

Strategic and Critical Elements in Produced Geothermal Fluids from Nevada and Utah

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Keywords: critical elements, geothermal, hydrocarbons, produced water geochemistry

ABSTRACT

Herein we summarize the results of an investigation dealing with the concentrations and inventories of strategic, critical and valuable materials (SCVM) in produced fluids from geothermal and hydrocarbon reservoirs (50-250° C) in Nevada and Utah. Water samples were collected from thirty-four production wells across eight geothermal fields, the Uinta Basin oil/gas province in northeast Utah, and the Covenant oil field in southwestern Utah; additional water samples were collected from six hot springs in the Sevier Thermal Belt in southwestern Utah.

Most SCVM concentrations in produced waters range from <0.1 to 100 µg/kg; the main exception is lithium, which has concentrations that range from <1000 to 25,000 ug/kg. Relatively high concentrations of gallium, germanium, scandium, selenium, and tellurium are measured too. Geothermal waters contain very low concentrations of REEs, below analytical detections limits (0.01 µg/kg), but the concentrations of lanthanum, cerium, and europium range from 0.05 to 5 µg/kg in Uinta basin waters.

Among the geothermal fields, the Roosevelt Hot Spring reservoir appears to have the largest inventories of germanium and lithium, and Patua appears to have the largest inventories of gallium, scandium, selenium, and tellurium. By comparison, the Uinta basin has larger inventories of gallium.

The concentrations of gallium, germanium, lithium, scandium, selenium, and tellurium in produced waters appear to be partly related to reservoir temperature and concentrations of total dissolved salts. The relatively high concentration and large inventory of lithium occurring at Roosevelt Hot Springs may be related to granitic-gneissic crystalline rocks, which host the reservoir. Analyses of calcite scales from Dixie Valley indicate enrichments in cobalt, gallium, gold, palladium, selenium and tellurium, and these metals appear to be depositing at deep levels in production wells due to boiling. Comparisons with SCVM mineral deposits suggest that brines in sedimentary basins, or derived from lacustrine evaporites, enable aqueous transport of gallium, germanium, and lithium.

1. INTRODUCTION

This project deals with resource assessment of strategic, critical and valuable materials (SCVM) in production fluids and reservoirs across several western states. SCVM comprise a wide range of diverse elements (e.g., Critical Metals Strategy, DoE, 2011; Energy Critical Elements, American Physical Society and Materials Research Society, 2011), including an alkali metal (Li), noble gases (He, ³He), metals and metalloids (Ag, Co, Ga, Ge, In, Ir, Nb, Os, Pd, Pt, Re, Rh, Ru, Se, Te), and rare earth elements (REEs: Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Pr, Nd, Sc, Sm, Tb, Tm, Y, Yb).

Previous work has been directed at targeted studies of subsets of SCVM, typically REEs, primarily in high temperature geothermal fluids from just a few sites in the USA. Accordingly, the aqueous concentrations of REEs are less than a few µg/kg, whereas some metals (Te and Ag) can reach mg/kg level, and aqueous Li can exceed 100 mg/kg (e.g., McKibben and Hardie, 1997; Simmons et al., 2016; Neupane and Wendt, 2017).

This report describes new data obtained from geothermal and oil/gas fields in Nevada and Utah (Fig. 1). Production fluids and rocks from a number of fields, with reservoir temperatures ranging from 50-250° C, were sampled and analyzed. The results have been used to calculate the grades and inventories of SCVM in reservoirs, and the numbers reported herein are provisional. The results are discussed in the light of the chemical, thermal, and geological controls on hydrothermal transport of SCVM. They are also compared to geological information of known SCVM deposits in the USA.

2. SAMPLING

Hot springs (37-83°C) and production wells were sampled for waters, and a subset of these sites was sampled for gases, but only the helium isotope data are reported herein. The methodology for acquiring fluid samples from geothermal wells depended on several factors, including the location(s) and availability of pipeline sample ports and temperature-pressure conditions. Where the wells are pumped to produce geothermal fluid (Blue Mountain, Patua, San Emidio, Soda Lake), samples were acquired with stainless steel coiled tubing submerged in an ice bath to prevent gas phase separation. Where the wells are self-flowing and fluid production is two-phase

(Beowawe, Dixie Valley and Roosevelt Hot Springs-Blundell), a mini-separator was attached to the pipeline to collect separate water and gas samples. At Dixie Valley and Roosevelt Hot Springs-Blundell, some wells also have drip tanks where separated water is conductively cooled, and these were sampled too. Helium and helium isotope samples were collected by filling a long copper tube with water (no gas bubbles) from the stainless steel coil submerged in an ice bath.

Oil and gas production wells were sampled for produced waters from the wellhead or separators. Some separators have a valve located on the bottom of the tank, which permitted acquisition of a sample that was relatively free of hydrocarbons. Other separator tanks were only accessible from the top, and to acquire a water sample, a bailer was lowered to the bottom of a tank through a layer of liquid hydrocarbons. Where the wellhead fluid could be sampled, a mixture of hydrocarbons and water were collected into a large clean bucket. Field treatment of samples was impractical, and most were contaminated with hydrocarbons. Hence, water samples were processed in the lab by letting them stand for 48 hours to allow immiscible liquid hydrocarbons to rise and separate from the underlying water, after which aliquots of water were decanted and treated. Two wells were directly sampled for helium and helium isotopes by filling copper tubes with water as described above.

Treated waters were filtered using a 0.45 µm Millipore filter kit into high density polyethylene plastic bottles (HDP) and then acidified with nitric acid (HNO₃) to pH 2. All HDP bottles were acid cleaned prior to filling with filtered water samples. To check for contamination, field blanks were prepared, in which deionized water (>12 MΩ-cm) from the lab was carried into the field and then subjected to field filtration and acidification. Production fluids from the Uinta basin were collected in commercially available 1 gallon plastic bottles that contained spring water for human consumption. Both the spring water and dionized water stored in a clean empty bottle were analyzed to check for potential contamination. No obvious sources of contamination from treatment and storage of samples were detected.

Untreated waters were collected in glass bottles fitted with a rubber tube extension and a clamp. These waters were only analyzed for pH and bicarbonate. The bottle was filled with hot water to the top of the rubber tube extension (10-20 cm long) and then clamped. As the hot water cools and contracts, the rubber tube collapses, preventing the formation of an air gap; this ensured that the CO₂ concentration was preserved for the pH and bicarbonate analysis.

Rock samples were collected from drill cuttings and field outcrops. Drill cuttings were available from the EGI core library for wells drilled at Beowawe, Dixie Valley, and Roosevelt Hot Springs. Drill cuttings from wells drilled in the Uinta basin were obtained from the Utah Geological Survey, and these were selected to represent likely hydrocarbon source and reservoir rocks. Outcrop samples in the Sevier Thermal Belt were obtained from exposures of reservoir host rocks, volcanic rocks, and travertine deposits.

