# SUMMARY OF COMPILED FLUID GEOCHEMISTRY WITH DEPTH ANALYSES IN THE GREAT BASIN AND ADJOINING REGIONS

*by Stefan M. Kirby*


OPEN-FILE REPORT 603
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2012

# SUMMARY OF COMPILED FLUID GEOCHEMISTRY WITH DEPTH ANALYSES IN THE GREAT BASIN AND ADJOINING REGIONS

*by Stefan M. Kirby*


**OPEN-FILE REPORT 603**
**UTAH GEOLOGICAL SURVEY**
**a division of**
**UTAH DEPARTMENT OF NATURAL RESOURCES**
**2012**

**STATE OF UTAH**
Gary R. Herbert, Governor

**DEPARTMENT OF NATURAL RESOURCES**
Michael Styler, Executive Director

**UTAH GEOLOGICAL SURVEY**
Richard G. Allis, Director

**PUBLICATIONS**
contact
Natural Resources Map & Bookstore
1594 W. North Temple
Salt Lake City, UT 84116
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
website: mapstore.utah.gov
email: geostore@utah.gov

**UTAH GEOLOGICAL SURVEY**
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
telephone: 801-537-3300
website: geology.utah.gov



*Research supported by the U.S. Department of Energy. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.*

## CONTENTS



## FIGURES



## TABLES

# SUMMARY OF COMPILED FLUID GEOCHEMISTRY WITH DEPTH ANALYSES IN THE GREAT BASIN AND ADJOINING REGIONS

*by Stefan M. Kirby*

## ABSTRACT

Fluid chemistry at depth places important constraints on deep-seated geothermal resource development. This database presents a compilation of published major ion fluid chemistry for samples of known depth from sources that include oil and gas exploration and development, standard groundwater samples collected from water wells, and samples associated with geothermal power exploration and development. The samples are from the lower 48 states west of 100 degrees latitude. The electrolytic charge balance of all samples was checked and only samples with an electrolytic charge balance within plus or minus 10 percent were retained in the compiled dataset. Geochemical samples were grouped into nine units based on the calculated water type. There is broad overlap between water chemistry at depth from samples in the Great Basin area and adjoining areas in the western U.S. Below 2000 meters most samples have sodium water types and Na-Cl water type comprises most of the samples at depth. Other sodium water types (including Na-$HCO_3$ and Na-$SO_4$) and Ca-Cl make up much of the remainder of samples from depths greater than 2000 meters. Solute concentrations for samples from the Great Basin area are slightly more dilute than those from adjoining areas. These data provide baseline chemistry for various depth intervals across a range of geologic settings that are relevant to potential deep geothermal exploration and development.

## INTRODUCTION

Fluid chemistry at depth places important constraints on deep-seated geothermal resource development. Complete and geochemically charge-balanced samples of known depth greater than 500 meters are generally rare. This database presents a compilation of existing major ion fluid chemistry for samples of known depth from sources that include oil and gas exploration and development, standard groundwater samples collected from water wells, and samples associated with geothermal power exploration and development. The data compiled from these sources span a variety of geologic and thermal settings and are meant to provide a broad background of potential fluid chemistry at various depths that are relevant to deep geothermal exploration, reservoir modeling, system engineering, and development.

## BACKGROUND

This report presents a compiled dataset of published geochemical data collected from known depths west of 100 degrees longitude in the lower 48 states (figure 1). The dataset includes fluid geochemical measurements collected from the oil and gas industry during exploration and development drilling and production, fluid samples from the geothermal power industry, and more typical groundwater samples from water wells. Measurements from four primary sources are compiled in this dataset, including 1) the national Produced Waters database (Breit, 2002), 2) the National Water Information System (NWIS) database (U.S. Geological Survey, 2012), 3) the Great Basin geothermal geochemical database (Nevada Bureau of Mines and Geology, 2006), and 4) the database of geothermal geochemical samples included in Clark and others (2010). All measurements compiled from these data sources include basic location and depth information and concentrations of the major solutes. Most samples from these datasets were collected from depths of less than 250 meters. In order to focus on chemistry trends at significant depth, only samples from depths greater than 250 meters below land surface are retained in the compiled dataset.

Each compiled sample includes measured solute concentrations of calcium, magnesium, sodium, potassium, chloride, bicarbonate, and sulfate. A limited subset of the data also includes pH and/or temperature measurements. Many samples do not include temperature or pH measurements, and these data are largely incomplete. Specific conductance data are lacking from the produced waters database (Breit, 2002) and are incomplete in the other sources, and are not included in the compiled data.

