

Lithium Resources in Wyoming

**Karl G. Taboga, Wayne M. Sutherland, Robert W. Gregory,
James E. Stafford, and James R. Rodgers**

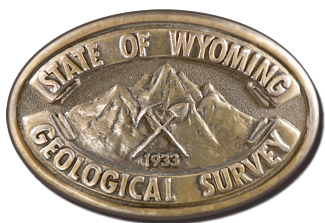


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WYOMING STATE GEOLOGICAL SURVEY

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Spodumene bearing ore from Black Mountain Spodumene Prospect in Natrona County, Wyo. *Photo by Elizabeth C. Cola, 2015.*

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Cover photo: Black Mountain Spodumene Prospect in Natrona County, Wyo. Photo by Elizabeth C. Cola, 2015.

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EXECUTIVE SUMMARY

The Wyoming State Geological Survey (WSGS) was directed by the 62nd Legislature of the State of Wyoming to “evaluate deposits, identify and advance opportunities for resource development and industrial applications for rare earth resources, zeolites, iron and lithium; and provide reports on the findings....” (Enrolled Act No. 41). This report presents the findings from the WSGS investigation of lithium occurrences in Wyoming and includes additional information about lithium in order to understand the state’s resource development potential. Finally, sample descriptions and geochemical data are available on the DVD attached to the inside back cover of this report and on the WSGS website at: www.wsgs.wyo.gov/minerals/wyodog available during the winter of 2016.

For this report, WSGS reviewed geochemical data for nearly 68,000 Wyoming sediment, soil, rock, and water samples obtained from seven state and federal databases. Additionally, WSGS geologists collected nearly 100 rock and soil samples for this study which were evaluated along with over 600 other WSGS samples that were collected in conjunction with other projects. Together, the database records and WSGS collected samples produced lithium concentration data for 26,386 samples; of which 118 had lithium concentrations that exceed 90 mg/L, or parts per million (ppm), which is about five times over crustal abundance (Kamienski and others, 2004). This criterion has been used by the WSGS as an indication that concentrations are anomalous to a degree that may warrant further investigation. However, the 90 ppm level does not indicate that lithium can be recovered economically. Almost all of the world’s lithium supplies are currently produced from subsurface playa brine deposits and mineral ores with minimum lithium concentrations of 200 ppm and 5,000 ppm respectively. Furthermore, the facilities that produce lithium at these minimal concentrations operate under financially advantageous conditions such as low production costs, or reduced capital expenditures.

Stream sediment samples collected and analyzed by the U.S Department of Energy’s National Uranium Resource Evaluation Hydro-geochemical and Stream Sediment Reconnaissance Program (NURE-HSSR) accounted for 88 of the samples above 90 ppm (Smith, 1997). Similarly, a recent USGS soil geochemistry study (Smith and others, 2014) recorded a single soil sample in southern Wyoming with a lithium concentration above 90 ppm. Nearly all of these samples overlie bedrock units containing significant components of volcanic material. The WSGS found no references to global operations that produce lithium from soils or sediments.

Over 7,200 of the water sample analyses reviewed for this report contained lithium concentration data. Lithium levels above 90 ppm were observed in a total of 10 oilfield brine samples listed in the U.S. Geological Survey’s Produced Water Geochemical Database (PWGD, 2015), or in the Wyoming Oil and Gas Conservation Commission’s Water Analysis Database (WADB, 2015). Unfortunately, the water analysis data cannot be independently confirmed for any of these samples and it is not possible to ascertain the quality of this data. Six water samples, collected by the Carbon Management Institute (CMI) from their RSU-#1 well in the Rock Springs Uplift, exhibited lithium concentrations that ranged from 90 to 105 ppm (Surdam and others, 2013). However, none of the world’s currently operating brine facilities produce lithium from brines with concentrations under 200 ppm.

Lithium concentrations exceeded 90 ppm in 22 rock samples collected by WSGS and analyzed by ALS Chemex™. Two samples from the Black Mountain Spodumene Prospect in southwestern Natrona County had lithium concentrations of 2,420 and 7,000 ppm. Both samples were taken from a prospect pit located on a narrow pegmatite near the top of Black Mountain. The spodumene-containing pegmatite is small and there is no known production from it. For comparison, extensive spodumene deposits of 7,000 ppm were actively extracted in the King’s Mountain district of North Carolina until 1998 (Ober, 1998). Although substantial documented reserves still exist there, the mines cannot compete with lithium salts extracted from high grade brines produced in the Atacama Desert in Argentina, Chile and Bolivia.

INTRODUCTION

Lithium (Li) is an element with atomic number 3. In its elemental (metallic) form, it is a soft silver shiny gray-white metal, the lightest of the alkali metal group on the periodic table of elements (fig. 1). The alkali metals group includes sodium, potassium, rubidium, and cesium. Alkali metals are shiny, soft, and highly reactive with water and air. Metallic lithium is so reactive that its elemental form, like other alkali metals, must be stored in mineral oil. If left exposed, metallic lithium quickly reacts with water or air to form lithium oxide (also highly reactive with water) or lithium hydroxide, respectively. Because of these properties, lithium does not occur naturally in its metallic state, but only in the form of various salts.

Lithium was first identified as a new element in samples of petalite ore in 1817 and in the minerals spodumene and lepidolite shortly after (Webelements.com, 2015), but the metallic form was not isolated until 1821. The first major commercial use for lithium was for lithium based aviation lubricants (lithium grease products) during World War II

PERIODIC TABLE OF ELEMENTS

| | | | |
|-----|---|-----|--|
| 1 | H Hydrogen 1.00794 1.400 | 2 | He Helium 4.0026 0.008 |
| 3 | Li Lithium 6.9411 20 | 4 | Be Beryllium 9.0122 3 |
| 5 | B Boron 10.811 10 | 6 | C Carbon 12.0107 200 |
| 7 | N Nitrogen 14.00674 20 | 8 | O Oxygen 15.9994 460.000 |
| 9 | F Fluorine 18.9984 600 | 10 | Ne Neon 20.1797 0.01 |
| 11 | Na Sodium 22.9898 23.000 | 12 | Mg Magnesium 24.305 24.000 |
| 13 | Al Aluminum 26.9815 83.000 | 14 | Si Silicon 28.0855 280.000 |
| 15 | P Phosphorus 30.97384 1.100 | 16 | S Sulfur 32.066 300 |
| 17 | Cl Chlorine 35.4527 130 | 18 | Ar Argon 39.948 3 |
| 19 | K Potassium 39.0983 20.000 | 20 | Ca Calcium 40.078 42.000 |
| 21 | Sc Scandium 44.9559 23 | 22 | Ti Titanium 47.867 6.000 |
| 23 | V Vanadium 50.9415 140 | 24 | Cr Chromium 51.9961 110 |
| 25 | Mn Manganese 54.938 1.000 | 26 | Fe Iron 55.845 58.000 |
| 27 | Co Cobalt 58.9332 27 | 28 | Ni Nickel 58.6934 80 |
| 29 | Cu Copper 63.546 60 | 30 | Zn Zinc 65.39 70 |
| 31 | Ga Gallium 69.723 20 | 32 | Ge Germanium 72.61 4 |
| 33 | As Arsenic 74.9216 2 | 34 | Se Selenium 78.96 0.05 |
| 35 | Br Bromine 79.904 2.5 | 36 | Kr Krypton 83.798 trace |
| 37 | Rb Rubidium 85.4678 90 | 38 | Sr Strontium 87.62 380 |
| 39 | Y Yttrium 88.9059 30 | 40 | Zr Zirconium 91.224 160 |
| 41 | Nb Niobium 92.9064 20 | 42 | Mo Molybdenum 95.94 1.3 |
| 43 | Tc Technetium (98) | 44 | Ru Ruthenium 101.07 0.001 |
| 45 | Rh Rhodium 102.9055 0.001 | 46 | Pd Palladium 106.42 0.01 |
| 47 | Ag Silver 107.8682 0.07 | 48 | Cd Cadmium 112.411 0.2 |
| 49 | In Indium 114.818 0.1 | 50 | Sn Tin 118.71 2.1 |
| 51 | Sb Antimony 121.76 0.2 | 52 | Te Tellurium 127.6 0.001 |
| 53 | I Iodine 126.9045 0.5 | 54 | Xe Xenon 131.29 trace |
| 55 | Cs Cesium 132.9055 2 | 56 | Ba Barium 137.327 400 |
| 57 | La Lanthanum 138.9055 30 | 58 | Ce Cerium 140.116 60 |
| 59 | Pr Praseodymium 140.9077 9 | 60 | Nd Neodymium 144.24 30 |
| 61 | Pm Promethium (145) | 62 | Sm Samarium 150.36 6 |
| 63 | Eu Europium 151.964 2 | 64 | Gd Gadolinium 157.25 6 |
| 65 | Tb Terbium 158.9253 1 | 66 | Dy Dysprosium 162.50 4 |
| 67 | Ho Holmium 164.9303 1 | 68 | Er Erbium 167.26 3 |
| 69 | Tm Thulium 168.9342 0.5 | 70 | Yb Ytterbium 173.04 3 |
| 71 | Lu Lutetium 174.967 0.6 | 72 | Hf Hafnium 178.49 3 |
| 73 | Ta Tantalum 180.9479 2 | 74 | W Tungsten 183.84 1.4 |
| 75 | Re Rhenium 186.207 0.005 | 76 | Os Osmium 190.23 0.003 |
| 77 | Ir Iridium 192.227 0.001 | 78 | Pt Platinum 195.078 0.01 |
| 79 | Au Gold 196.9666 0.004 | 80 | Hg Mercury 200.59 0.08 |
| 81 | Tl Thallium 204.3833 0.6 | 82 | Pb Lead 207.2 13 |
| 83 | Bi Bismuth 208.9804 0.05 | 84 | Po Polonium (209) |
| 85 | At Astatine (210) | 86 | Rn Radon (222) |
| 87 | Fr Francium (223) | 88 | Ra Radium (226) |
| 89 | Ac Actinium (227) | 90 | Th Thorium 232.0381 60 |
| 91 | Pa Protactinium 231.0359 9 | 92 | U Uranium 238.0289 30 |
| 93 | Np Neptunium (237) | 94 | Pu Plutonium (244) |
| 95 | Am Americium (243) | 96 | Cm Curium (247) |
| 97 | Bk Berkelium (247) | 98 | Cf Californium (251) |
| 99 | Es Einsteinium (252) | 100 | Fm Fermium (257) |
| 101 | Md Mendelevium (258) | 102 | No Nobelium (259) |
| 103 | Lr Lawrencium (262) | 104 | Rf Rutherfordium (267) |
| 105 | Db Dubnium (268) | 106 | Sg Seaborgium (269) |
| 107 | Bh Bohrium (270) | 108 | Hs Hassium (277) |
| 109 | Mt Meitnerium (278) | 110 | Ds Darmstadtium (281) |
| 111 | Rg Roentgenium (281) | 112 | Cn Copernicium (285) |
| 113 | Uut Ununtrium (286) | 114 | Fl Flerovium (289) |
| 115 | Uup Ununpentium (288) | 116 | Lv Livermorium (293) |
| 117 | Uus Ununseptium (294) | 118 | Uuo Ununoctium (294) |