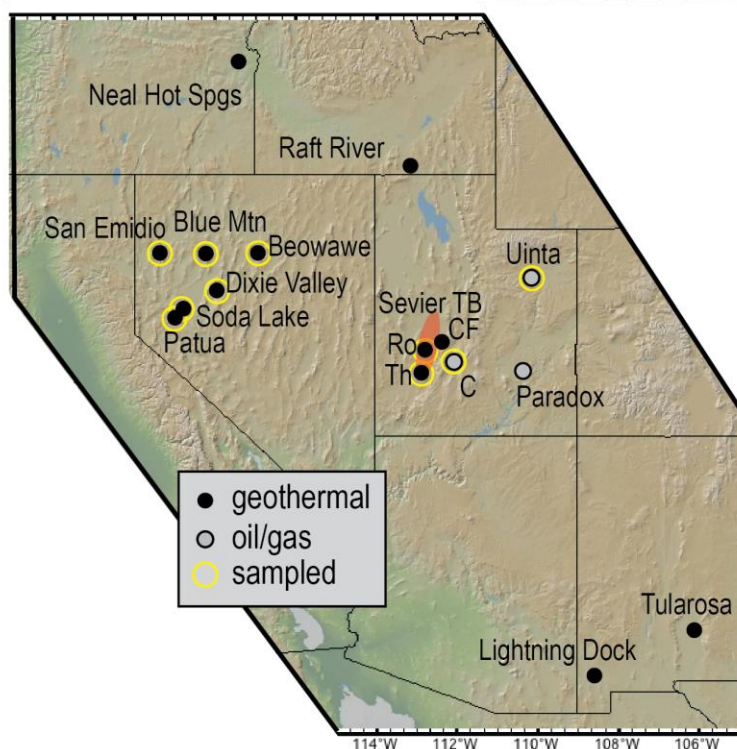


Figure 1. Production fluid sampling sites. Abbreviations: C=Covenant; CF=Cove Fort; Ro=Roosevelt Hot Springs; Sevier TB=Sevier Thermal Belt (orange); Th=Thermo. Yellow circles denote sites sampled in 2017 and discussed herein.

Samples of pipe scales made of calcite were supplied by Terra-Gen from two wells at Dixie Valley. These scales formed on small diameter coiled tubing that had been inserted into the well to continuously supply anti-scalant to the feed points at reservoir depths. The calcite likely deposited due to boiling and separation of gas from the liquid.

2. ANALYTICAL METHODS

Aliquots (50ml) of filtered and acidified water were submitted for analysis at the University of Minnesota geochemistry lab. Major elements were analyzed by ICP-OES, and major anions (Cl, F, SO_4) were analyzed by ion chromatography. Minor and trace cations were analyzed by ICP-MS. Blanks and standards for trace elements were prepared and utilized for calibrating analytical results. The detection limits for trace elements, transition metals, and metalloids are 100 $\mu\text{g}/\text{kg}$ (Li), 1-2 $\mu\text{g}/\text{kg}$ (Al & Se), 0.1-0.2 $\mu\text{g}/\text{kg}$ (Sr, Mn, Fe, Ge, As, W, Au), 0.05 $\mu\text{g}/\text{kg}$ (Sc, Co, Ni, Cu, Ga, Y, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Sb, Te, Ta, Rh, Ir, Pt, Tl, Pb), 0.01 $\mu\text{g}/\text{kg}$ (In, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Th, U). At these detection limits, the accuracy and precision of results for standards is within 20% of their known elemental concentrations. Untreated waters were analyzed for pH and bicarbonate at the Utah Department of Health laboratory in Salt Lake City. Copper tube water samples were analyzed for helium and helium isotopes by mass spectroscopy in the noble gas laboratory, Department of Geology and Geophysics, University of Utah.

Rock and mineral samples (~1.5 grams of solids) were dissolved into an aqueous solution using strong acids (HCl, HNO_3 , HF), sealed vessels, and a microwave digester. The solutions were analyzed for trace elements via standard addition by ICP-MS. Many elements, including Sc, Co, Cu, Zn, Ga, Nb, Sb, La, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb, were within 20% accuracy and precision. The analytical results for As, Ru, Rh, Sb, Te, showed much stronger variance in precision exceeding 50%. Germanium is missing from the reported compositions of the standards, so the analytical results are semi-quantitative, with order of magnitude accuracy.

3. SCVM CONCENTRATIONS & INVENTORIES IN PRODUCED WATERS

The concentrations of most SCVM in produced waters range from <0.1 to 100 $\mu\text{g}/\text{kg}$. Lithium, however, has concentrations that range from <1000 to 25,000 $\mu\text{g}/\text{kg}$. Other elements that attain relatively high concentrations are gallium (10-80 $\mu\text{g}/\text{kg}$ geothermal Nevada and Utah; 5-10,000 $\mu\text{g}/\text{kg}$ Uinta basin), germanium (1-70 $\mu\text{g}/\text{kg}$ geothermal Nevada and Utah; 2-200 $\mu\text{g}/\text{kg}$ Uinta basin), scandium (0.1-0.4 $\mu\text{g}/\text{kg}$ geothermal Nevada and Utah; 0.03-0.2 $\mu\text{g}/\text{kg}$ Uinta basin), selenium (1-80 $\mu\text{g}/\text{kg}$ geothermal Nevada and Utah; 5-2000 $\mu\text{g}/\text{kg}$ Uinta basin), and tellurium (0.1-15 $\mu\text{g}/\text{kg}$ geothermal Nevada and Utah; <1-100 $\mu\text{g}/\text{kg}$ Uinta basin). Low concentrations of rhodium in the range of 0.1-1.0 $\mu\text{g}/\text{kg}$ were measured in samples from Roosevelt Hot Springs, San Emidio, Soda Lake, and the Sevier thermal belt, and up to 6 $\mu\text{g}/\text{kg}$ in Uinta basin waters. Iridium concentrations of 0.1-0.3 $\mu\text{g}/\text{kg}$ were detected in waters from Patua and the Uinta basin. Geothermal waters contain very low concentrations of REEs below the analytical detection limits of 0.01 $\mu\text{g}/\text{kg}$. The concentrations of some REEs in Uinta basin waters, by contrast, range from 0.05 to 5 $\mu\text{g}/\text{kg}$, notably lanthanum, cerium, and europium.

The concentrations of helium and the ratios of $^3\text{He}/^4\text{He}$ were measured at San Emidio and Patua, giving concentrations of 3.6×10^8 to 1.3×10^{10} He ccSTP and helium isotope ratios of 0.279-0.918 R/Ra. In two samples from the Uinta basin, helium concentrations range from 1.1×10^7 to 7.9×10^8 He ccSTP, and helium isotope ratios are 0.04 R/Ra.