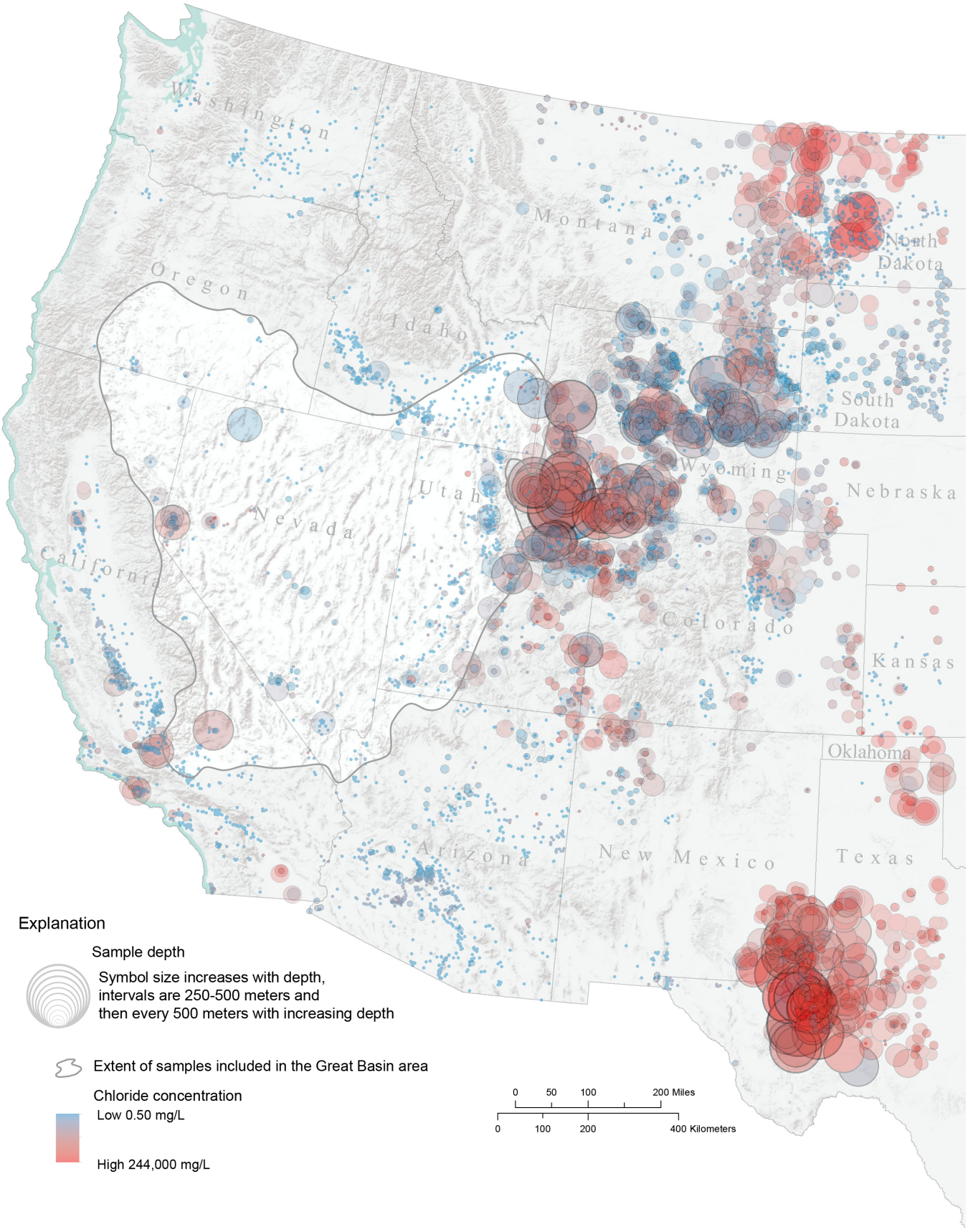


***Figure 1.*** *Sample location map for the compiled geochemical database.*

The electrolytic charge balance of all samples was checked using standard techniques where the molar charge equivalent of dissolved solutes was calculated using the AquaChem software. The charge balance was calculated as the percent difference between the sum of the anion and sum of the cation charge equivalents. Samples with an electrolytic charge balance within plus or minus 10 percent were retained in the compiled dataset. This is greater than the more typical value of plus or minus 5 percent used for most water samples to include as many potentially valid samples as possible.

The sources from which the data are compiled overlap in part, and duplicate measurements were removed from the initial compilation based on location and depth. Each analysis included in the final database contains a unique location and depth. The samples are divided by location into two groups, Great Basin area samples and all other samples, based on the geographic extent of data in the Great Basin geothermal geochemical database (Nevada Bureau of Mines and Geology, 2006). This extent corresponds to the Great Basin area and includes samples within approximately 150 kilometers of the hydrographic boundary of the Great Basin (figure 1). The sources from which the data are compiled contain incomplete and complicated information for the geologic unit from which a sample was obtained, and no lithology information is included with samples in the compiled dataset.

Geochemical samples were subdivided based on calculated water type or hydrochemical facies. Water type was calculated for all samples using AquaChem geochemical software following standard methodologies for hydrochemical facies delineation similar to those presented by Kehew (2000). Water type is only stated with respect to the greatest relative concentration of cation and anion. This yields 12 possible water types that include Na-Cl, Na-$HCO_3$, Na-$SO_4$, Ca-Cl, Ca-$HCO_3$, Ca-$SO_4$, Mg-Cl, Mg-$HCO_3$, Mg-$SO_4$, K-Cl, K-$HCO_3$, and K-$SO_4$. No samples in the compiled dataset have potassium as the dominant cation and water type is therefore limited to the nine chemistry types excluding potassium.

## DATA SUMMARY

The compiled dataset of geochemistry with depth includes a total of 7485 samples (table 1). Of the total number of samples, 5255 are from the national Produced Waters database (Breit, 2002), 2049 are from the NWIS database (U.S. Geological Survey, 2012), 107 are from the Great Basin geochemical database (Nevada Bureau of Mines and Geology, 2006), and 74 are from the database of geothermal geochemical samples (Clark and others, 2010). Within the total data set 336 measurements are from the Great Basin area.

***Table 1.*** *Compiled dataset of solute chemistry with depth.* *(Click to view Excel file).*

The location of the compiled samples is shown in figure 1. Most samples of significant depths (greater than 2000 meters) are from oil and gas fields of the Rocky Mountains and west Texas. Away from these areas most samples come from depths of less than 1000 meters. Samples from the Great Basin area are located primarily along the margin of the province and are generally from depths of less than 1000 meters.

Depth of measurement ranges between 250 and 6433 meters with a median of 1807 meters for the entire database. Within the Great Basin area depth of measurement ranges between 250 and 4337 meters; most of these measurements are taken from samples collected within 500 meters of the land surface, and the median depth of samples from the Great Basin area is 351 meters. The total number of samples from depths greater than 2000 meters is 2266, and 22 of these samples are from the Great Basin.

Figure 2 shows depth versus chloride concentration for all water types. Samples are symbolized based on water type, and all samples from the Great Basin area are differentiated. Chloride concentration generally increases with depth across the data set although high concentrations of chloride exist at all depths. Water types that include calcium or magnesium as the dominant cation occur primarily within 1000 meters of the land surface. Magnesium water types are generally uncommon and primarily occur at shallow depths less than 500 meters. Below 1000 meters most samples have sodium water types, and Na-Cl water type comprises most of the samples at depth. Other sodium water types (including Na-$HCO_3$ and Na-$SO_4$) and Ca-Cl or Ca-$HCO_3$ make up much of the remainder of samples from depths greater than 1000 meters. There is general overlap of water type and chloride concentration with depth among samples collected in the Great Basin area and samples collected elsewhere.

To quantify chemistry trends with depth in figure 2, simple descriptive statistics were calculated for each water type and solute for a series of depth intervals (tables 2 and 3). Statistical summaries were computed using the R statistical software (R Development Core Team, 2012). Depth intervals examined include 250 to 500 meters followed by 500-meter intervals from 500 to 5000-meter depths, and lastly all samples of more than 5000 meters in depth. Statistics were calculated separately for each depth interval for all samples together and for samples from the Great Basin area. Table 2 presents the number of occurrences and the relative frequency of water types (e.g. Na-Cl) as percent of total measurements for a given depth interval. These data are used to plot the frequency as percent of the various water types for each depth interval for all samples and samples from the Great Basin area (figure 3).