| | | | | | | | | | | | | | | | |
|-------------|--|--|--|--|----------------------------------|--------------------------------------|---------------------------------------|--|---------------------------------------|--|---------------------------------------|------------------------------------|---|---------------------------------------|---|
| Lanthanides | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 |
| | La Lanthanum 138.9055 30 | Ce Cerium 140.116 60 | Pr Praseodymium 140.9077 9 | Nd Neodymium 144.24 30 | Pm Promethium (145) | Sm Samarium 150.36 6 | Eu Europium 151.964 2 | Gd Gadolinium 157.25 6 | Tb Terbium 158.9253 1 | Dy Dysprosium 162.50 4 | Ho Holmium 164.9303 1 | Er Erbium 167.26 3 | Tm Thulium 168.9342 0.5 | Yb Ytterbium 173.04 3 | Lu Lutetium 174.967 0.6 |
| Actinides | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 |
| | Ac Actinium (227) | Th Thorium 232.0381 60 | Pa Protactinium 231.0359 9 | U Uranium 238.0289 30 | Np Neptunium (237) | Pu Plutonium (244) | Am Americium (243) | Cm Curium (247) | Bk Berkelium (247) | Cf Californium (251) | Es Einsteinium (252) | Fm Fermium (257) | Md Mendelevium (258) | No Nobelium (259) | Lr Lawrencium (262) |

Figure 1. The Periodic Table of the Elements with lithium highlighted in black.

(WWII). This limited demand for lithium was easily met by production from small mines in the U.S. Demand rose drastically in the years following WWII as lithium was used as a fusion fuel in thermonuclear weapons. With the end of the nuclear arms race, the demand in this sector of the lithium market fell sharply and was replaced by developing commercial demands from the glass making, ceramic, cement, and the aluminum smelting industries. Even with these fluctuations, market demand for lithium was met by U.S. production from the late 1950s to the mid-1980s.

Since 2007, the demand for lithium compounds has risen dramatically for use in rechargeable batteries that power many small, portable electrical devices such as cellphones, digital cameras, watches, cordless power tools and laptop computers (Jaskula, 2015). Additionally, the use of lithium ion batteries in the growing number of electric and hybrid powered vehicles is expected to further increase the demand for lithium compounds well into the future. As of 2011, Chile, Australia, China, and Argentina accounted for most of the world's lithium production (fig. 2) while minor amounts are produced by Portugal, Brazil and Zimbabwe (Jaskula, 2015).

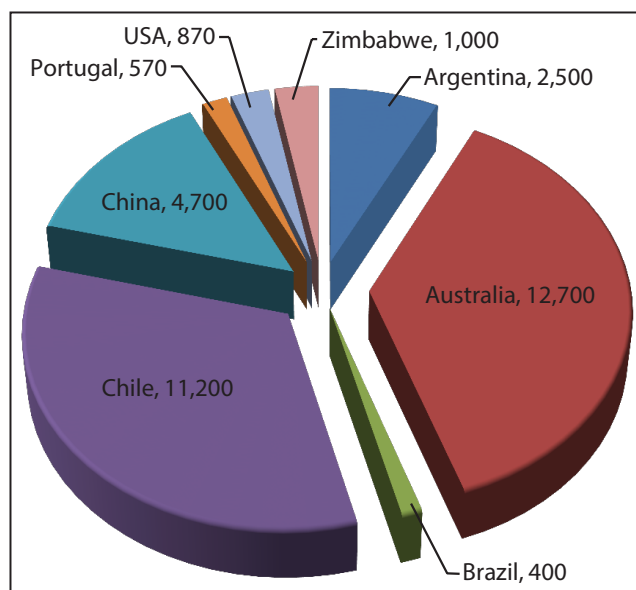


Figure 2. Lithium production for 2014 in tons (Jaskula, 2015).

SCOPE AND RESULTS OF PROJECT

This report summarizes lithium concentration data for numerous samples of various geological materials in Wyoming. The data was obtained from previous geochemical investigations (NWIS, 2015; PWGD, 2015, Smith, 1997; Smith and others, 2014; WADB, 2015) along with some new analyses where information was absent or incomplete. Rock, soil, groundwater, and surface water samples

were analyzed for lithium content as well as for other potential economic elements. Although many samples were collected, sampling of all known or potential lithium occurrences was not possible during the time-frame of the project. An attempt was made for this report to address as many lithium occurrences noted in earlier literature as possible.

Information from this project will provide individuals, consultants, and industry with a base for initiating lithium exploration in Wyoming. Data, including sample analyses, locations, and geologic settings may aid in the identification of not only lithium concentrations, but of other potentially economic elements as well. Educational institutions may use these data to better understand the often complex geologic environments in Wyoming. Decision makers at state and community levels may also find this information useful in identifying potential areas for economic development.

Products of this investigation include this summary report and related maps, a CD with the raw analytical data (attached to inside backcover), and a publicly available online database. The Survey's Wyo-DOG online database includes all elemental analyses along with brief write-ups and photographs for most samples. Wyo-DOG makes the results of this study available to a wide audience for exploration, evaluation, and education.

PREVIOUS LITHIUM INVESTIGATIONS IN WYOMING

The earliest reference to the occurrence of lithium minerals in Wyoming was made by the Territorial Geologist who reported that a Wyoming landowner displayed a large lepidolite crystal found in his beryl mine to dinner guests (Aughey, 1886). Following the development of lithium aviation greases during WW II, the USGS and WSGS reported on the limited occurrence of the lithium bearing minerals spodumene and lepidolite in Wyoming rocks, (Hanley and others, 1950; Osterwald and others, 1959). Hanley and others (1950) noted that neither mineral occurred in mineable quantities in the Wyoming prospects cited. Norton and others (1955) made general reference to the probable occurrence of pegmatites containing petalite, lepidolite, spodumene, and amblygonite in Wyoming but also noted the lack of reported significant deposits.

Interest in the world's lithium resources grew as new applications for lithium compounds were discovered in the 1970s and 1980s. Vine (1975) discussed global lithium resources and reported the existence of an unquantified hectorite clay deposit in Teton County, Wyoming. In the following year, the USGS held a symposium in Golden,

Colorado where a series of papers were presented that discussed global lithium resources and projected requirements by the year 2000 (Vine, 1976). Wyoming resources were mentioned in three papers at the symposium. White and others (1976) looked at lithium levels in the geothermal waters of Yellowstone National Park and Collins (1976) reported elevated lithium concentrations in a few oilfield brines from the Minnelusa and Rock Springs formations. Finally, Clark and others (1976) reported that a query for lithium deposit data from an early USGS mineral database yielded Wyoming records for a spodumene deposit near Black Mountain in Natrona County and numbers for two mining claims staked in areas thought to contain lithium-bearing minerals among other mineral deposits.