Inventories of SCVM in geothermal reservoir waters were calculated by multiplying the average concentrations in produced fluids by the reservoir volume, assuming a porosity of 15%. The reservoir volume was estimated from the plan distribution of production wells multiplied by 1 km, which represents an arbitrarily assigned, but geologically reasonable, reservoir thickness. In the case of the Uinta basin wells, the known history of water production was used to calculate the reservoir water volumes. Figures 2, 3 and 4 graphically portray the concentrations of gallium, germanium, lithium, scandium, selenium, and tellurium versus reservoir inventories. Among the geothermal fields, the Roosevelt Hot Spring reservoir has the largest endowments of germanium and lithium, whereas the Patua reservoir has the largest endowments of gallium, scandium, selenium, and tellurium. By comparison, the Uinta basin reservoirs have larger inventories of gallium.

All reported values of SCVM concentrations and inventories are provisional. The reliability of the geochemical data needs to be checked with multiple repeat analyses to test for uniformity and consistency of elemental concentrations, and the reservoir volumes need to be confirmed based on information held by field operators regarding the occurrence and distributions of production well feed zones. Furthermore, some production waters are modified by injection of additives, and these need to be checked as possible sources of SCVM elements.

As some SCVM elements might be depositing as well scales (i.e., upstream of the well head fluid sampling site), six samples of calcite scale from Dixie Valley were analyzed. One sample contained anomalously high concentrations of cobalt (13,000 $\mu\text{g}/\text{kg}$), gallium (800 $\mu\text{g}/\text{kg}$), germanium (45 $\mu\text{g}/\text{kg}$), selenium (14,000 $\mu\text{g}/\text{kg}$), tellurium (4000 $\mu\text{g}/\text{kg}$), gold (20,000 $\mu\text{g}/\text{kg}$) and palladium (500 $\mu\text{g}/\text{kg}$). Trace amounts (10-100 $\mu\text{g}/\text{kg}$) of yttrium, niobium, rhodium, lanthanum, cerium, neodymium, europium, gadolinium, and rhenium were also detected. These data suggest that some SCVM deposit from produced fluids before reaching the surface, likely due to phase separation in the well.

The concentrations of gallium, germanium, scandium and tellurium in rock samples are graphically portrayed along with concentrations of these elements in produced waters in Figure 5. Their concentrations in waters are generally much lower than in rocks.

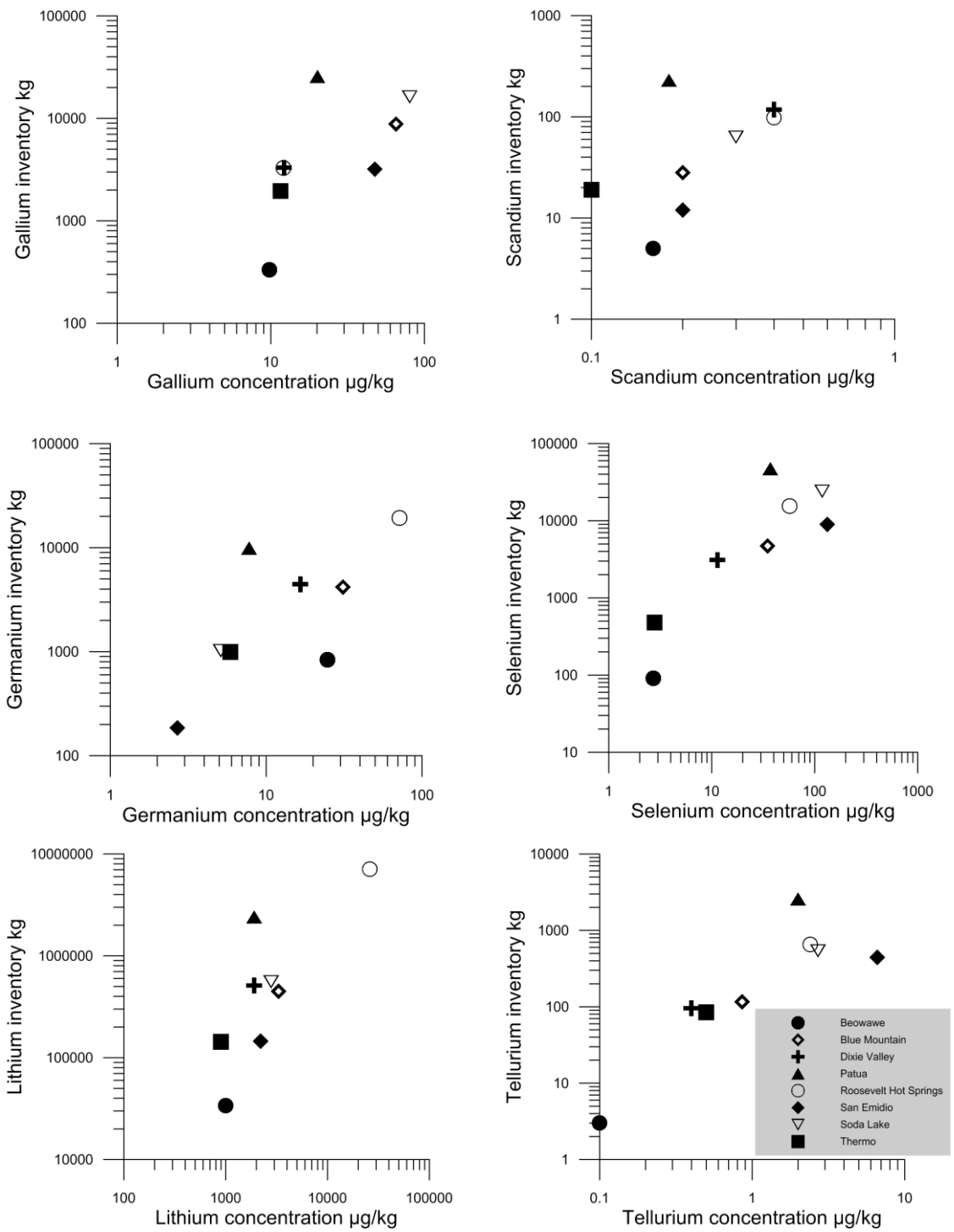


Figure 2. Average concentrations (µg/kg) of gallium, germanium, lithium, scandium, selenium, and tellurium in produced waters from geothermal fields in Nevada and Utah, plotted against estimates of inventories in reservoirs.

