring areas in the 1970s, indicating good data quality for both data sets, and limited temporal variability in spring chemistries.
- Most areas are characterized by relatively low discharge springs.
- Water from most sites is not fully equilibrated (Giggenbach, 1988), and hence, the Na-K-Ca, Mg-corr geothermometer may not be appropriate, and often overestimates the reservoir temperature.
- While the chalcedony geothermometer tends to underestimate reservoir temperatures, it is useful in the Great Basin for providing a conservative indicator of minimum expected temperatures from which subsequent development activities can be planned.
- ^{14}C and δD and $\delta^{18}\text{O}$ indicate waters in Nevada are typically old and were recharged during the Pleistocene (Buchanan, 1990; Flynn and Buchanan, 1990, and current work). Hence current production requires thoughtful reinjection strategies to preserve the resource as most are not expected to be replenished with modern waters, except, perhaps, through drawing in shallower waters as systems are produced.
- Reed and Spycher (1984) method may work at estimating temperatures of the lower temperature systems encountered in Nevada (Shevenell and DeRocher, 2005) but is labor intensive for the modest improvement in results obtained.
- We are currently working on new models based on mixing that may provide better estimates of reservoir temperatures under certain conditions (Shevenell and Coolbaugh, 2011). Additional evaluations of the range at which chalcedony and quartz geothermometers are valid are being investigated as the range in the Great Basin appears to differ from commonly reported values.
- Time series data are needed to better evaluate the geothermal potential of some sites, along with case studies of existing production facilities to provide a retrospective view of success of various geothermometers in estimating actual reservoir temperatures. This was initiated by Shevenell and DeRocher (2005) and can be augmented using data in the National Geothermal Data System for Nevada and other western states.
- It is currently unclear why some cold waters have anomalous geothermometer values. This relationship was observed repeatedly in Nevada, and it bears further work because mechanisms to result in these elevated estimated temperatures are not well understood. However, it is now

documented that, in some cases, these anomalous geothermometer temperatures indicate proximity to geothermal activity.

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