Lithium concentration data for Wyoming are found most frequently in broad USGS geochemical studies that examine concentrations of numerous elements in one or more geomaterials. Ebens and others (1982) presented the results from a series of USGS field studies of the geochemistry of rocks, mine spoils, stream sediments, soils, plants, and groundwaters in the western energy region of the United States that included extensive sampling in the Powder River Basin and a few samples collected in the Wind River and Bighorn basins. USGS scientists examined the geochemistry, including lithium, of geothermal waters (Ball and others, 1998a, 1998b, 2001, 2002, 2008, 2010; McCleskey and others, 2004), soils (Shacklette and others, 1973, 1984; Boerngen and others, 1981; Smith and others, 2014), aquatic sediments (Smith, 1997) environmental surface, and groundwater (NWIS, 2015; Smith, 1997) and groundwater produced as a byproduct of oil and gas development (PWGB, 2015; WADB, 2015; NETL, 2015). Results from these studies are summarized in this report, or are specifically cited, in cases where lithium concentrations are sufficiently high to justify further discussion.

LITHIUM OCCURRENCES AND DESCRIPTIONS

Locations, descriptions, and tonnages in this report may not directly coincide with those of earlier reports on lithium in various locations. A detailed search through a number of earlier references uncovered several errors that may have been caused by transposition of numbers, lack of detailed editing, single deposits with more than one name, or a lack of attention to detail. Data in this report was tracked back to original references wherever possible to ensure accuracy of locations and descriptions. Some early reports and letters describe a number of small lithium mineral deposits (Norton and others, 1955) but did not give locations or lacked quantitative data; these lithium occurrences were omitted from this report.

ACCESS

Many areas described in this report may not currently be publicly accessible based on land ownership. Private lands may not be accessed without permission from the landowner. Descriptions of sites that occur on private land or on the Wind River Indian Reservation are compiled from historical sources. Access to the Wind River Indian Reservation can only be obtained by the permission of reservation officials. No sites were visited within the Wind River Indian Reservation. The WSGS does not investigate mineral rights, nor does it provide economic evaluation for specific properties. Evaluations of mineral rights and the economics of specific properties are left to private companies and individuals.

Mining claims may cover some areas of interest, and prospecting cannot be conducted on claims without the claimant's permission. Mining claim information, along with claimant contact information, should be available in the courthouse for the county in which the claim is staked. That information is also available at the U.S. Bureau of Land Management (USBLM), Wyoming State Office in Cheyenne. The phone number for the USBLM in Cheyenne is 307-775-6200, and their web page is www.blm.gov/wy/st/en.html. Contact information for claimants may also be found on claim posts that mark the claims on the ground.

Public lands administered by the State of Wyoming, the U.S. Forest Service (USFS), or the USBLM each have their own set of rules governing these activities in specific areas. Check with the proper agency before proceeding. USBLM information concerning exploration and development regulations for locatable minerals are found at www.blm.gov/wy/st/en/programs/mineral_resources/Surface.html.

The USBLM and USFS have both produced maps that show general land ownership. The WSGS publications sales desk (307-766-2286 or <https://sales.wsgs.wyo.gov/catalog/index.php>) carries many of these maps. However, land ownership changes with time and current land ownership information can only be obtained from the Tax Assessor's office within the particular county of occurrence.

TERMINOLOGY

Ore

The term "ore" generally refers to material from which minerals or elements of economic value can be extracted at a reasonable profit, and is often appended with the type of metal in the ore, such as iron ore (Neuendorf and others, 2005). This is also the historical definition of ore. However, in common usage, the term is often loosely

applied to material from which someone hopes to derive economic gain (Sutherland and Cola, 2015). Descriptions of lithium deposits within this report use the term “ore,” or “lithium mineral ore,” in its historical sense as the deposits were described in the referenced sources. No current economic extraction from these deposits is implied. The current potential for economic extraction of lithium from these deposits can only be determined through detailed evaluations using modern exploration techniques.

Resources vs Reserves

Resources and reserves, as applied to the amounts of a valuable mineral commodity in any particular deposit, have often had a variety of meanings to geologists and mining engineers. The USGS (1980), in collaboration with the U.S. Bureau of Mines (USBM), defined the terms resources and reserves, along with modifiers for subcategories of each, for more precise usage in relation to mineral deposits. A resource is a concentration of material in such form and amount that economic extraction of a commodity from the concentration is potentially or currently feasible. A reserve applies to a concentration of material that, using current technology, is demonstrated to be economically extractable. For clarity, geographic and geologic parameters, along with the author and date of the measurements or estimates must be included. Various modifiers may be applied to these terms to add more detailed meanings.

Since these terms have economic implications, the USGS and the USBM emphasized that the use of them must be continuously reassessed based on improving geologic knowledge, advances in technology, and changes in economic and political conditions. These terms were redefined, with minor modification, by the Canadian Institute of Mining, Metallurgy and Petroleum (Postle and others, 2000) to ensure uniformity of their usage and to clarify other definitions that are used in Canadian National Instrument 43-101 (NI 43-101).

NI 43-101 is a rule issued by the Canadian Securities Administrators, last updated in 2011, designed to promote public confidence in mining-related stocks through enhanced accuracy and integrity of public disclosures related to mining and to ensure that misleading or fraudulent data related to mineral properties is not presented to investors in stock exchanges under the Canadian Securities Authority. NI 43-101 governs public disclosures of scientific and technical information by publicly-traded mining companies, including oral statements, websites, and written documents. NI 43-101 is generally accepted internationally and several exploration and mining companies operating in Wyoming use this standard and are listed on Canadian stock exchanges (Sutherland and Cola, 2015).

In this report, metric tons (tonnes) or short tons (tons) at a particular grade have been cited from various references. The historic figures are all cited in their original unit of tons; the few modern figures include both tonnes and tons. Similarly, U.S. feet and miles are used from historical citations without metric conversions. One tonne is equal to 1000 kilograms (kg) or 2,204.62 pounds (lb); one ton is approximately equal to 0.907 tonnes or 2000 lbs or approximately 907.2 kg. No statement as to the current economics, potential for development, or to the lack thereof for any deposit within this report is implied.

SAMPLES AND ANALYSES

For this study, WSGS geologists reviewed lithium concentrations for thousands of historical samples obtained from databases compiled by state and federal scientific and environmental agencies. Additionally, WSGS geologists obtained rock and playa deposit samples at selected sites to augment the historical data.

Samples collected during this investigation are grab samples (i.e. small, unmeasured samples), not necessarily representative of a larger volume of material. Analyses of these grab samples can neither confirm nor deny the presence or absence of economic concentrations of lithium or other elements. A grab sample only represents one small piece of evidence for the occurrence of a mineral concentration or deposit. The grab sample is not associated with nor does it indicate a volume of material greater than the size of the individual sample. The elemental concentrations associated with a grab sample may or may not extend into the geologic unit from which the sample was collected (Sutherland and Cola, 2015).

A thorough assessment of a deposit, as opposed to a survey of occurrences as presented in this report, requires evaluation of multiple samples across the range of geologic environments that occur at a specific location. Each of those samples must represent a specific volume of relatively uniform material such that elemental concentrations can be converted to tonnage estimates across the deposit. Only then can the economic tenor of the deposit be estimated. No single sample can define, identify, or eliminate the possibility of an economic deposit (Sutherland and Cola, 2015).

Analytical units are those expressed in the references cited or in values as received from an analytical laboratory. Lithium content is often listed in terms of parts per billion (ppb) or its metric equivalent, micrograms per liter ($\mu\text{g/L}$), or in parts per million (ppm) or its metric equivalent, milligrams per liter (mg/L) under the headings “lithium” or “Li.” In some cases, a lithium concentration is listed as a

percent of the total mass of the sample. To convert percent to ppm, or mg/L, 1.0 percent is equal to 10,000 ppm.

All analyses of samples obtained by WSGS for this project were completed by ALS Chemex™ of Reno, Nevada. Analytical methods for historical samples included within this report or in Wyo-DOG are referred to as generic if either the laboratory or the method of analysis is not known. Geochemical analyses on rock and soil samples included whole media analyses (major element concentrations) by inductively coupled plasma (ICP), atomic emission spectrometry or mass spectrometry, and atomic adsorption. These methods, when preceded by effective preparation techniques, can generally detect most elements in a sample from very low concentrations in the range of less than 0.1–5 parts per million (ppm) up to concentrations that are considered to be economically developable.

LITHIUM CHARACTERISTICS

Lithium is the earth's 25th most abundant element. It is present in many geologic materials but almost always in low concentrations (<20 ppm). The earth's crust is thought to contain 20 – 70 ppm of lithium by weight (Kamienski and others, 2004). Lithium contents of saline/briny surface waters range from about 0.2 ppm in seawater (Anthoni, 2006), to 18 ppm in the Dead Sea (Epstein and others, 1981), to 30 – 60 ppm in the Great Salt Lake (Butts, 1975). Garrett (2004) notes in *The Handbook of Lithium and Natural Calcium* that, "There are a fairly large number of both lithium mineral and brine deposits but only comparatively few of them are of actual or potential commercial value. Many are very small; others are too low in grade."