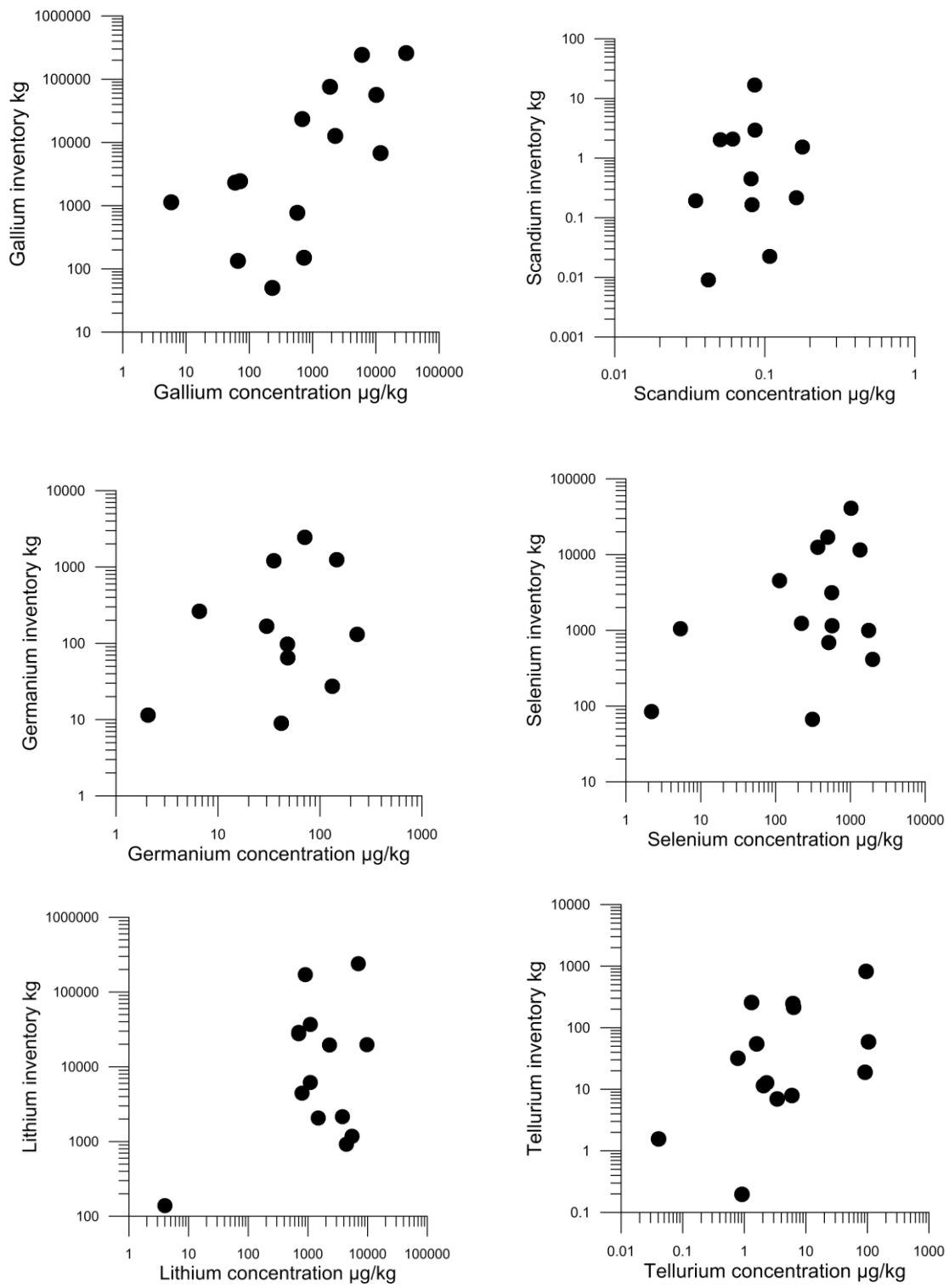


Figure 3. Concentrations ($\mu\text{g/kg}$) of gallium, germanium, lithium, scandium, selenium, and tellurium in produced waters from the Uinta basin, plotted against estimates of inventories in reservoirs.

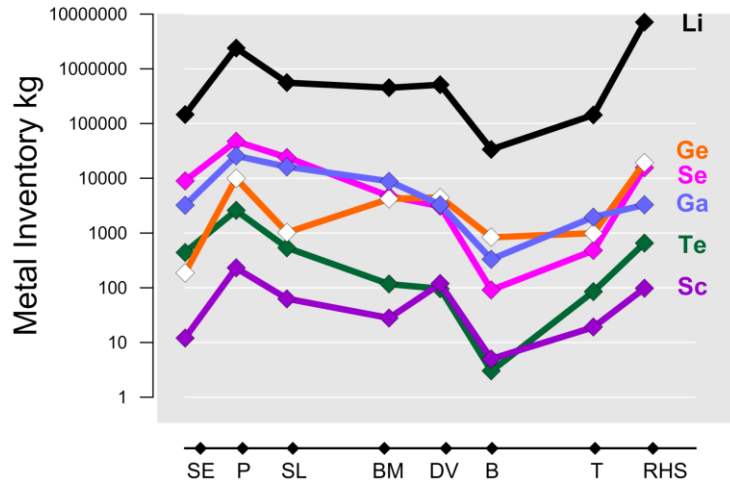


Figure 4. Calculated inventories (kg) of gallium, germanium, lithium, scandium, selenium, and tellurium in produced waters from geothermal reservoirs in Nevada and Utah. Abbreviations: B=Beowawe; BM=Blue Mountain; DV=Dixie Valley; P=Patua; RHS=Roosevelt Hot Springs; SE=San Emidio; SL=Soda Lake; T=Thermo.