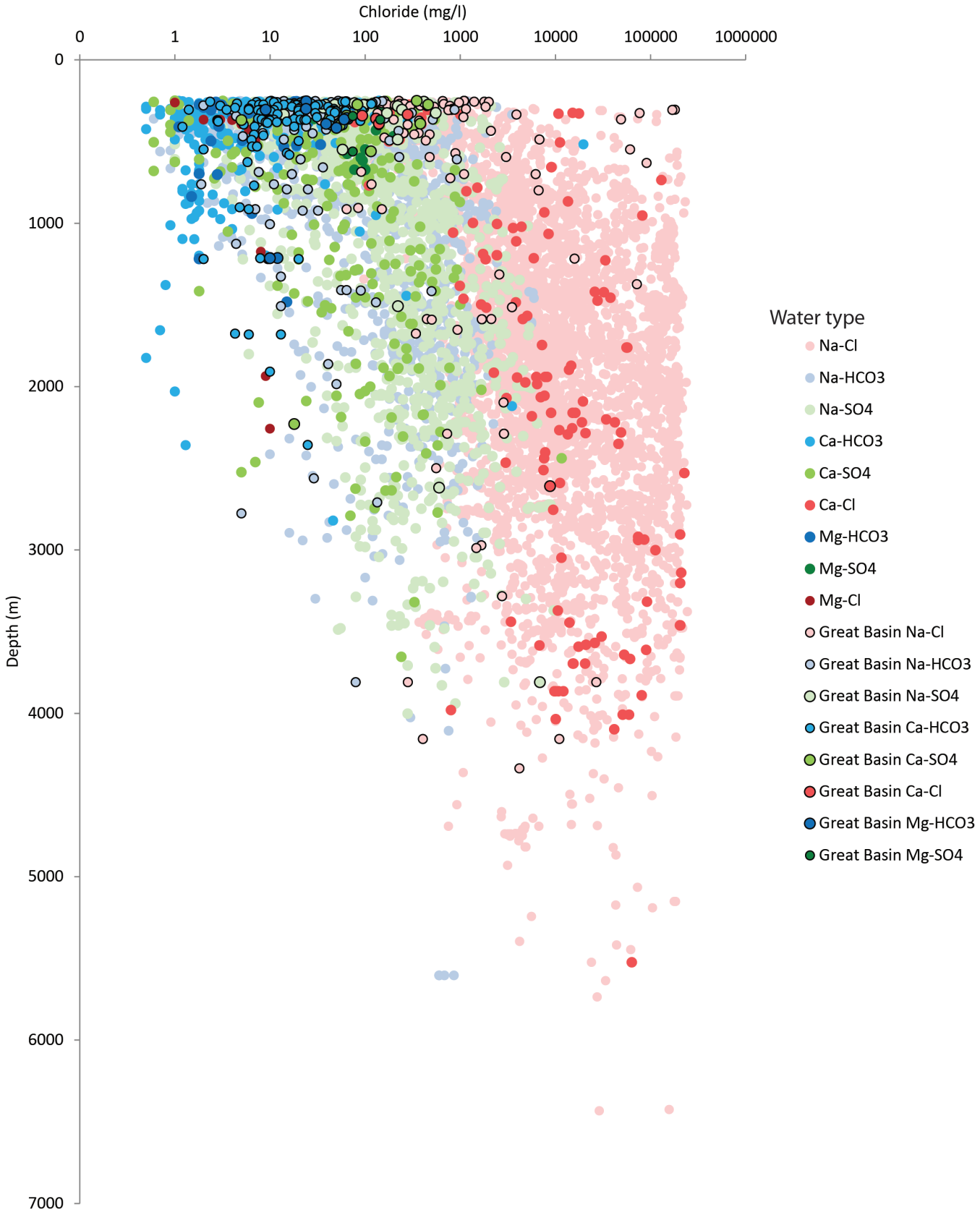


***Figure 2.*** *Water chemistry versus depth.*

***Table 2.*** *Water type frequency of occurrence by depth interval.*

All samples

| | | Ca-Cl | | Ca-$HCO_3$ | | Ca-$SO_4$ | | Mg-Cl | | Mg-$HCO_3$ | | Mg-$SO_4$ | | Na-Cl | | Na-$HCO_3$ | | Na-$SO_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth[1] | N[2] | n[3] | Freq[4] | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq |
| 250-500 | 1649 | 18 | 1.1% | 304 | 18.4% | 87 | 5.3% | 7 | 0.4% | 31 | 1.9% | 9 | 0.5% | 319 | 19.3% | 669 | 40.6% | 205 | 12.4% |
| 500-1000 | 1158 | 11 | 0.9% | 54 | 4.7% | 66 | 5.7% | -- | -- | 7 | 0.6% | 8 | 0.7% | 460 | 39.7% | 310 | 26.8% | 242 | 20.9% |
| 1000-1500 | 1194 | 20 | 1.7% | 12 | 1.0% | 42 | 3.5% | 1 | 0.1% | 5 | 0.4% | -- | -- | 787 | 65.9% | 157 | 13.1% | 170 | 14.2% |
| 1500-2000 | 1240 | 15 | 1.2% | 6 | 0.5% | 18 | 1.5% | 1 | 0.1% | -- | -- | -- | -- | 898 | 72.4% | 142 | 11.5% | 160 | 12.9% |
| 2000-2500 | 1045 | 20 | 1.9% | 4 | 0.4% | 19 | 1.8% | 1 | 0.1% | -- | -- | -- | -- | 820 | 78.5% | 64 | 6.1% | 118 | 11.3% |
| 2500-3000 | 641 | 9 | 1.4% | 1 | 0.2% | 8 | 1.2% | -- | -- | -- | -- | -- | -- | 516 | 80.5% | 35 | 5.5% | 71 | 11.1% |
| 3000-3500 | 329 | 10 | 3.0% | -- | -- | 1 | 0.3% | -- | -- | -- | -- | -- | -- | 280 | 85.1% | 9 | 2.7% | 29 | 8.8% |
| 3500-4000 | 139 | 17 | 12.2% | -- | -- | 1 | 0.7% | -- | -- | -- | -- | -- | -- | 112 | 80.6% | 2 | 1.4% | 7 | 5.0% |
| 4000-4500 | 39 | 4 | 10.3% | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 32 | 82.1% | 2 | 5.1% | 1 | 2.6% |
| 4500-5000 | 32 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 32 | 100.0% | -- | -- | -- | -- |
| >5000 | 19 | 1 | 5.3% | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 14 | 73.7% | 4 | 21.1% | -- | -- |

Great Basin area samples

| | | Ca-Cl | | Ca-$HCO_3$ | | Ca-$SO_4$ | | Mg-Cl | | Mg-$HCO_3$ | | Mg-$SO_4$ | | Na-Cl | | Na-$HCO_3$ | | Na-$SO_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth[1] | N[2] | n[3] | Freq[4] | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq | n | Freq |
| 250-500 | 240 | 4 | 1.7% | 90 | 37.5% | 8 | 3.3% | -- | -- | 7 | 2.9% | 2 | 0.8% | 56 | 23.3% | 57 | 23.8% | 16 | 6.7% |
| 500-1000 | 41 | -- | -- | 9 | 22.0% | 1 | 2.4% | -- | -- | -- | -- | 1 | 2.4% | 14 | 34.1% | 15 | 36.6% | 1 | 2.4% |
| 1000-1500 | 18 | -- | -- | 3 | 16.7% | -- | -- | -- | -- | 3 | 16.7% | -- | -- | 3 | 16.7% | 9 | 50.0% | -- | -- |
| 1500-2000 | 17 | -- | -- | 4 | 23.5% | -- | -- | -- | -- | -- | -- | -- | -- | 9 | 52.9% | 3 | 17.6% | 1 | 5.9% |
| 2000-2500 | 6 | -- | -- | 1 | 16.7% | 1 | 16.7% | -- | -- | -- | -- | -- | -- | 5 | 83.3% | -- | -- | -- | -- |
| 2500-3000 | 8 | 1 | 12.5% | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 2 | 25.0% | 3 | 37.5% | 1 | 12.5% |
| 3000-3500 | 1 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 1 | 100.0% | -- | -- | -- | -- |
| 3500-4000 | 4 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 2 | 50.0% | 1 | 25.0% | 1 | 25.0% |
| 4000-4500 | 3 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 3 | 100.0% | -- | -- | -- | -- |
| 4500-5000 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| >5000 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