USES OF LITHIUM

Lithium was first identified as a new elemental component of the mineral petalite in 1817 (webelements.com, 2015) and isolated in 1821. During the 19th century, lithium salts were used on a limited medicinal basis to treat the complications associated with gout and some psychological conditions such as "nervousness" (Johnson and Amdisen, 1983). The first commercial application of lithium was limited to its use in alloys of lead for the German railway industry in the mid-1920s (rockwoodlithium.com, 2015). Demand for lithium compounds grew rapidly, however, with the development of lithium aircraft greases during WW II. Demand increased further during the arms race of the Cold War with the use of lithium compounds in the production of nuclear fusion weapons. As the nuclear arms race wound down, new industrial applications for lithium were being developed in the production of glass and ceramics. While, the manufacture of these materials currently dominate the lithium market, accelerating growth in the use of rechargeable batteries will drive industry demand

for lithium compounds in the near future (Jaskula, 2015). Proportions of demand for other uses (lubricating greases, certain air conditioning processes, aluminum production, and other metallurgical production, and pharmaceuticals) have decreased in recent years (fig. 3). Other chemical compounds can be substituted for lithium salts in ceramics and glass, rechargeable batteries, aluminum alloys, and lubricants. Further commercial development of lithium replacement compounds may take place as industry technology improves or as the costs of using replacement compounds decrease (Jaskula, 2015).

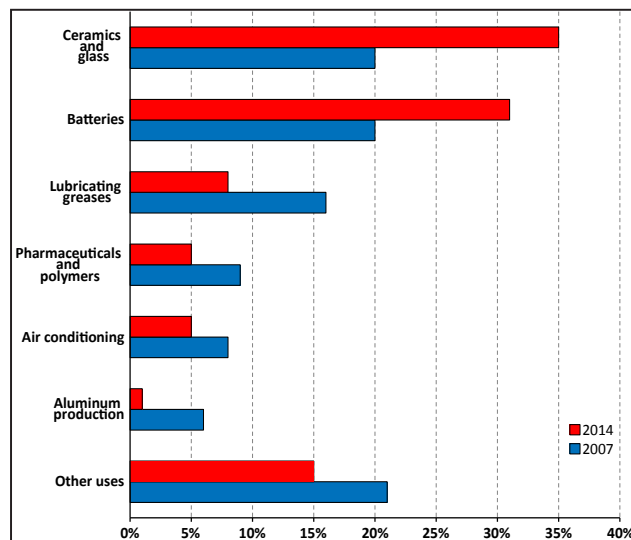


Figure 3. Comparison of primary uses for lithium compounds for the years 2007 (blue) and 2014 (red). Adapted from Jaskula (2015) and Ober (2008).

WORLD LITHIUM SUPPLIES (JASKULA, 2015)

The production of lithium has changed greatly over the past century as new industrial uses for lithium compounds were discovered. The limited demand for lithium was easily met by U.S. hard rock mining operations until the mid-1980s. As demand increased, mining companies developed processes to recover lithium from brine pools and subsurface brine deposits associated with saline lakes first in California and Nevada then subsequently in Argentina and Chile. Currently, Australia, Chile, and China account for about 84 percent of global annual lithium production. Furthermore, these countries hold over 90 percent of the entire world's identified reserves (table 1).

At the time of this report, two brine operations in Chile and the Greenbushes spodumene mine in Australia produce the majority of the world's lithium. Numerous lithium mining operations are in various stages of development throughout the world; the most promising of which is the Salar de Uyuni in Bolivia, thought to contain 5 – 9 million tons of

lithium salts. Other prospects are under development in Ireland, Congo, Serbia, Russia, Argentina, Canada, and Finland.

Table 1. Current estimates of identified lithium reserves and resources (in tons) by country. Values for world totals are rounded (Adapted From Kesler and others, 2012).

| Country | Reserves (tons) | Identified Resources (tons) |
|--------------------|-------------------|-----------------------------|
| Argentina | 850,000 | 6,500,000 |
| Australia | 1,500,000 | 1,700,000 |
| Bolivia | N/A | 9,000,000 |
| Brazil | 48,000 | 180,000 |
| Canada | N/A | 1,000,000 |
| Chile | 7,500,000 | 7,500,000 |
| China | 3,500,000 | 5,400,000 |
| Congo D.R. | N/A | 1,000,000 |
| Portugal | 60,000 | N/A |
| Russia | N/A | 1,000,000 |
| Serbia | N/A | 1,000,000 |
| USA | 38,000 | 2,000,000* |
| Zimbabwe | 23,000 | N/A |
| World total | 13,500,000 | 36,300,00 |

* actual data is proprietary

Production in the U.S. is limited to a single brine operation owned by Rockwood Holdings (recently acquired by Albemarle Corporation) in Silver Peak, Nevada. In 2014, Simbol Materials began construction of a lithium recovery facility on the Salton Sea in California (The Desert Sun, 2014). It is expected that mineral companies will look for other sources of lithium in North America as industrial demands grow. Currently, several companies are exploring additional brine recovery operations in Nevada. Recycling will probably provide additional sources although the technology is in the early stage of development. Retrieval Technologies™ (formerly Toxco Inc.) of Anaheim, California has developed a patented process for recovering and regenerating lithium batteries (Retrievtech.com, 2015).

LITHIUM PRICES, PRODUCTION AND FUTURE DEMAND (JASKULA, 2015)

Lithium prices are given per metric ton which equals about 2,205 pounds or 1.1023 U.S. tons. Lithium carbonate prices hovered around \$1,500 per metric ton from 2000 to 2004. Prices increased threefold to \$4,530/metric ton from 2004 to 2008 as demand grew, largely with the increased use of lithium ion batteries in consumer goods. Prices levelled off briefly following the Financial Crisis of 2008 – 2009 and then resumed their upward trend.

Although prices showed a moderate decrease in 2014, lithium carbonate sold for around \$6,500, per metric ton (fig. 4), a price increase of greater than 300 percent over 2004 levels. During the same period, annual global production increased from around 14,000 tons to 36,000 tons. Production declined steeply in 2009 but then recovered the following year and has since followed a generally upward trend.

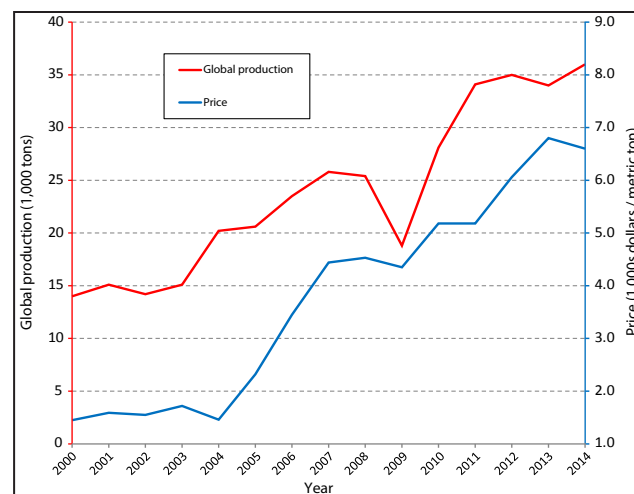


Figure 4. Annual global production of lithium compounds in 1,000 tons (shown in red) and price of lithium carbonate in \$1,000 dollars/metric ton (shown in blue) from Jaskula (2015).

The demand for lithium compounds is expected to grow drastically in the next 35 years at a rate that will outstrip the growth in production using currently available methods. Although short term supplies appear to be adequate, annual demand is expected to reach up to 280,000 metric tons by 2030 and nearly 1,000,000 metric tons by 2050 (Mining.com, 2015). Over the long term, improved extractive technologies may combine with continued price increases to make extraction from lower grade deposits profitable. Until that time, new prospects may need to be found and developed.

EXTRACTION OF LITHIUM

This section of the report contains an overview of the processes commonly used in industry to extract lithium compounds from ores and brines. Further information regarding new or developing extractive technologies can be found online by searching “Lithium Extraction Processes” or by searching online records on the U.S. Patent Office website.

Historically, lithium compounds were most often extracted from pegmatitic ores that contain adequate concentrations of lithium bearing minerals such as spodumene and petalite. However, by the mid-1980s, extraction of

lithium compounds from saline continental brines began on a commercial scale at the Salar de Atacama in Chile (Rodinia, 2015). More recently, other geomaterials that contain appreciable levels of lithium salts, with example locations in parentheses, such as geothermal brines (Salton Sea, California), oilfield brines (Valleyview Project, NW Alberta, Canada) and hectorite clays (Kings Valley Clay Mine Project, Nevada) have attracted the attention of mineral development companies.