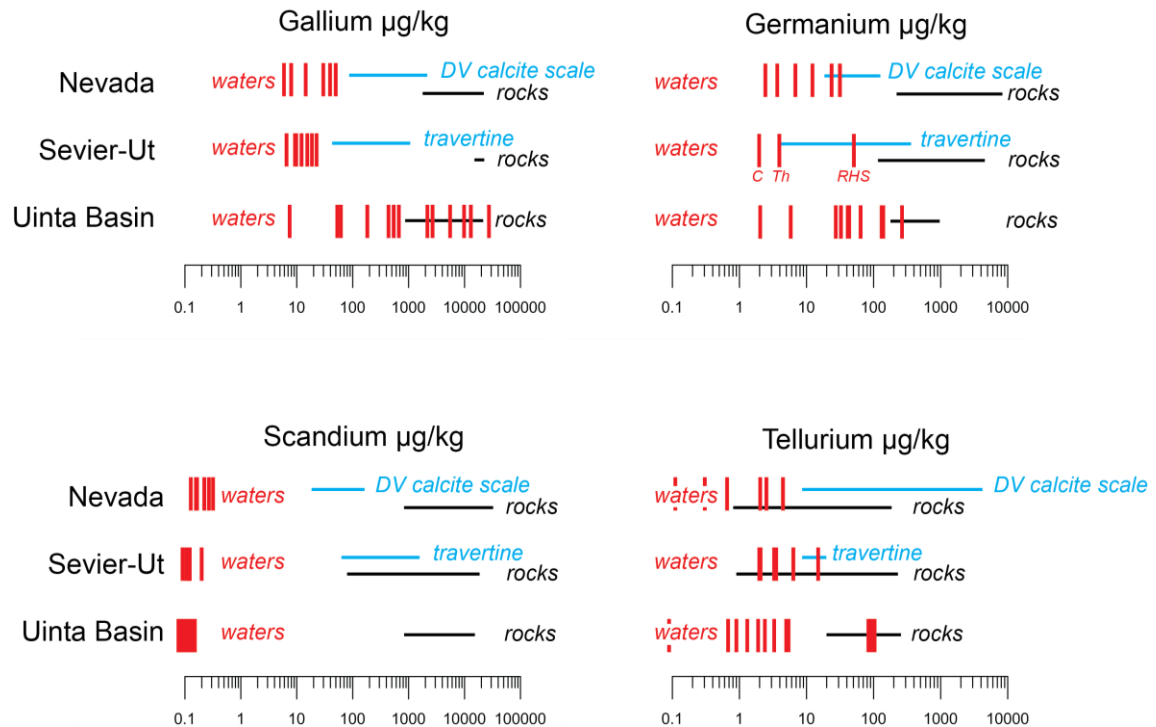


Figure 5. Comparison of the range of concentrations of gallium, germanium, scandium, and tellurium in produced waters, rocks, travertine (Hatton, Utah; Sevier Thermal Belt), and Dixie Valley calcite scales from Nevada and Utah.

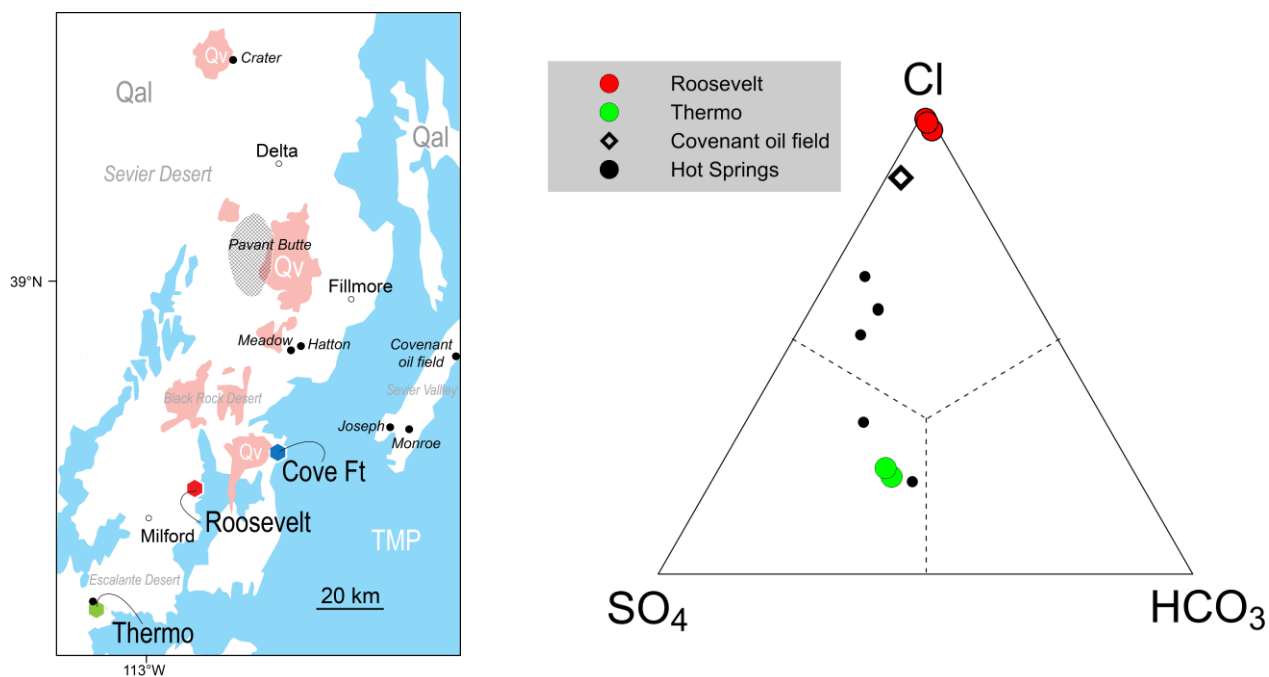


Figure 6. Map of the Sevier Thermal Belt, southwestern Utah (Simmons et al., 2015), and ternary plot showing relative concentrations of Cl-HCO₃-SO₄ in thermal waters.

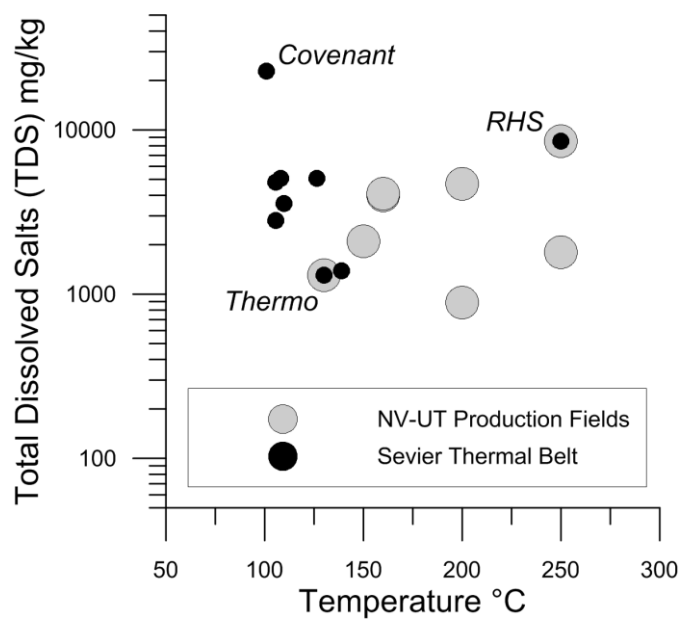


Figure 7. Total dissolved salt concentrations (mg/kg) of Sevier Thermal Belt and produced geothermal waters plotted against measured or quartz-silica equilibration temperatures. Roosevelt Hot Springs (RHS) and Thermo values are denoted by the black-filled circle surrounded by a larger grey-filled circle. The most saline water is from the Covenant oil field.

4. PROCESSES CONTROLLING SCVM IN GEOTHERMAL FLUIDS IN THE SEVIER THERMAL BELT

The Sevier Thermal Belt, southwestern Utah, covers 20,000 km² and is located along the eastern edge of the Great Basin; it encompasses geothermal production fields at Cove Fort, Roosevelt Hot Springs, and Thermo, plus scattered hot spring activity, and the Covenant oil field (Fig. 6). Regionally, the belt is characterized by elevated heat flow, active seismicity, and Quaternary basalt-rhyolite magmatism (Mabey and Budding, 1987; Blackett, 2007). This province has been the subject of several investigations, including geothermal play fairway analysis, geothermal resources in hot sedimentary aquifers, and development of a FORGE laboratory site (e.g. Allis et al., 2015; Simmons et al., 2015; Wannamaker et al., 2016). By comparing results from this relatively compact region, some of the prevailing processes controlling SCVM behavior in geothermal fluids are potentially resolvable.