[1] Depth interval in meters

[2] Total number of samples for a given depth interval, -- indicates no occurrences

[3] Number of occurrences of given water type

[4] Frequency in percent of total water type occurrences for a given depth interval

***Table 3.*** *Summary statistics for solute concentrations by depth intervals.*

| | All samples | | | | | | | | Great Basin area samples | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solute | Depth[1] | n[2] | Min | 25[3] | Median | Mean | 75 | Max | n[2] | Min | 25[3] | Median[4] | Mean | 75 | Max |
| Ca | 250-500 | 1649 | 0.04 | 8.60 | 28.00 | 92.11 | 63.00 | 7448.00 | 240 | 0.70 | 23.00 | 42.50 | 83.59 | 70.19 | 1700.00 |
| | 500-1000 | 1158 | 0.50 | 15.00 | 47.00 | 478.06 | 253.25 | 62208.00 | 41 | 0.80 | 12.00 | 28.00 | 109.53 | 55.94 | 1889.00 |
| | 1000-1500 | 1194 | 0.80 | 22.00 | 159.00 | 1735.92 | 773.50 | 42112.00 | 18 | 0.80 | 11.28 | 39.50 | 516.00 | 77.00 | 6773.00 |
| | 1500-2000 | 1240 | 0.80 | 27.00 | 188.50 | 2028.24 | 1113.00 | 38000.00 | 17 | 5.80 | 28.10 | 41.95 | 50.71 | 74.32 | 130.00 |
| | 2000-2500 | 1045 | 1.00 | 72.00 | 388.00 | 1950.65 | 2000.00 | 32000.00 | 6 | 33.96 | 78.49 | 110.37 | 108.25 | 122.97 | 199.77 |
| | 2500-3000 | 641 | 1.00 | 81.00 | 352.00 | 2550.61 | 1665.00 | 65582.00 | 8 | 9.65 | 20.23 | 32.96 | 392.06 | 77.56 | 2794.00 |
| | 3000-3500 | 329 | 8.00 | 114.00 | 591.00 | 4646.54 | 2368.00 | 55104.00 | 1 | -- | -- | 25.00 | -- | -- | -- |
| | 3500-4000 | 139 | 5.00 | 162.90 | 1440.00 | 5239.84 | 5999.00 | 43056.00 | 4 | 6.09 | 54.77 | 120.40 | 169.10 | 234.73 | 429.51 |
| | 4000-4500 | 39 | 6.00 | 371.50 | 1465.00 | 4331.46 | 5926.00 | 28100.00 | 3 | 27.00 | 78.43 | 129.85 | 268.28 | 388.93 | 648.00 |
| | 4500-5000 | 32 | 15.00 | 32.00 | 94.00 | 539.38 | 326.25 | 5080.00 | -- | -- | -- | -- | -- | -- | -- |
| | >5000 | 19 | 7.00 | 67.00 | 996.00 | 2593.26 | 2425.00 | 17253.00 | -- | -- | -- | -- | -- | -- | -- |
| Na | 250-500 | 1649 | 1.00 | 45.00 | 160.00 | 724.04 | 450.00 | 99885.90 | 240 | 1.20 | 19.00 | 51.70 | 1318.87 | 215.25 | 99885.90 |
| | 500-1000 | 1158 | 1.10 | 270.00 | 932.50 | 4704.91 | 2937.00 | 146770.00 | 41 | 6.60 | 39.90 | 82.00 | 2793.52 | 479.45 | 55716.00 |
| | 1000-1500 | 1194 | 1.60 | 1340.00 | 3099.00 | 12043.23 | 9333.25 | 124529.00 | 18 | 18.00 | 32.97 | 114.00 | 2875.50 | 797.50 | 36925.00 |
| | 1500-2000 | 1240 | 0.40 | 2098.50 | 4218.00 | 15815.09 | 12884.75 | 118001.00 | 17 | 6.50 | 64.93 | 338.61 | 578.38 | 1138.70 | 2070.00 |
| | 2000-2500 | 1045 | 2.00 | 2611.00 | 6144.00 | 20534.96 | 21172.00 | 124491.00 | 6 | 16.00 | 113.37 | 1058.79 | 994.53 | 1867.87 | 1897.83 |
| | 2500-3000 | 641 | 59.93 | 2491.00 | 7937.00 | 21465.09 | 30902.00 | 130631.00 | 8 | 59.93 | 388.81 | 782.97 | 1601.18 | 1630.47 | 6492.58 |
| | 3000-3500 | 329 | 264.00 | 3771.00 | 8788.00 | 21128.93 | 30911.00 | 119460.00 | 1 | -- | -- | 2549.00 | -- | -- | -- |
| | 3500-4000 | 139 | 163.00 | 3889.50 | 10488.00 | 21297.31 | 29367.00 | 99666.00 | 4 | 163.00 | 425.02 | 4950.81 | 7260.74 | 11786.54 | 18978.32 |
| | 4000-4500 | 39 | 370.00 | 4565.50 | 10243.00 | 15710.08 | 16247.50 | 78000.00 | 3 | 370.00 | 3023.00 | 5676.00 | 4878.73 | 7133.09 | 8590.19 |
| | 4500-5000 | 32 | 571.00 | 2913.75 | 3420.00 | 7650.47 | 6884.25 | 62935.00 | -- | -- | -- | -- | -- | -- | -- |
| | >5000 | 19 | 1355.00 | 3740.00 | 18752.00 | 32001.11 | 37850.50 | 115841.00 | -- | -- | -- | -- | -- | -- | -- |
| Mg | 250-500 | 1649 | 0.00 | 1.80 | 7.30 | 38.28 | 21.00 | 8000.00 | 240 | 0.00 | 4.40 | 12.00 | 66.93 | 22.25 | 8000.00 |
| | 500-1000 | 1158 | 0.01 | 3.60 | 19.00 | 222.91 | 70.00 | 18454.00 | 41 | 0.02 | 0.91 | 6.39 | 32.27 | 17.00 | 599.00 |
| | 1000-1500 | 1194 | 0.02 | 9.00 | 39.00 | 493.96 | 210.50 | 11165.00 | 18 | 0.02 | 3.10 | 11.00 | 74.00 | 40.49 | 872.00 |
| | 1500-2000 | 1240 | 0.00 | 10.00 | 43.00 | 447.93 | 211.25 | 14600.00 | 17 | 0.00 | 1.00 | 19.18 | 19.64 | 30.00 | 59.00 |
| | 2000-2500 | 1045 | 0.10 | 20.00 | 70.00 | 374.29 | 428.00 | 9960.00 | 6 | 1.00 | 3.92 | 6.39 | 20.27 | 26.20 | 71.92 |
| | 2500-3000 | 641 | 0.01 | 20.00 | 104.00 | 441.21 | 412.00 | 25772.00 | 8 | 0.01 | 1.60 | 7.35 | 45.88 | 16.73 | 309.00 |
| | 3000-3500 | 329 | 1.00 | 18.00 | 91.00 | 690.18 | 627.00 | 9150.00 | 1 | -- | -- | 6.00 | -- | -- | -- |
| | 3500-4000 | 139 | 0.41 | 24.00 | 182.00 | 671.94 | 1087.00 | 5040.00 | 4 | 0.41 | 20.35 | 34.98 | 29.08 | 43.70 | 45.95 |
| | 4000-4500 | 39 | 0.00 | 55.50 | 326.00 | 786.31 | 896.50 | 4394.00 | 3 | 0.00 | 3.00 | 5.99 | 21.00 | 31.50 | 57.00 |
| | 4500-5000 | 32 | 3.00 | 6.75 | 19.50 | 81.66 | 76.25 | 518.00 | -- | -- | -- | -- | -- | -- | -- |