Generally, extraction from lithium rich brines is much less time, energy and cost intensive than extraction from hard rock ores. (Rodinia, 2015). Commonly, production costs for brines are about one half of those for processing pegmatitic ores. The main lithium producers from brines in Chile and Argentina, where lithium grades are high and contamination by deleterious elements is low, have the lowest operating costs (around \$2,000 to \$2,200 per metric ton). Whereas, producers of brine-based lithium carbonate in the Tibet region of China have higher operating costs, typically over \$3,000 per metric ton. In comparison, Australian, Canadian, and Chinese mineral ore-based lithium producers (as well as Portugal and Zimbabwe) have operating costs that range from nearly \$3,500 to \$5,000 per metric ton (Orocobre, 2015). The lower production costs for brine operations have created a shift away from ore mining and processing toward brine production and extraction. Mining operations have been suspended at several existing lithium ore mines (e.g. King's Mountain, N.C.) because of the comparably low operating costs associated with brine extraction (Jaskula, 2015).

The extraction of lithium from an ore deposit (About money.com, 2015) requires first the presence of an economically developable grade of lithium. Lithium grades for several pegmatite mineral mines are listed in table 2. Once the ore is mined, the extraction of lithium involves several energy intensive hydrometallurgical processes. The spodumene ore is first crushed and ground into powder. Due to the hard and abrasive nature of pegmatitic ores this process, called "comminution," accounts for up to 50 percent of the processing cost. The crushed ore is then heated in a rotary calcining kiln at temperatures above 1400° F to create an acid leachable mineral concentrate (calcination). The resultant concentrate is mixed with sulfuric acid and heated again to leach metals into a concentrated lithium enriched chemical liquor. The liquor is filtered, purified and treated with soda ash. Lithium is then precipitated out as a carbonate. Production costs from pegmatitic ores are determined by the costs of mining, comminution, calcination, leaching with sulfuric acid, and the conversion of the lithium sulfate solution with sodium carbonate (soda ash). In addition to the cost of comminution, the costs of acid, soda ash and energy constitute a significant percentage of total costs.

Lithium extraction from other minerals (petalite, lepidolite, jadarite, hectorite, zinnwaldite, polyolithionite, or amblygonite) may require further hydrometallurgical treatments.

Table 2. Lithium grades, in parts per million (ppm), for ore mines located throughout the world (Adapted From Kesler and others, 2012).

| Ore Deposit | Status | Grade (ppm) |
|-----------------------------------|--------------|-------------|
| Greenbushes, Australia | In operation | 14,000 |
| Kings Mountain, USA | Abandoned | 7,000 |
| Bessemer City, N.C., USA | Abandoned | 6,500 |
| Minono-Kitolo, Dem. Rep. of Congo | In operation | 6,500 |
| Bikita, Zimbabwe | In operation | 6,300 |
| Tanco, Canada | In operation | 6,200 |
| Vishnyakovskoe, Russia | In operation | 5,000 |

As with ore deposits, lithium recovery from brines requires the presence of economically recoverable concentrations of lithium (table 3). However in contrast to lithium extraction from ores, brine extraction techniques generally require less energy intensive techniques. In South America, the brine is pumped to the surface into evaporation ponds where the Atacama Desert's high solar evaporation rates enrich the brine's salt concentrations over the course of several months (Rodinia, 2015). The concentrated brine is then shipped to a processing plant where lithium salts and the other recoverable products (compounds of potassium and boron) are recovered and purified. The recovered lithium salts may be treated with soda ash and then precipitated out as a carbonate or left, untreated, as lithium chloride. Processing costs for brines vary widely and depend on local evaporation/rainfall rates, the cost of soda ash, the lithium grade of the raw brine, the geographic location of deposits, and the presence of other recoverable products or of deleterious elements, particularly magnesium.

Table 3. Lithium content, in parts per million (ppm), for brine operations located throughout the world (Adapted From Kesler and others, 2012).

| Brine Deposit | Status | Content (ppm) |
|--------------------------|----------------|---------------|
| Zabuye, China | In operation | 1,500 |
| Atacama, Chile | In operation | 1,400 |
| Olaroz, Argentina | In operation | 800 |
| Uyuni, Bolivia | In development | 600 |
| Hombre Muerto, Argentina | In operation | 600 |
| Rincon, Argentina | In operation | 350 |
| Silver Peak, NV, USA | In operation | 200 |

Many alternate extraction technologies are currently being developed and evaluated. Simbol Materials, LLC is investigating the use of reverse osmosis filtration technologies to recover lithium salts from geothermal brines extracted from the Salton Sea. According to Simbol, the recovery process produces high-purity lithium hydroxide in 90 minutes to two hours as opposed to the 18 months required for conventional brine evaporation operations. At present, however, recovery rates and production costs have not been released to the public (Power, 2015).

MINEROLOGY OF LITHIUM DEPOSITS (WEBMINERAL.COM, 2015)

Lithium mineral deposits are found throughout the world. These deposits occur in pegmatites or in geological settings derived from pegmatitic deposits such as hectorite clays and various naturally occurring brines. Spodumene, petalite, lepidolite, hectorite, zinnwaldite, and amblygonite are important lithium bearing minerals.

Spodumene: $\text{LiAl}(\text{SiO}_3)_2$

Spodumene, a lithium aluminum silicate, has a lithium content of 3.73 percent by weight. Spodumene is called Hiddenite if it is emerald green and Kunzite if colored pink, violet or purple. A small spodumene deposit is located northwest of Casper by Black Mountain in the Rattlesnake Hills.

Petalite: $\text{LiAlSi}_4\text{O}_{10}$

Petalite is a phyllosilicate mineral and a member of the feldspathoid group. It occurs as a colorless, gray, yellow or white mineral in granitic pegmatites often in association with other lithium bearing minerals such as spodumene, lepidolite and tourmaline. It usually occurs in massive groups of indistinguishable crystals. It contains 2.09 percent lithium by weight. Hanley and others (1950) reported an occurrence of petalite in the Whippet No. 8 prospect in Fremont County.

Lepidolite: $\text{K}(\text{Li},\text{Al})_3(\text{Si},\text{Al})_4\text{O}_{10}(\text{F},\text{OH})_2$

Lepidolite is a phyllosilicate mineral and member of the mica group. It is found in granite pegmatites often associated with other lithium bearing minerals such as spodumene. It is a colorless, gray, yellow, lilac, or white platy mineral. Lepidolite contains 3.58 percent lithium by weight. Hanley and others (1950) reported an occurrence of lepidolite in the Whippet No. 1 prospect in Fremont County. The earliest reference to the occurrence of lithium minerals in Wyoming was made by the Territorial Geologist who reported that a Wyoming landowner displayed a large lepidolite crystal found in his beryl mine to dinner guests (Aughey, 1886).

Triphylite: $\text{LiFe}^{2+}\text{PO}_4$

Triphylite is a greenish gray or brownish phosphate crystalline mineral that contains 4.40 percent lithium. This mineral has not been reported in Wyoming.

Zinnwaldite: $\text{KLiFe}^{2+}\text{Al}(\text{AlSi}_3)\text{O}_{10}(\text{F},\text{OH})_2$

Zinnwaldite is a phyllosilicate mineral and member of the mica group. It is brownish mineral with shades of green, yellow, gray, and violet found in topaz bearing pegmatites. Zinnwaldite has a lithium content of 1.59 percent by weight. This mineral has not been reported in Wyoming.

Amblygonite: $(\text{Li},\text{Na})\text{Al}(\text{PO}_4)(\text{F},\text{OH})$

Amblygonite is a fluorophosphate mineral that occurs in granite pegmatites usually associated with other lithium bearing minerals such as spodumene, lepidolite and tourmaline. Amblygonite contains 3.44 percent lithium by weight. It is generally white, but can also be yellow, gray, bluish gray, or greenish gray. This mineral has not been reported in Wyoming.

Hectorite: $\text{Na}_{0.3}(\text{Mg},\text{Li})_3\text{Si}_4\text{O}_{10}(\text{OH})_2$

Hectorite is a white clay mineral of the smectite group that is formed by the reaction of volcanic tuff ash with geothermal waters. It contains 0.54 percent lithium. Based on a personal communication with J.D Love, Vine (1975) reported the existence of an unquantified hectorite clay deposit in Teton County, Wyoming.

GEOLOGY AND OCCURRENCES OF LITHIUM MINERALS AND BRINES IN WYOMING

Although lithium occurs in numerous minerals and brines, relatively few deposits with significant concentrations occur in Wyoming. WSGS reviewed lithium concentration data for thousands of samples in numerous types of geomaterials (table 4).

This section contains descriptions of the available lithium data as well as discussions of the occurrence of lithium at concentrations that equal or exceed 90 ppm which is about five times the minimum estimated crustal abundance of lithium. It should be pointed out that 90 ppm is below levels that are currently being mined commercially across the world. To facilitate discussion and visualization, the numerous datasets shown in table 4 were sorted based on sample type and the number of data points into similar groups:

- USGS National Water Information System (NWIS) Data

- USGS Produced Waters Geochemical Database (PWGD) and WOGCC Water Analysis Database (WADB)
- NURE – Hydrogeochemical Water Data
- NURE – Stream Sediment Data
- WSGS Rock and Playa Sample Data, and USGS Soils Data

USGS National Water Information System (NWIS, 2015)

The USGS NWIS database contains water quality analysis data from one or more historical samples obtained at 6,593 sites in Wyoming. Site types include lakes, streams, canals and ditches, groundwater wells, and wetlands. The USGS

Wyoming-Montana Water Science Center in Cheyenne, Wyoming queried the NWIS database and provided WSGS with water quality data all for samples with lithium results (2,903 samples). Lithium levels in these samples ranged from 0.00 – 4.60 mg/L (ppm) (fig. 5).