All thermal waters in the Sevier Thermal Belt are near neutral pH, and isotopically are similar to local meteoric water (Simmons et al., 2015). Based on the major anion compositions, thermal waters are classified as chloride and hybrid chloride-sulfate or sulfate-chloride waters, with chloride concentrations that range from ~100 to 5000 mg/kg, sulfate concentrations that range from ~40 to 2000 mg/kg, and bicarbonate concentrations that range from ~50 to 500 mg/kg. Roosevelt Hot Springs is a chloride water having reservoir host rocks made of crystalline Precambrian gneiss/Tertiary granite. Thermo waters are sulfate-chloride waters, with elevated bicarbonate; reservoir host rocks are made of Paleozoic-Mesozoic marine carbonates and siliciclastic units. Crater, Hatton, Joseph, and Meadow hot springs are chloride-sulfate waters and Monroe is a sulfate-chloride water. The Covenant oil field water comprises saline (12,000 mg/kg Cl) chloride water, and the reservoir is hosted by Jurassic quartz sandstone sealed by mudstone and evaporites. Although TDS values of Sevier Thermal Belt waters overlap produced geothermal waters from Nevada and Utah, there is poor correlation between TDS and temperature (Fig. 7).

Produced thermal waters at Roosevelt Hot Springs and Thermo originate as deeply circulated meteoric waters that have been modified by hot water-rock interaction (>250° C). Geological evidence suggests that the main deep lithology is made up of crystalline basement rocks (i.e., gneiss, granite); however, the precise sources of Cl, SO₄, and HCO₃ are unclear and they could be derived from magmatic intrusions (Simmons et al., 2015). At reservoir depths, there is indication that thermal waters are partially modified by interaction with Paleozoic-Mesozoic sedimentary rocks. During continued ascent to the surface, steam-loss through boiling affects the concentrations of aqueous and gaseous constituents. Where waters reach shallow aquifers, they are affected by dilution and outflow under the influence of hydraulic gradients.

The compositions of hot spring waters suggest they are fed by separate, isolated geothermal systems, albeit with modest resource temperature (<150° C), judging from aqueous silica concentrations and quartz-silica equilibration temperatures. Simmons et al. (2015) infer from high Mg and high Cl/B ratios coupled with enrichments in SO₄, and to a lesser extent HCO₃, that these waters are strongly modified by interaction with salts and clays in alluvial basin fill. They may have also interacted with brine pore fluids in subjacent Mesozoic-Paleozoic sedimentary rocks.

In Figure 8, gallium, germanium, lithium, scandium, selenium and tellurium concentrations in produced geothermal waters (Fig. 2) are compared to Sevier Thermal Belt waters as a function of temperature. The first thing to note is that Sevier Thermal Belt waters are generally lower in concentrations of gallium, germanium, and scandium, but similar in concentrations of selenium and lithium, and higher in concentrations of tellurium, in comparison to other produced thermal waters. Secondly, the hottest production water at Roosevelt Hot Springs has the highest concentrations of germanium, lithium, and scandium, and close to the highest concentrations of selenium; by contrast, the coolest production water at Thermo has the lowest concentrations of lithium, scandium and tellurium, and close to the lowest concentrations of gallium, germanium, and selenium. Thirdly, only scandium shows a strong linear correlation with temperature in produced geothermal waters; correlation with temperature is modest for germanium and lithium, but nonexistent for gallium, selenium, and tellurium. From these trends, it seems that the effect of temperature on gallium, germanium, lithium, scandium, selenium and tellurium concentrations is variable.

In Figure 9, gallium, germanium, lithium, scandium, selenium and tellurium concentrations in produced geothermal waters are compared to Sevier Thermal Belt waters as a function of TDS. Tellurium shows the strongest correlation with TDS, with the highest concentration being found in the most saline water from Covenant oil field. Scandium and selenium also show coherent correlations with TDS. If the Covenant oil field water is omitted, then in all other thermal waters lithium shows a strong correlation with TDS. For gallium and germanium correlations with TDS are weak. These trends imply that the influence of TDS on the concentrations of lithium, scandium, selenium and tellurium in thermal waters is important, but less so for gallium and germanium, which is consistent with their aqueous speciation (Wood and Samson, 2006).

The role of rock geochemistry as a control on SCVM concentrations appears ambiguous, judging from trends in Figure 5. Although rock lithium data are not yet available, the high Li concentrations found in Roosevelt Hot Springs waters could be influenced by the granitic-gneissic crystalline rocks, which host the reservoir. As noted above, one sample of the calcite scales from Dixie Valley contains elevated concentrations of cobalt, gallium, gold, palladium, selenium, and tellurium, plus detectable REEs, which suggests that boiling causes deposition of these elements down-hole in wells where flashing occurs (Fig. 5). Travertine contains elevated concentrations of gallium, germanium, scandium, and tellurium (Fig. 5), and it is not yet clear if these precipitate due to degassing or some other physical/chemical process.