| | >5000 | 19 | 1.00 | 8.50 | 104.00 | 575.47 | 467.50 | 6542.00 | -- | -- | -- | -- | -- | -- | -- |
| K | 250-500 | 1649 | 0.04 | 2.00 | 3.60 | 22.37 | 7.60 | 13000.00 | 240 | 0.50 | 2.40 | 5.40 | 91.77 | 9.99 | 13000.00 |
| | 500-1000 | 1158 | 0.10 | 5.00 | 13.00 | 94.51 | 49.94 | 7960.00 | 41 | 1.00 | 3.60 | 6.90 | 73.47 | 33.30 | 1830.00 |
| | 1000-1500 | 1194 | 0.70 | 13.00 | 36.00 | 293.04 | 132.25 | 6900.00 | 18 | 1.10 | 3.83 | 8.45 | 46.49 | 20.75 | 505.00 |
| | 1500-2000 | 1240 | 0.60 | 18.00 | 52.00 | 371.95 | 200.00 | 17500.00 | 17 | 2.70 | 4.89 | 16.38 | 38.28 | 56.14 | 245.00 |
| | 2000-2500 | 1045 | 1.00 | 35.00 | 95.00 | 516.11 | 419.00 | 9000.00 | 6 | 2.80 | 19.98 | 140.34 | 157.62 | 217.25 | 439.50 |
| | 2500-3000 | 641 | 1.30 | 43.00 | 230.00 | 722.73 | 784.00 | 9080.00 | 8 | 4.89 | 33.75 | 70.82 | 78.98 | 97.34 | 220.00 |
| | 3000-3500 | 329 | 3.00 | 65.00 | 192.00 | 1005.74 | 900.00 | 10100.00 | 1 | -- | -- | 25.00 | -- | -- | -- |
| | 3500-4000 | 139 | 9.00 | 83.00 | 250.00 | 1044.24 | 812.50 | 11000.00 | 4 | 17.08 | 33.52 | 254.23 | 655.79 | 876.50 | 2097.60 |
| | 4000-4500 | 39 | 7.00 | 100.00 | 400.00 | 517.37 | 598.00 | 4400.00 | 3 | 26.00 | 113.00 | 200.00 | 238.48 | 344.72 | 489.44 |
| | 4500-5000 | 32 | 4.00 | 10.00 | 85.00 | 255.38 | 264.00 | 1852.00 | -- | -- | -- | -- | -- | -- | -- |
| | >5000 | 19 | 17.00 | 36.50 | 213.00 | 523.63 | 985.00 | 1857.00 | -- | -- | -- | -- | -- | -- | -- |
| Cl | 250-500 | 1649 | 0.50 | 12.00 | 43.00 | 922.94 | 189.00 | 180000.00 | 240 | 1.20 | 11.80 | 36.08 | 2195.73 | 172.50 | 180000.00 |
| | 500-1000 | 1158 | 0.60 | 70.00 | 371.00 | 7546.22 | 3122.50 | 231485.00 | 41 | 1.90 | 10.99 | 32.00 | 4227.79 | 227.74 | 91000.00 |
| | 1000-1500 | 1194 | 0.80 | 592.50 | 3511.50 | 21565.01 | 13760.75 | 217968.00 | 18 | 2.00 | 9.99 | 16.50 | 5071.77 | 120.00 | 71873.00 |
| | 1500-2000 | 1240 | 0.50 | 1300.00 | 5050.00 | 27819.92 | 19700.00 | 237245.00 | 17 | 4.30 | 13.00 | 341.61 | 701.21 | 935.93 | 3500.00 |
| | 2000-2500 | 1045 | 1.00 | 2620.00 | 9000.00 | 34866.32 | 36500.00 | 225351.00 | 6 | 18.00 | 201.02 | 1792.95 | 1564.55 | 2871.72 | 2881.71 |
| | 2500-3000 | 641 | 4.99 | 2450.00 | 9200.00 | 37492.69 | 54300.00 | 240236.00 | 8 | 4.99 | 107.74 | 578.34 | 1658.26 | 1522.51 | 8800.00 |
| | 3000-3500 | 329 | 30.00 | 3750.00 | 12000.00 | 41687.57 | 54000.00 | 244228.00 | 1 | -- | -- | 2760.00 | -- | -- | -- |
| | 3500-4000 | 139 | 79.51 | 5290.00 | 20500.00 | 43630.86 | 56350.00 | 205000.00 | 4 | 79.51 | 231.38 | 3587.06 | 8555.71 | 11911.39 | 26969.19 |
| | 4000-4500 | 39 | 280.00 | 6800.00 | 25300.00 | 32829.86 | 37950.00 | 185000.00 | 3 | 405.00 | 2292.50 | 4180.00 | 5190.82 | 7583.72 | 10987.45 |
| | 4500-5000 | 32 | 750.00 | 3307.50 | 4525.00 | 11706.78 | 8700.00 | 104000.00 | -- | -- | -- | -- | -- | -- | -- |
| | >5000 | 19 | 600.00 | 4900.00 | 33800.00 | 54467.53 | 68300.00 | 182783.00 | -- | -- | -- | -- | -- | -- | -- |
| SO4 | 250-500 | 1649 | 0.10 | 16.00 | 66.00 | 297.48 | 250.00 | 10050.00 | 240 | 0.30 | 16.00 | 36.48 | 210.63 | 110.50 | 6300.00 |
| | 500-1000 | 1158 | 0.20 | 32.00 | 230.00 | 966.92 | 1187.50 | 12500.00 | 41 | 7.89 | 22.00 | 44.00 | 209.12 | 155.82 | 2225.00 |
| | 1000-1500 | 1194 | 1.00 | 74.00 | 559.50 | 1540.91 | 2179.25 | 14000.00 | 18 | 11.00 | 91.75 | 149.91 | 302.98 | 284.75 | 2650.00 |
| | 1500-2000 | 1240 | 0.80 | 140.00 | 704.00 | 1403.44 | 1852.50 | 14600.00 | 17 | 0.80 | 1.20 | 59.00 | 90.03 | 68.00 | 424.52 |
| | 2000-2500 | 1045 | 0.50 | 170.00 | 895.00 | 1611.55 | 2350.00 | 15000.00 | 6 | 0.50 | 58.68 | 85.40 | 99.69 | 111.37 | 257.00 |
| | 2500-3000 | 641 | 2.00 | 450.00 | 1300.00 | 2246.19 | 3136.00 | 12500.00 | 8 | 9.99 | 67.20 | 333.38 | 1824.21 | 1192.42 | 10987.45 |
| | 3000-3500 | 329 | 1.00 | 270.00 | 937.00 | 1881.32 | 2440.00 | 14970.00 | 1 | -- | -- | 155.00 | -- | -- | -- |
| | 3500-4000 | 139 | 4.00 | 233.50 | 731.00 | 1137.57 | 1517.00 | 9400.00 | 4 | 66.00 | 180.56 | 1008.35 | 2867.99 | 3695.78 | 9389.27 |
| | 4000-4500 | 39 | 13.00 | 323.00 | 1050.00 | 1470.28 | 1860.50 | 8500.00 | 3 | 64.00 | 1430.40 | 2796.81 | 2520.27 | 3748.40 | 4700.00 |
| | 4500-5000 | 32 | 73.00 | 324.50 | 426.00 | 960.25 | 1643.75 | 3550.00 | -- | -- | -- | -- | -- | -- | -- |
| | >5000 | 19 | 87.00 | 223.50 | 560.00 | 1044.89 | 1425.00 | 3900.00 | -- | -- | -- | -- | -- | -- | -- |
| HCO3 | 250-500 | 1649 | 3.00 | 150.00 | 220.00 | 457.13 | 500.00 | 29400.00 | 240 | 3.00 | 150.00 | 190.00 | 249.20 | 258.25 | 2252.43 |
| | 500-1000 | 1158 | 18.00 | 217.25 | 570.50 | 1000.15 | 1342.00 | 9206.48 | 41 | 43.95 | 130.00 | 193.00 | 491.25 | 264.70 | 9206.48 |