USGS Produced Water Geochemical Database (PWGD, 2015), WOGCC Water Analysis Database (WADB, 2015 and Surdam and others, 2013)

WSGS examined water quality analysis records obtained from oil and gas wells in Wyoming. The records are shared and managed by three agencies: the USGS, the WOGCC and the National Energy Technology Laboratory (NETL), and there is considerable duplication between their respective databases. The USGS PWGD contains water analysis data for 24,290 water samples. Much of this data originated

Table 4. Sample data reviewed for this report.

| Agency | Program | Number of samples | Host media | Number of samples with lithium data | Samples of interest |
|---------------------------------|------------------------|-------------------|--|-------------------------------------|--------------------------------------|
| United States Geological Survey | NWIS ¹ | 6,593 | Environmental water samples | 2,903 | 0 (Max: 5.52 ppm) |
| | PWGD ² | 25,041 | Produced water samples | 1,571 | 10 over 90 ppm |
| | MAS ³ | 5,219 | Mineral Resources (Bureau of Mines data) | 5 claims; no concentrations | Claims, prospects: no concentrations |
| | MRDS ⁴ | 1,400 | | 2 claims; no concentrations | Claims, prospects: no concentrations |
| | Soils ⁵ | 486 | Soils | 481 | 1 over 90 ppm |
| U.S. Atomic Energy Commission | NURE-HSSR ⁶ | 11,118 | Streams, marshes | 1,208 | 0 (Max: 1.261 ppm) |
| | | | Wells - groundwater | 1,001 | 0 (Max: 0.868 ppm) |
| | | | Springs - groundwater | 370 | 0 (Max: 0.888 ppm) |
| | | | Artificial ponds | 141 | 0 (Max: 1.377ppm) |
| | | | Natural ponds | 29 | 0 (Max: 0.336 ppm) |
| | | 18,424 | Sediments | 17,956 | 88 over 90 ppm |
| Wyoming Oil and Gas Commission | WADB ⁷ | ---- | Produced water | 21 | 1 over 90 ppm |
| WSGS | REE/Li ⁸ | 646 | Rock and soil samples | 646 | 19 over 90 ppm |
| | | 51 | Playa soil samples | 51 | 0 (Max: 37.7 ppm) |
| Carbon Management Institute | RSU#1 ⁹ | 6 | Water samples | 6 | 6 over 90 ppm |
| Total | | | | 26,384 | 124 |

¹National Water Information System

²Produced Waters Geochemical Database

³Minerals Availability System

⁴Mineral Resources Data System

⁵Smith and others, 2014

⁶National Uranium Resource Evaluation Hydro-geochemical and Stream Sediment Reconnaissance Program

⁷Water Analysis Database

⁸WSGS Rare Earth Elements and Lithium Database

⁹Surdam and others, 2013

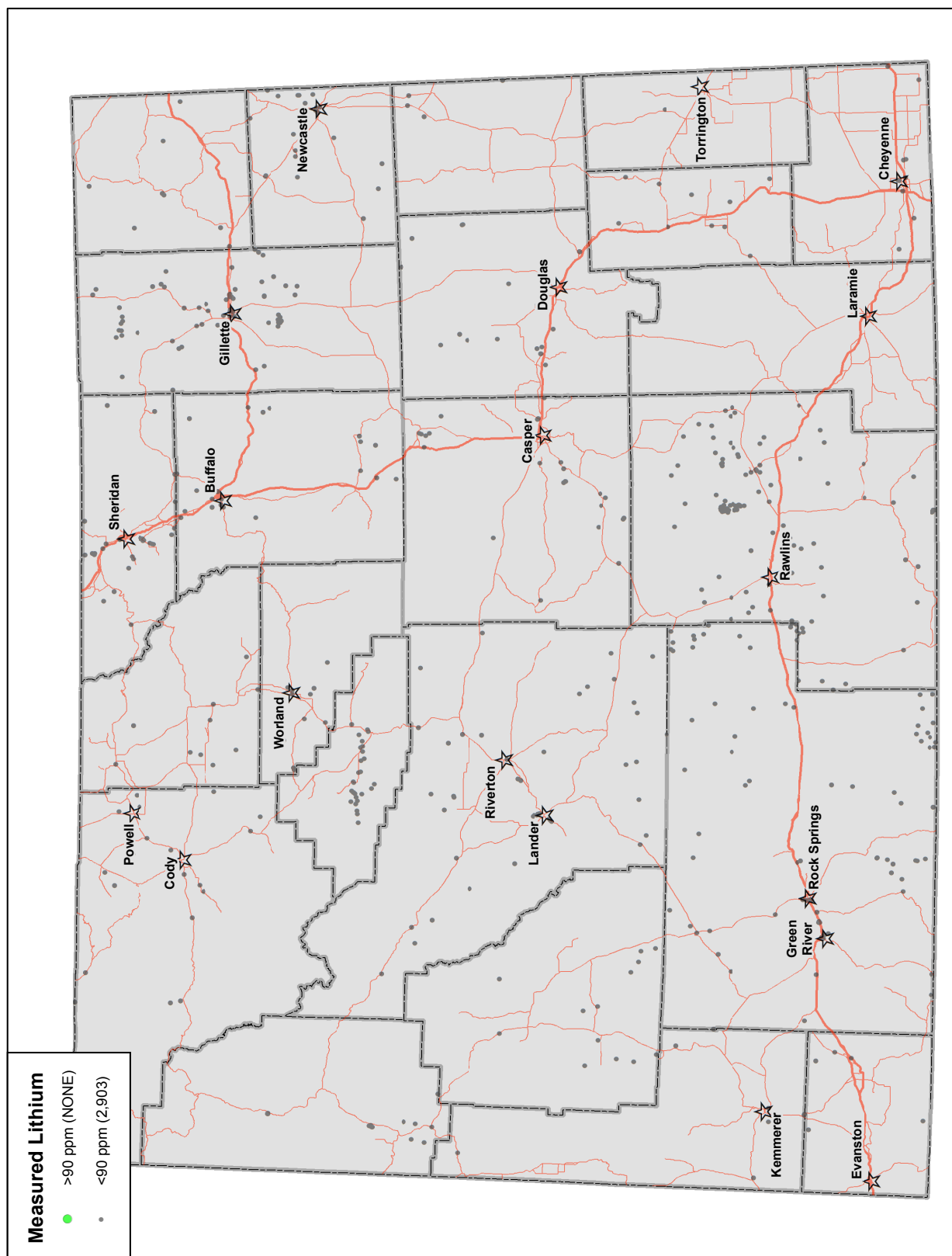


Figure 5. National Water Information System (NWIS) water samples with lithium concentration data (NWIS, 2015).

with the WOGCC WADB which currently includes water quality records for over 11,000 samples. After removing duplicate records, WSGS extracted 1,635 unique records with lithium values from the PWGD and the WADB. Twenty one WADB records, all dated after 12/31/2012 were not found in the PWGD. WSGS also compared water analysis records for 7,909 Wyoming samples from the National Energy Technology Laboratory (NETL) and determined that all of the NETL records were included in the WADB and the PWGD (fig. 6).

These three databases contain water quality analyses on samples that were collected by oil and gas companies and their contractors since the early 1900s. The USGS makes the following disclaimer: “The information in the USGS National Produced Waters Geochemical Database v2.1 should be used with careful consideration of its limitations. The database is considered sufficiently accurate to provide an indication of tendencies in water composition from geographically and geologically defined areas. It is not appropriate for depiction of modern produced water compositions or examination of trends on small scales. The USGS makes no warranty regarding the accuracy or completeness of information presented in this database. Specific limitations of the database should be considered. Much of the information in the database cannot be independently verified.” The full disclaimer is available online, http://energy.usgs.gov/Portals/0/Rooms/produced_waters/text/USGS_Produced_Waters_Database_Documentation.pdf.

Ten water quality analyses showed lithium concentrations that exceeded 90 ppm; see table 5. The samples in the top two rows, both with API number 4902510731, appear to have been taken from the same tank two days apart (June 19 and 21, 1979) and have identical lithium concentrations. In fact, the two samples share identical concentrations for a number of constituents (Ca, HCO₃, Cl, Na, etc.) and appear to be duplicates. The unusually high lithium levels appear anomalous and may indicate contamination within the tank by lithium soap or grease. The well was resampled in 1980 and lithium levels were 0.00 (which may indicate that lithium levels were not analyzed), but sodium, potassium, calcium and chloride levels in the 1980 sample differ markedly from those listed in the June 1979 analysis.