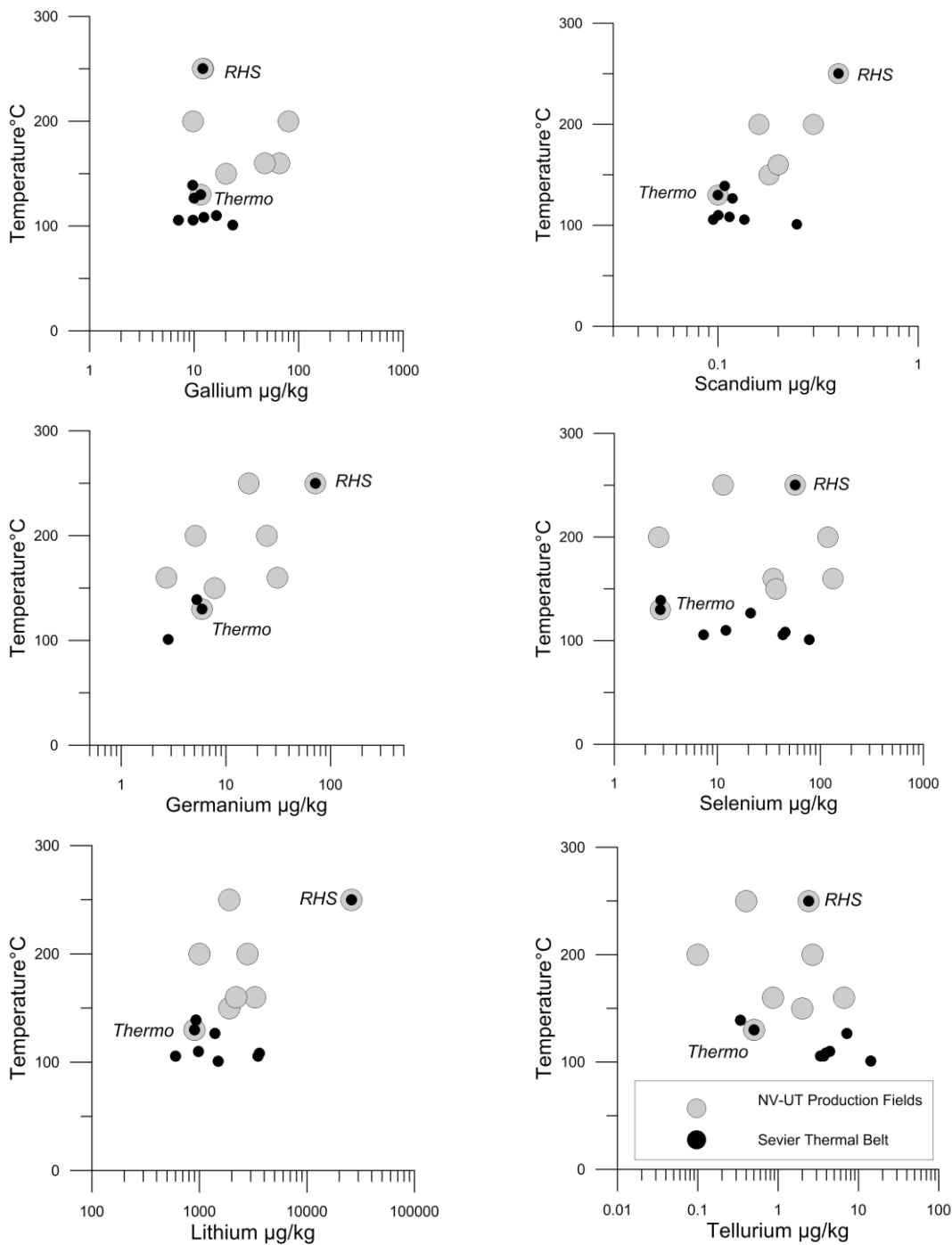


Figure 8. Concentrations (µg/kg) of gallium, germanium, lithium, scandium, selenium, and tellurium in Sevier Thermal Belt and produced geothermal waters (Fig. 2) plotted against measured or quartz-silica equilibration temperatures. Roosevelt Hot Springs (RHS) and Thermo values are denoted by the black-filled circle surrounded by a larger grey-filled circle.

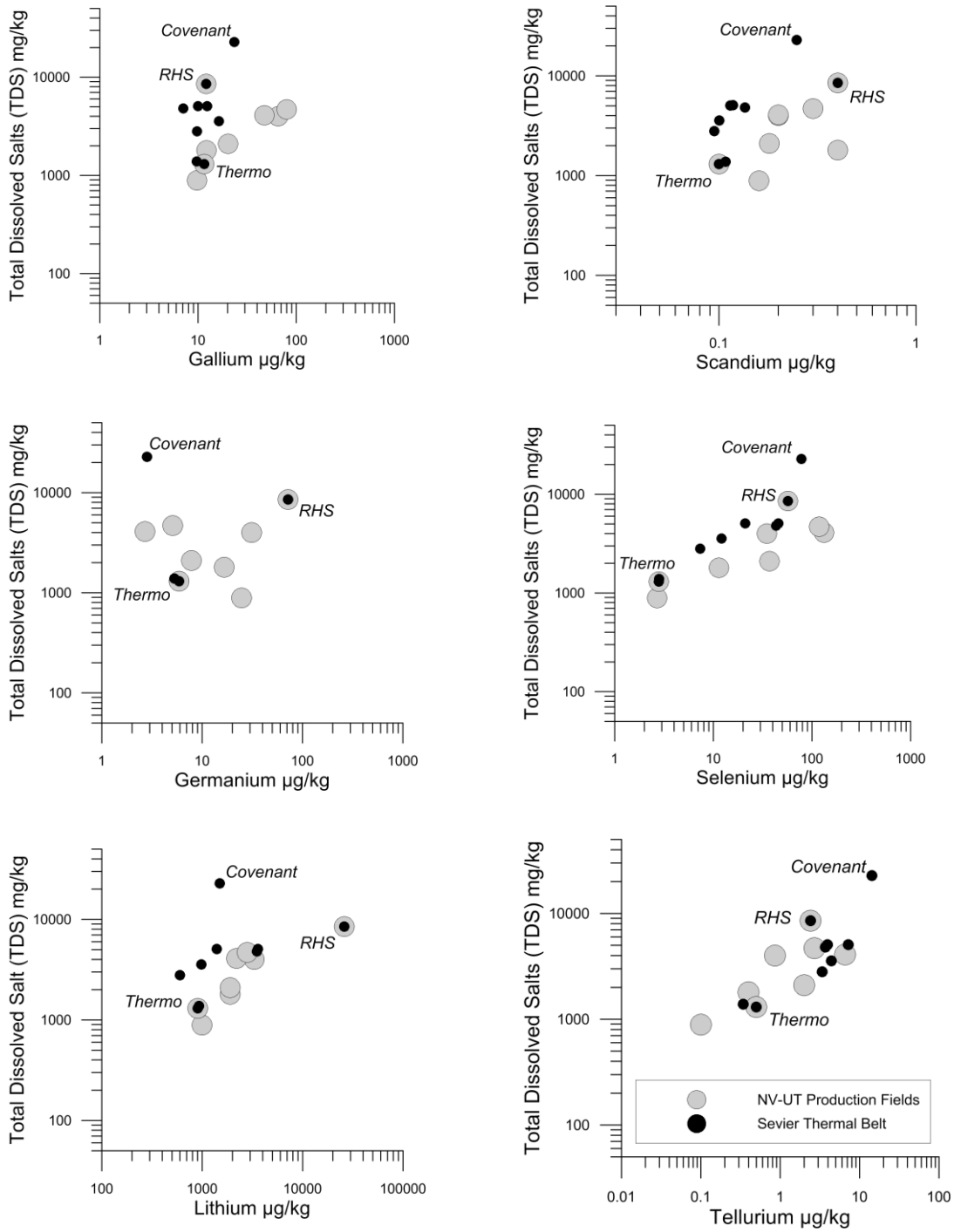


Figure 9. Concentrations ($\mu\text{g}/\text{kg}$) of gallium, germanium, lithium, scandium, selenium, and tellurium in Sevier Thermal Belt and produced geothermal waters (Fig. 2) plotted against total dissolved salts (mg/kg). Roosevelt Hot Springs (RHS) and Thermo values are denoted by the black-filled circle surrounded by a larger grey-filled circle. The most saline water is from the Covenant oil field.

5. COMPARISONS WITH SCVM MINERAL DEPOSITS

SCVM elements are recovered either as primary commodities or as by-products from mining of other metals. For example, nearly 90% of the world production of niobium is from the Araxá niobium mine (Brazil), and gallium is recovered primarily as a byproduct of bauxite extraction or as a byproduct of zinc processing. Whereas niobium, gallium and tellurium are well documented as enriched in specific deposit types, the various geological occurrences of many other SCVM are less well known. The geologic and geochemical processes that lead to ore-grade enrichment of critical elements are summarized in Gunn (2014), Verplanck and Hitzman (2016), and Schulz et al. (2017).