***Table 3.*** *continued*

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000-1500 | 1194 | 12.00 | 390.00 | 1000.00 | 1236.65 | 1706.00 | 17200.00 | 18 | 115.00 | 194.60 | 310.00 | 584.68 | 856.00 | 1818.00 |
| 1500-2000 | 1240 | 1.00 | 354.00 | 916.00 | 1337.04 | 1809.00 | 14700.00 | 17 | 132.85 | 286.00 | 440.00 | 535.88 | 579.34 | 1780.00 |
| 2000-2500 | 1045 | 12.00 | 329.00 | 746.00 | 1113.23 | 1573.00 | 39300.00 | 6 | 143.84 | 283.86 | 516.91 | 448.20 | 598.07 | 680.22 |
| 2500-3000 | 641 | 18.00 | 334.00 | 675.00 | 914.65 | 1171.00 | 7076.00 | 8 | 27.37 | 189.03 | 252.71 | 695.10 | 725.75 | 3096.46 |
| 3000-3500 | 329 | 27.00 | 281.00 | 610.00 | 1007.33 | 1476.00 | 11590.00 | 1 | -- | -- | 1964.00 | -- | -- | -- |
| 3500-4000 | 139 | 7.00 | 287.00 | 545.00 | 855.75 | 1044.42 | 5514.00 | 4 | 224.00 | 820.13 | 2157.54 | 2133.63 | 3471.04 | 3995.44 |
| 4000-4500 | 39 | 51.00 | 458.50 | 708.00 | 1860.01 | 2319.69 | 9516.00 | 3 | 378.00 | 1337.69 | 2297.38 | 2384.13 | 3387.19 | 4477.00 |
| 4500-5000 | 32 | 5.00 | 770.25 | 1140.50 | 1409.75 | 1574.00 | 6137.00 | -- | -- | -- | -- | -- | -- | -- |
| >5000 | 19 | 34.00 | 338.00 | 1110.00 | 1735.42 | 2598.50 | 5978.00 | -- | -- | -- | -- | -- | -- | -- |

[1] Depth interval in meters

[2] Number of occurrences, -- indicates no measurements in a given depth range

[3] Percentiles calculated using the R statistical software

[4] Median values for depth intervals with 1 measurement are the actual measurement