In fact, it is not possible to confirm the elevated lithium levels given for any of the oil and gas wells listed in table 5. No further information can be found on the two wells without API numbers. Water analyses could not be confirmed for the Blair or Minnelusa Formation wells (API numbers 4903705098, 4900506399, 4900505284, 4900505074) all of which have been plugged and abandoned. The Bear River - Frontier well has only the one analysis conducted in 2012. The Parkman Formation well

had an earlier water analysis with a lithium concentration of zero. Charge balance calculations for both the Bear River-Frontier and the Parkman wells produce the best results if lithium concentrations are omitted, suggesting that the elevated concentrations as given are anomalous or in error.

Six water samples, collected by the Carbon Management Institute (CMI) from their RSU-#1 well in the Rock Springs Uplift, exhibited lithium concentrations that ranged from 90 to 105 ppm (Surdam and others, 2013). However, none of the world’s currently operating brine facilities produce lithium from brines with concentrations under 200 ppm.

Another possible explanation for some of the elevated lithium levels seen in produced water samples is the use of hectorite clays as an additive in oil based drilling muds. As noted in the Minerology section of this report, hectorite contains 0.54 percent lithium by weight. The Schlumberger Oilfield Glossary (2015) contains the following description of hectorite, “A clay mineral similar in structure to bentonite but with more negative charges on its surface. Organophilic hectorite, made by the wet process, is a premium performance additive for use in oil-base drilling mud.”

National Uranium Resource Evaluation (NURE) Hydrogeochemical Water Data (Smith, 1997)

The U.S. Department of Energy’s National Uranium Resource Evaluation (NURE) Hydro-geochemical and Stream Sediment Reconnaissance Program collected 11,118 hydrologic samples for analysis in Wyoming. The Los Alamos Scientific Laboratory, New Mexico analyzed most of the samples collected in the Rocky Mountain States for a wide suite of chemical and isotopic constituents. Lithium concentrations in water samples were determined using Optical Emission Spectrochemical (ICP) Analysis. Only 2,748 samples had non-zero lithium concentrations; the maximum concentration was 1,377 parts per billion, or 1.377 ppm observed in an artificial pond sample from Sheridan County. Groundwater samples from wells (1,001 samples) and springs (370 samples) gave maximum lithium concentrations of 0.868 ppm and 0.888 ppm respectively. There were no samples that had lithium concentrations that exceed 90 ppm (fig. 7).

National Uranium Resource Evaluation (NURE) Stream Sediment Data (Smith, 1997)

The NURE program also collected 18,424 sediment and soil samples in Wyoming which were analyzed for an extensive suite of chemical and isotopic constituents at Los Alamos Scientific Laboratory. Arc-Source Emission Spectrography Analysis was used to determine soil lithium

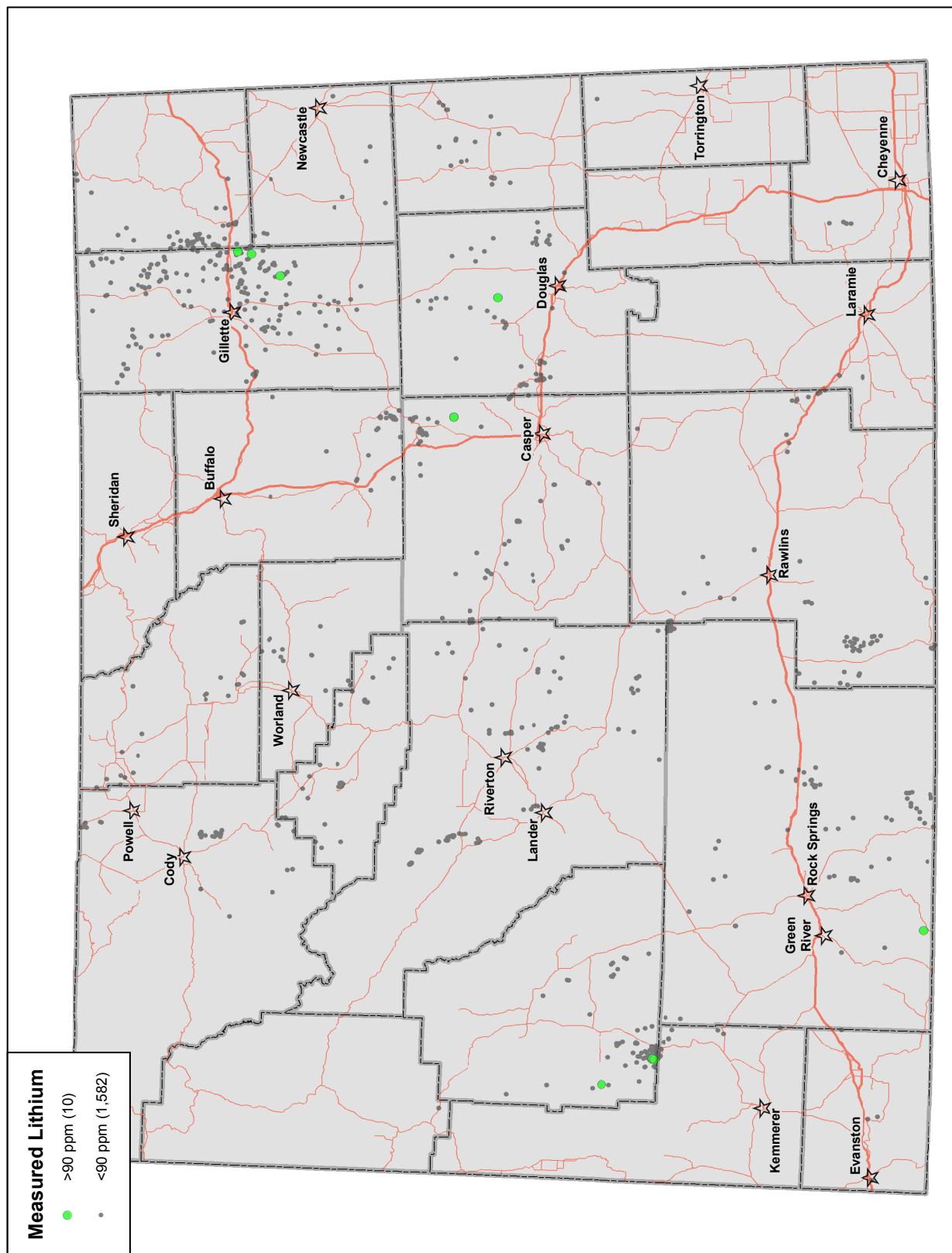


Figure 6. Produced water samples with lithium concentration data (PWGD, 2015; WADB, 2015).

Table 5. Produced waters with lithium concentrations exceeding 90 mg/l (ppm).

| API Number | Date of Sample | Basin | County | Field | Well Name | Sec/T/R | Method | Formation | Lithium (mg/L) |
|------------|----------------|--------------|------------|----------------------|--------------------------|---------------|--------------------------------|-------------------------|----------------|
| 4902510731 | 6/21/1979 | Powder River | Natrona | Teapot Naval Reserve | NPR 3 | 22/38N/78W | Tank | Dakota | 481 |
| 4902510731 | 6/19/1979 | Powder River | Natrona | Teapot Naval Reserve | 32 DX 22 | 22/38N/78W | 300 Bbl Tank Frm Wel | Dakota | 481 |
| 4900921966 | 11/6/1991 | Powder River | Converse | Scott | 1-11 Scott | 1/35N/72W | Wellbore 8603-8868 | Parkman | 246 |
| 4903521014 | 1/19/2012 | Green River | Sublette | Labarge | Labarge Unit 8 | 28/27N/113W | ----- | Bear River-Frontier | 204 |
| 4900505074 | 7/9/1965 | Powder River | Campbell | Unnamed | 1 State 0-19293 | 16/47N/70W | Dst Mfe Chamber | Minnelusa | 140 |
| ----- | ----- | Wind River | Fremont | Winkelman Dome | Conaco Tribal Well No. 1 | ----- | ----- | Tensleep | 111 |
| 4900506399 | 7/9/1965 | Powder River | Campbell | Duval Ranch | 1 Erickson | 11/49N/69W | ----- | Minnelusa | 105 |
| 4900505284 | 7/6/1965 | Powder River | Campbell | Raven Creek | F43-34s | 34/49N/69W | Swab Test After Acid Treatment | Newcastle/ Minnelusa | 97 |
| ----- | 12/18/1970 | Green River | Sublette | Hogback | Hogback #32-31 | 28/27N/113W | Production | Nugget | 97 |
| 4903705098 | 7/1/1965 | Green River | Sweetwater | Marsh Creek | Unit No. 1 | 1/12N/107W | DST No. 3 | Blair | 93 |
| 4903707154 | 8/27/2011 | Green River | Sweetwater | None | RSU-#1 | 16/1/20N/101W | Energy Labs* | Weber/Madison | 92.8/90.5 |
| 4903707154 | 8/27/2011 | Green River | Sweetwater | None | RSU-#1 | 16/1/20N/101W | Core Labs* | Weber/Madison | 100/105 |
| 4903707154 | 12/3/2012 | Green River | Sweetwater | None | RSU-#1 | 16/1/20N/101W | Energy Labs† | Madison | 92 |
| 4903707154 | 12/14/2012 | Green River | Sweetwater | None | RSU-#1 | 16/1/20N/101W | Energy Labs† | Weber | 91 |

* Sampled with capture cylinder at reservoir pressure.