5.1 SCVM Mineral Deposits in Utah and Nevada

The known mineral deposit types with potential for SCVM in Nevada and Utah include: (1) porphyry Cu, (2) epithermal, (3) volcanogenic massive sulfide, (4) skarn, (5) magmatic Ni-Cu, (6) tin-bearing rhyolite commonly associated with porphyry Mo deposits, (7) solution collapse breccias (Kipushi?), (8) heavy mineral sand deposits, and (9) small REE-bearing (allanite) intrusive centers. Specific commodity information and trace element contents of mineral deposits and occurrences are available from <https://mrdata.usgs.gov/mrds/find-mrds.php>.

Gallium (average grade of 0.0419 wt. % or 419,000 µg/kg) and germanium (0.115 wt. % or 1,115,000 µg/kg) were historically considered primary products (along with Cu, Pb, and Ag) of mining from solution collapse breccias in marine carbonate rocks at the Dixie and Apex mines. These are located in southwestern Utah about 140 km southwest of the Thermo hot springs site, and Mississippian-Pennsylvanian limestone locally represent prospective host rocks. Tin-bearing rhyolite porphyry/breccia occurrences at Tetons Breccia, about 30 km west of Thermo hot springs, and the Gallium prospect, located ~70 km southwest of the Roosevelt Hot Springs site, reportedly contain elevated concentrations of gallium and niobium.

Although never historically produced, high average concentrations of tellurium of ~4.8 mg/kg are reported in the Bingham porphyry deposit, Utah. The tellurium-bearing ore minerals volynskite and hedleyite, are relatively common in the Fortitude and Copper Canyon skarn deposits, Nevada, whereas the nearby Telluride vein deposit hosted in shale contains tetradymite, a bismuth-tellurium bearing sulfide mineral; these deposits are located about 45 km west of the Beowawe. Epithermal deposits also have potential for tellurium such as Sleeper in northern Nevada, which is about 35 km north northeast of the Blue Mountain, and Buster, which is about 30 km west of the Patua. Carlin-type deposits having high reported tellurium contents include Getchell (as much as 180 mg/kg), which is located about 75 km northeast of Blue Mountain.

Cobalt concentrations are high in some skarn deposits (Fortitude and Copper Canyon deposits), the volcanic massive sulfide Big Mike deposit (~60 km northeast of Dixie Valley), and in particular in small gabbro-hosted Ni-Co deposits such as Cottonwood Canyon, Bell, and Lovelock deposits (~7 km southwest of the Dixie Valley). Similar to tellurium, epithermal deposits such as Sleeper also contain high cobalt.

Elevated concentrations of selenium occur in the Bingham porphyry Cu deposit (high grade ore averages 12 mg/kg), and in the Mule Canyon epithermal Au-Ag deposit (near Beowawe). Epithermal veins at the Rosebud and Lantern prospects (~50 km southwest of Blue Mountain), the Sleeper deposit, and the Hazel and Green deposits (~75 km west of Dixie Valley and 40 km northeast of Patua) contain elevated selenium, owing to occurrences of naumannite, a silver selenide mineral.

Anomalously high REE-niobium concentrations are reported at the Sheeprock deposit, ~200 km west of the Uinta Basin, and allanite, a REE silicate mineral, occurs in the Red Rock prospect in western Nevada, about 95 km west of Soda Lake, which is likely associated with alkaline intrusive rocks. Heavy mineral sands near Lake Bonneville in Utah, as well as scattered occurrences across western and southern Nevada, contain monazite, sphene, and zircon, and these may contain high concentrations of REE.

5.2 Comparison with SCVM in Produced Waters

Comparative analysis between mineral deposits and produce water compositions is mostly useful for understanding processes controlling gallium, germanium, lithium, scandium, selenium, and tellurium. For other elements, including niobium, platinum group elements, REE, and rhenium, the environments conducive to metal transport and deposition are hotter (>300° C) than those represented by the modern reservoir conditions. It is not surprising that produced thermal waters from Nevada-Utah contain low REE concentrations (<5 µg/kg), as recent compilations for neutral pH waters show these elements are highly insoluble (e.g., Neupane and Wendt, 2017; Smith et al., 2017).

Gallium and germanium are recovered from Mississippi Valley-Type base-metal deposits, which form at <200° C from basinal brines, which is consistent with the high concentrations found in Uinta basin waters compared to Nevada-Utah geothermal waters (Figs. 2 and 3).

Lithium is recovered from brines produced from lacustrine evaporite deposits/salars and from spodumene, a Li-rich feldspar occurring in pegmatites. Of all the SCVM elements evaluated in this study, lithium is the most concentrated metal in produced waters, with Roosevelt Hot Springs having the highest measured concentration (20-30 mg/kg) and the largest calculated inventory (7 million kg; Fig.). For comparison, lithium concentrations in the highly saline brines produced from the Salton Sea contain up to 400 mg/kg Li (McKibben and Hardie, 1997; Neupane and Wendt, 2017).

Scandium is a by-product of mining, including those mined for uranium and REE. Production in the USA is sparse (US Geological Survey Mineral Commodity Summary, 2012), and most scandium comes from deposits in China, Kazakhstan, Russia, and Ukraine.

Produced geothermal waters contain low but measurable concentrations of scandium (0.01-0.5 µg/kg), whereas the Uinta basin waters being slightly lower (0.02-0.2 µg/kg; Figs. 2 and 3).

Selenium and tellurium are commonly found in association with epithermal gold-silver deposits, which form at temperatures of 200-250° C from dilute near neutral pH solutions. The produced geothermal waters represent similar aqueous chemistry, but the concentrations of both elements are relatively low in comparison to the concentrations found in the Uinta basin waters (Figs. 2 and 3). The analysis of Dixie Valley calcite scales contains significant selenium (14 mg/kg) and tellurium (4 mg/kg) suggesting that these elements might be depositing in geothermal wells and pipelines due to boiling. It also suggest that concentrations of these elements in reservoir waters are higher than those measured in water samples acquired from the surface.

6. FUTURE WORK

Additional data will be acquired this year from produced fluids sampled in Idaho, New Mexico, Oregon, and Utah. The plan includes sampling/analysis of produced fluids of oil wells in the Paradox basin. By the end of the project, all of the data will be publically available on the Geothermal Data Repository.

7. ACKNOWLEDGMENTS

This work is sponsored by the DOE EERE Geothermal Technologies Office project DE-EE0007604. Special thanks are extended to Alta Rock, Cyrrq, Newfield, PacificCorp, QEP, Terra-Gen, and US Geothermal for permission and assistance with the sampling of production fluids.

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