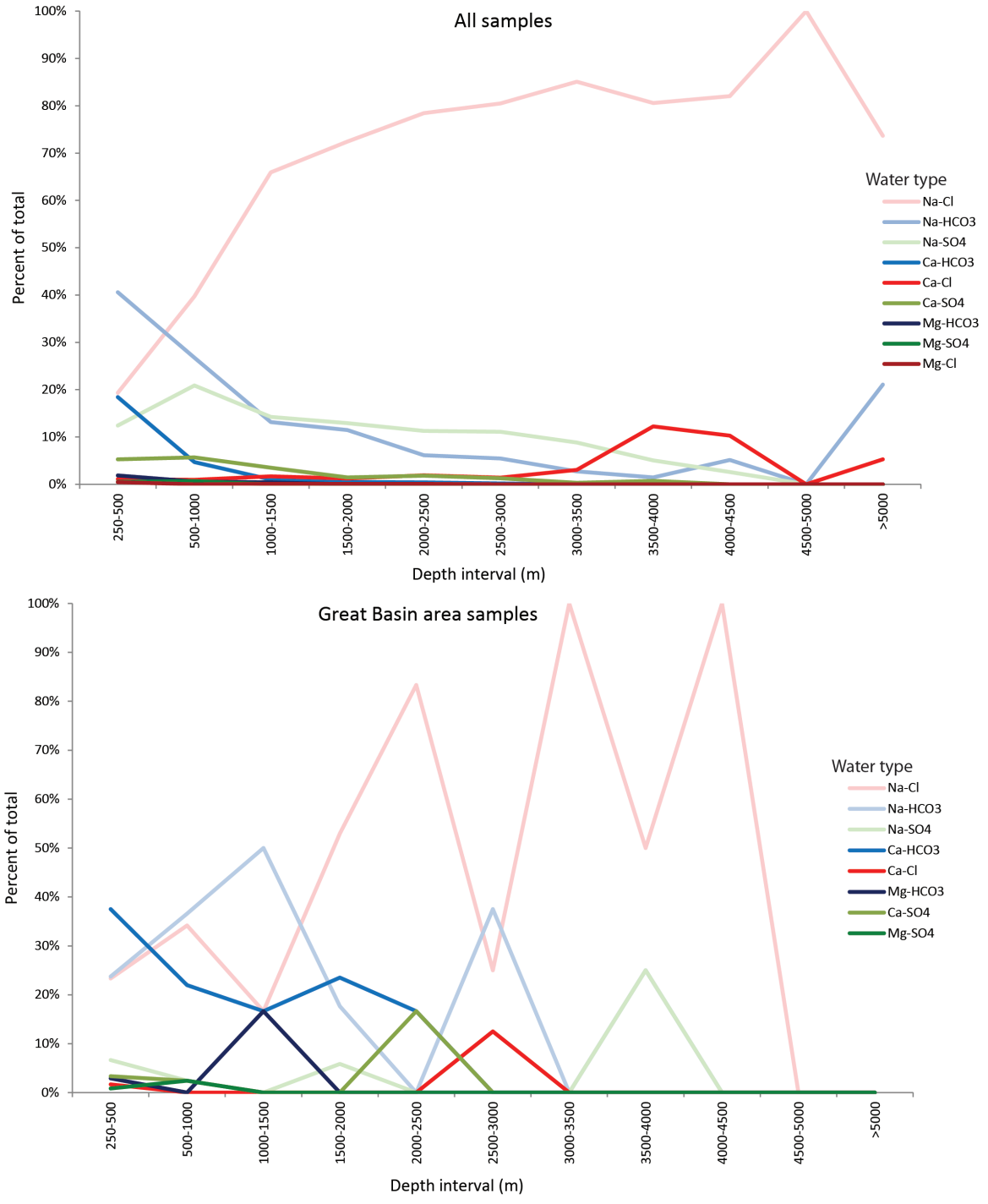


***Figure 3.*** *Frequency of water type by depth interval.*

For all samples sodium water types comprise most of the water types at all depths, and at depths greater than 1000 meters more than 50 percent of all water types are Na-Cl. Na-Cl water types increase in frequency with depth and comprise between 70 and 100 percent of all water types at depths greater than 2500 meters for all samples. Na-$HCO_3$ and Na-$SO_4$ water types combine to comprise between 47 and 53 percent of water types; as depth increases the frequency of these water types decreases to a combined total of 6 percent at depths of 3500 to 4500 meters. Calcium water types (Ca-$HCO_3$, Ca-$SO_4$, and Ca-Cl) combine to comprise 24 percent of samples in the 250 to 500-meter depth interval. Ca-$HCO_3$ water type is 18 percent of total samples at these depths, with its frequency decreasing rapidly below 500 meters to less than 1 percent of samples to depths of 3000 meters. Ca-Cl water type is generally 1 percent of samples, but between 3500 and 4500 meters this water type accounts for 10 to 12 percent of samples. Magnesium water types combined (Mg-Cl, Mg-$HCO_3$, Mg-$SO_4$) are generally less than 1 percent in the upper 2500 meters, and magnesium water types are absent altogether below 2500 meters.

Water type frequency patterns for samples in the Great Basin area are broadly similar to those described above. A greater percentage of samples in the upper 2500 meters are calcium bicarbonate water types, ranging from 17 to 38 percent of samples for depths less than 2500 meters. Sodium water types again dominate samples at depth intervals greater than 2000 meters, and Na-Cl water type is between 25 and 100 percent of samples at depths greater than 2000 meters.

Figure 4 shows median values of solute concentration relative to depth intervals. For all samples, median concentrations of all solutes increase rapidly with depth to 1500 meters. Below 1500 meters the rate of concentration increase is lower. The greatest median concentrations of sodium and chloride are 18,750 mg/L and 33,800 mg/L and occur in the greater than 5000 meter depth interval. For depth intervals between 2000 and 5000 meters, sodium and chloride have median concentrations ranging from 6100 to 10,500 mg/L and from 9000 to 25,300 mg/L, respectively.

Median values of concentrations for solutes in the Great Basin area are generally lower than those of all samples for a given depth interval (figure 4). The median concentration of calcium in the Great Basin area ranges between 28 and 43 mg/L for depth intervals less than 2000 meters. For depth intervals greater than 2000 meters median calcium concentrations range between 25 and 130 mg/L. The median concentration of sodium ranges between 51 and 339 mg/L for depth intervals less than 2000 meters in the Great Basin area. Below this depth median sodium concentration ranges from 783 mg/L at the 2500 to 3000-meter depth interval to 5676 mg/L at the 4000 to 4500-meter depth interval. Median magnesium concentrations in the Great Basin area range from 6 to 20 mg/L in the upper 2000 meters; at depths greater than 2000 meters most depth intervals have median concentrations of less than 10 mg/L. The largest median magnesium concentration is 35 mg/L at the 4000 to 4500-meter depth interval. Median potassium concentrations range from 5 to 16 mg/L for depth intervals less than 2000 meters in the Great Basin area. Median concentration of potassium for depth intervals between 2000 and 4500 meters ranges from 25 to 254 mg/L. Concentrations of the chloride anion in the Great Basin area range between 17 and 342 mg/L for depth intervals less than 2000 meters. At depth intervals greater than 2000 meters median chloride concentrations range from 578 to 4180 mg/L. The median sulfate concentration in the Great Basin area ranges from 37 to 150 mg/L for depth intervals less than 2000 meters. At depths greater than 2000 meters sulfate has median concentrations between 85 and 2796 mg/L. The median bicarbonate concentration in the Great Basin area ranges from 190 to 440 mg/L for depth intervals less than 2000 meters. Below 2000 meters median bicarbonate concentrations range from 517 to 2297 mg/L.

## DISCUSSION

The compiled dataset presented here is clustered in its geographic extent. This leaves large areas with no or few samples at a given depth and likely skews results relative to locations having significant data. Most samples from depths greater than 1000 meters are from the oil and gas industry and are necessarily located in producing oil and gas basins. These settings have unique geochemistry relative to other areas and their inclusion here may also affect these results. The incomplete nature of field parameters of pH and temperature included in this dataset also raises the potential for error. Samples that were collected from deep, warm locations may have re-equilibrated due to changes in mineral solubility resulting from large temperature changes.

Based on the compiled geochemical data, fluid chemistry is generally dominated by sodium water types, in particular Na-Cl water types, which comprise most of the samples particularly below 2000 meters in depth. Other sodium water types, including Na-$HCO_3$ and Na-$SO_4$, comprise lesser but important fractions of total water types for a given depth interval. At shallow depths less than 2000 meters, Ca-$HCO_3$ and Ca-$SO_4$ water types comprise important fractions of the dataset, particularly in the Great Basin area. Mg water types are rare across all depth intervals.

Previous work on deep fluid geochemistry has found dominant chemistries of Ca-Na-Cl (Moller and others, 1997; Stober and Bucher, 1999; Stober and Bucher, 2005) and Na-Cl (Stober and Bucher, 2004; Bucher and Stober, 2010)

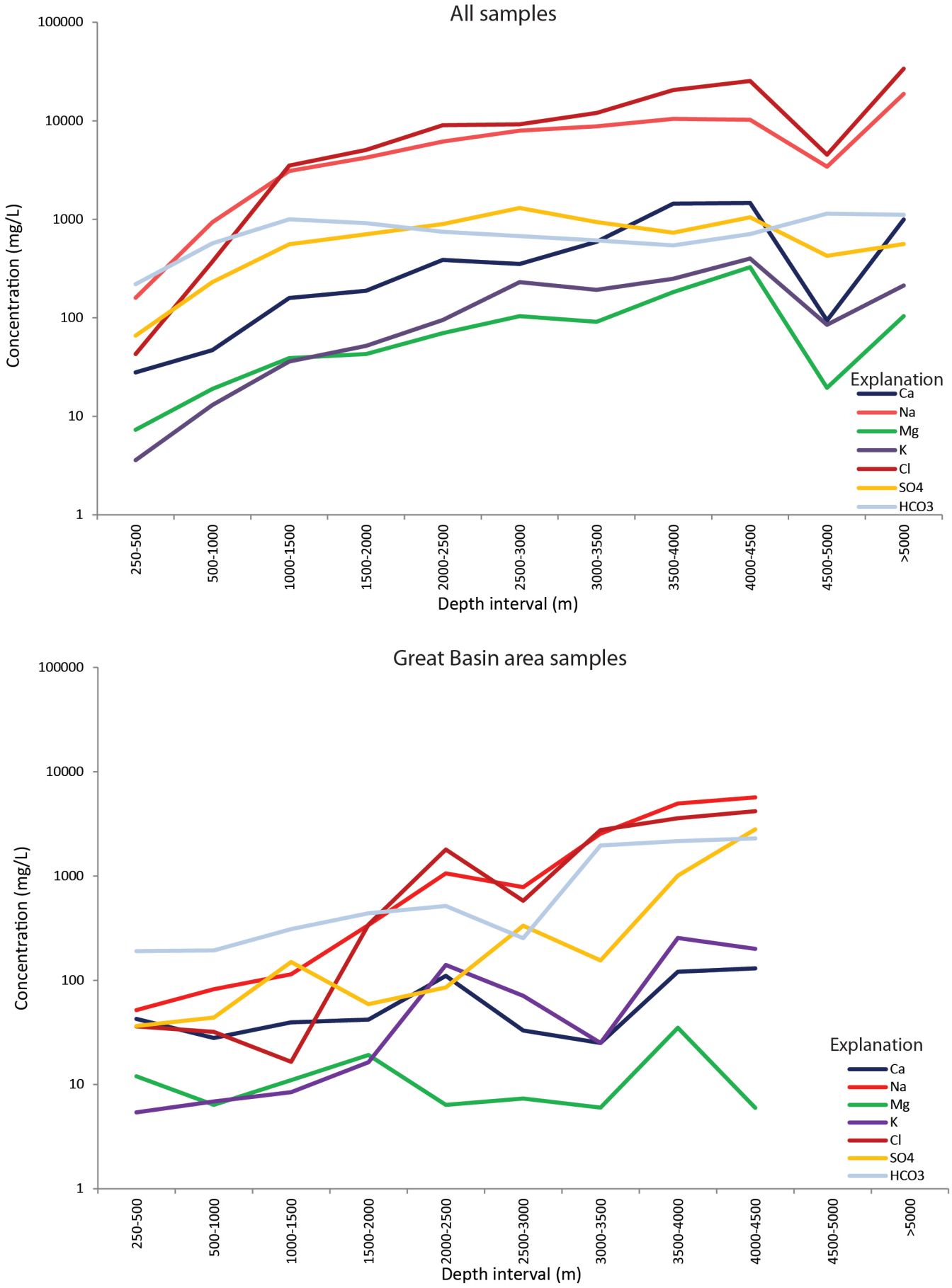


***Figure 4.*** *Median solute concentrations by depth intervals.*

brines at depths greater than several thousand meters. The concentrations of these brines are within an order of magnitude of the calculated median solute concentrations for comparable depth intervals from the entire compiled dataset, and are generally higher than samples from corresponding depths in the Great Basin area. As such, the sample data presented in the compiled dataset are likely a reasonable estimate of fluid geochemistry at various depths despite the limitations of geographic and geologic setting previously discussed.

## ACKNOWLEDGMENTS

Partial funding for this project was provided by DOE grant award DE-EE0005128/000. This report benefitted from discussions with Rick Allis and Paul Inkenbrandt. Prompt and thorough reviews from Mike Lowe, Michael Hylland, Kimm Harty, and Rick Allis improved the content of the report.

## REFERENCES

Breit, G., 2002, Produced waters database: U.S. Geological Survey: Online, http://energy.cr.usgs.gov/prov/prodwat/index.htm, accessed April 12th, 2012.

Bucher, K., and Stober, I., 2010, Fluids in the upper continental crust: Geofluids, v. 10, p. 241–253.

Clark, C.E., Harto, C.B., Sullivan, J.L., and Wang, M.Q., 2010, Water use in the development and operation of geothermal power plants: Report prepared for Argonne National Laboratory under contract DE-AC02-06CH11357, variously paginated: Online, http://web.anl.gov/renewables/research/geothermal_aggd.html, accessed May 3rd, 2012.

Kehew, A.E., 2000, Applied chemical hydrogeology: Upper Saddle River, New Jersey, Prentice Hall, 368 p.

Möller, P., Weise, S.M., Althaus, E., Bach, W., Behr, H.J., Burchardt, R., Bräuer, K., Drescher, J., Erzinger, J., Faber, E., Hansen, B.T., Horn, E.E., Huenges, E., Kämpf, H., Kessels, W., Kirsten, T., Landwehr, D., Lodemann, M., Machon, L., Pekdeger, A., Pielow, H.-U., Reutel, C., Simon, K., Walther, J., Weinlich, F.H., and Zimmer, M., 1997, Paleofluids and recent fluids in the upper continental crust—results from the German Continental Deep Drilling Program (KTB): Journal of Geophysical Research, v. 102, p. 18,233–18,254.

Nevada Bureau of Mines and Geology, 2006, Great Basin groundwater geochemical database: Online, http://www.unr.edu/geothermal/GeochemDB.htm, accessed December 9, 2011.

R Development Core Team, 2012, R— a language and environment for statistical computing: Online, R Foundation for Statistical Computing, Vienna, Austria, http://www.R-project.org, accessed July 2012.

Stober, I., and Bucher, K., 1999, Deep groundwater in the crystalline basement of the Black Forest region: Applied Geochemistry, v. 14, p. 237–254.

Stober, I., and Bucher, K., 2004, Fluid sinks within the earth's crust: Geofluids, v. 4, p. 143–151.

Stober, I., and Bucher, K., 2005, The upper continental crust, an aquifer and its fluid—hydraulic and chemical data from 4 km depth in fractured crystalline basement rocks at the KTB test site: Geofluids, v. 5, p. 8–19.

U.S. Geological Survey, 2012, National Water Information System database: Online, http://waterdata.usgs.gov/nwis, accessed February 17, 2012.