†Sampled with wireline bailer

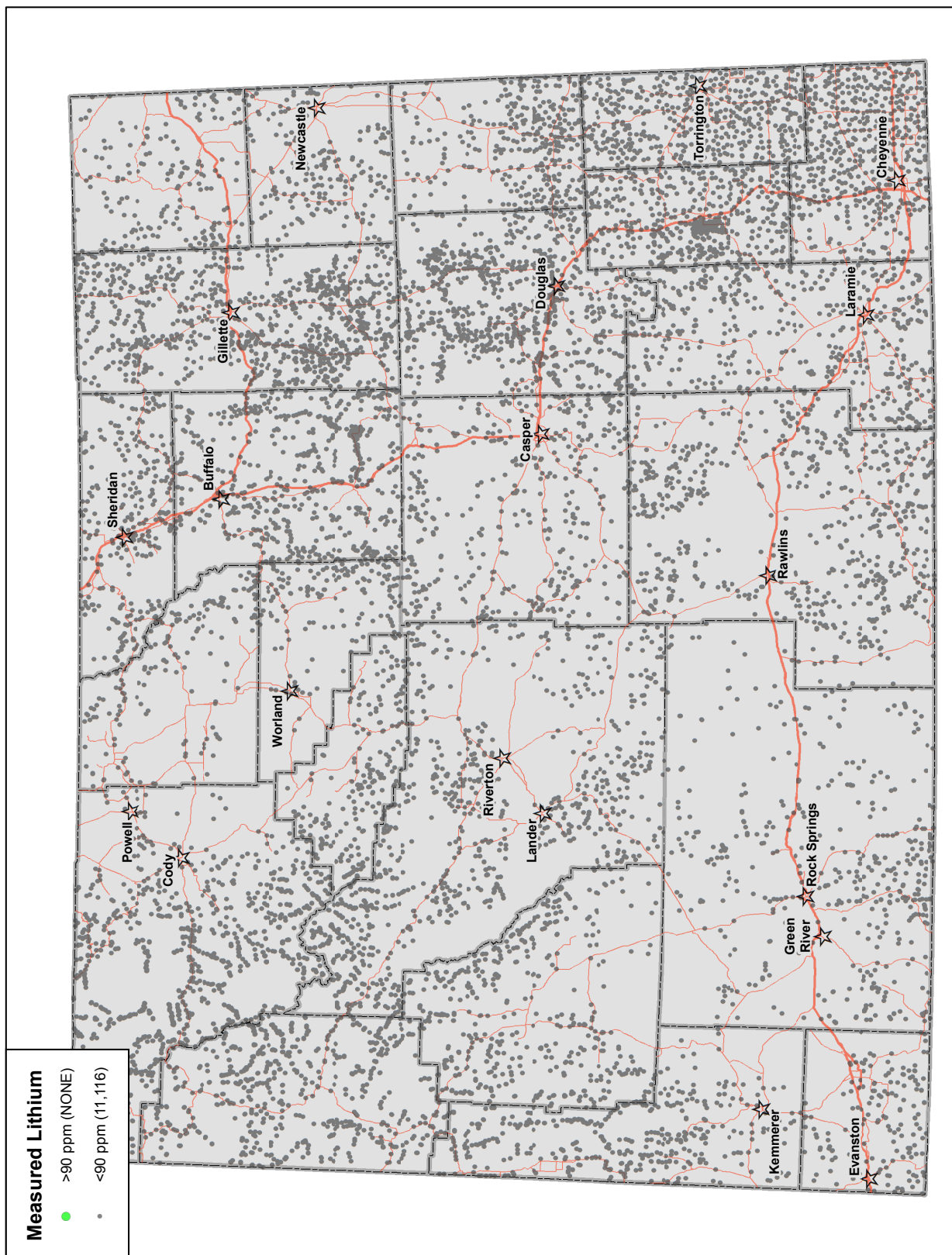


Figure 7. NURE water samples with lithium concentration data (Smith, 1997).

concentrations. Lithium concentrations were obtained for 17,956 samples; 88 samples had lithium concentrations that exceeded 90 ppm. Sediments with elevated lithium levels are concentrated in Yellowstone National Park (YNP) and in the central Greater Green River Basin in proximity to the northern border of Sweetwater County. In YNP, 22 elevated samples (mean concentration = 130 ppm) were obtained from stream sites located on undifferentiated Tertiary and Quaternary volcanic units. Stream sediments with lithium concentrations greater than 90 ppm in the Green River and Wind River Basins are associated with outcrops of tuffaceous Tertiary units (e. g. Green River, Wasatch, Wagon Bed and Wind River formations). This is consistent with the observation of Price and others (2000) that felsic tuffs may constitute the primary lithium source rocks in Nevada. In the eastern half of the state, lithium enriched sediments overlie Upper Cretaceous shales (Cody, Carlisle, and Pierre), Paleozoic limestones (Minnelusa, Pahasapa, and Englewood) and scattered granitic volcanic and meta-volcanic units (fig. 8).

None of the sediments listed in the extensive NURE sediment database occur at concentrations that are currently considered to be economically developable. Furthermore, the two sediment samples with the highest lithium levels (253 and 263 ppm) are both located in YNP.

USGS Soils Data and WSGS Playa and Rock Sample Data

The USGS has conducted several extensive geochemical studies of soils in the lower 48 states (Shacklette and others, 1984; Smith and others, 2014). The most recent comprehensive survey (Smith and others, 2014) collected 486 soil samples at 162 sites in Wyoming; 481 samples were analyzed for lithium concentrations. One sample from southwestern Carbon County collected at a depth of between 39 and 45 inches below the surface had a lithium concentration above 90 ppm (131 ppm). The sample site overlies the tuffaceous Laney member of the Green River Formation (Love and Christiansen, 1980) (fig. 9).

In July 2015, WSGS geologists collected 51 playa soil samples in northeastern Sweetwater County. Seventeen sample sites were selected based on their proximity to lithium enriched soils identified in the USGS soil geochemical study by Smith and others (2014). Three composite playa soil samples were collected at depths of 0 – 6 inches, 10 – 16 inches and 20 – 24 inches below ground surface at each site. Lithium concentrations were determined by ALS Chemex™ using weak acid leach analysis (Code ME-MS41W). Lithium concentrations in the 51 samples ranged from 5 to 37.7 ppm.

During the last four years, WSGS geologists have collected and compiled 645 hard rock samples that have been analyzed for lithium concentrations. Many of these samples were collected in association with WSGS Rare Earth Elements and Zeolite Projects. Only 19 samples had lithium levels that exceed 90 ppm (table 6); two samples from the site described below had concentrations that exceed 2,000 ppm.

Black Mountain Spodumene, NW ¼ SW ¼ sec. 1, T.32N, R.89W, Natrona County

The Black Mountain Spodumene Prospect (see inside cover picture) was first referenced as a deposit in WSGS Bulletin 50 (Osterwald, 1959/ rev. 1966, p. 127). Tuffaceous claystones, sandstones and conglomerates of the Wagon Bed Formation crop out intermittently along the base of the mountain except for the southeastern side where Late Archean granitic rocks are exposed. Multiple pits have been excavated in the metavolcanics, dark mafic dikes and pegmatites near the mountain's summit. The prospect is located on the northern spur of the mountain in a pegmatite that is approximately 5 feet wide. WSGS geologists collected five samples in the area of the prospect; three samples had lithium concentrations of 70 ppm or less. The first sample, however, obtained from the prospect pit, containing greenish-grey spodumene and quartz, tourmaline, and an unidentified turquoise colored mineral had 7,000 ppm lithium. Another sample composed of quartzite with veins containing the turquoise colored mineral and tourmaline had a lithium concentration of 2,420 ppm. The spodumene-containing pegmatite is small and there is no known production from it (fig. 10).

Lithium in Coal

Wyoming contains significant coal resources most notably in the Powder River Basin. This section briefly addresses the question of lithium recovery from coal and its residual product coal ash.

The recovery of lithium from coal combustion products (coal ash) was investigated in China by Qin and others (2015). They tested two extraction processes: sulfur sintering of the ash followed by acid leaching to obtain lithium carbonate, which yielded an actual recovery of 60 percent of the contained lithium; and a simpler alkali sintering process that recovered 55 percent of the lithium.

Jones (2010) cited an average lithium content of Wyoming coals of 4.6 ppm, and a U.S. average lithium content of 20 ppm on a whole coal basis. Recent WSGS samples of coal varied from <10 ppm to 20 ppm, with concentrations in carbonaceous shale and related claystones up to 30 ppm. Stricker and others (2007) show Powder River basin coals

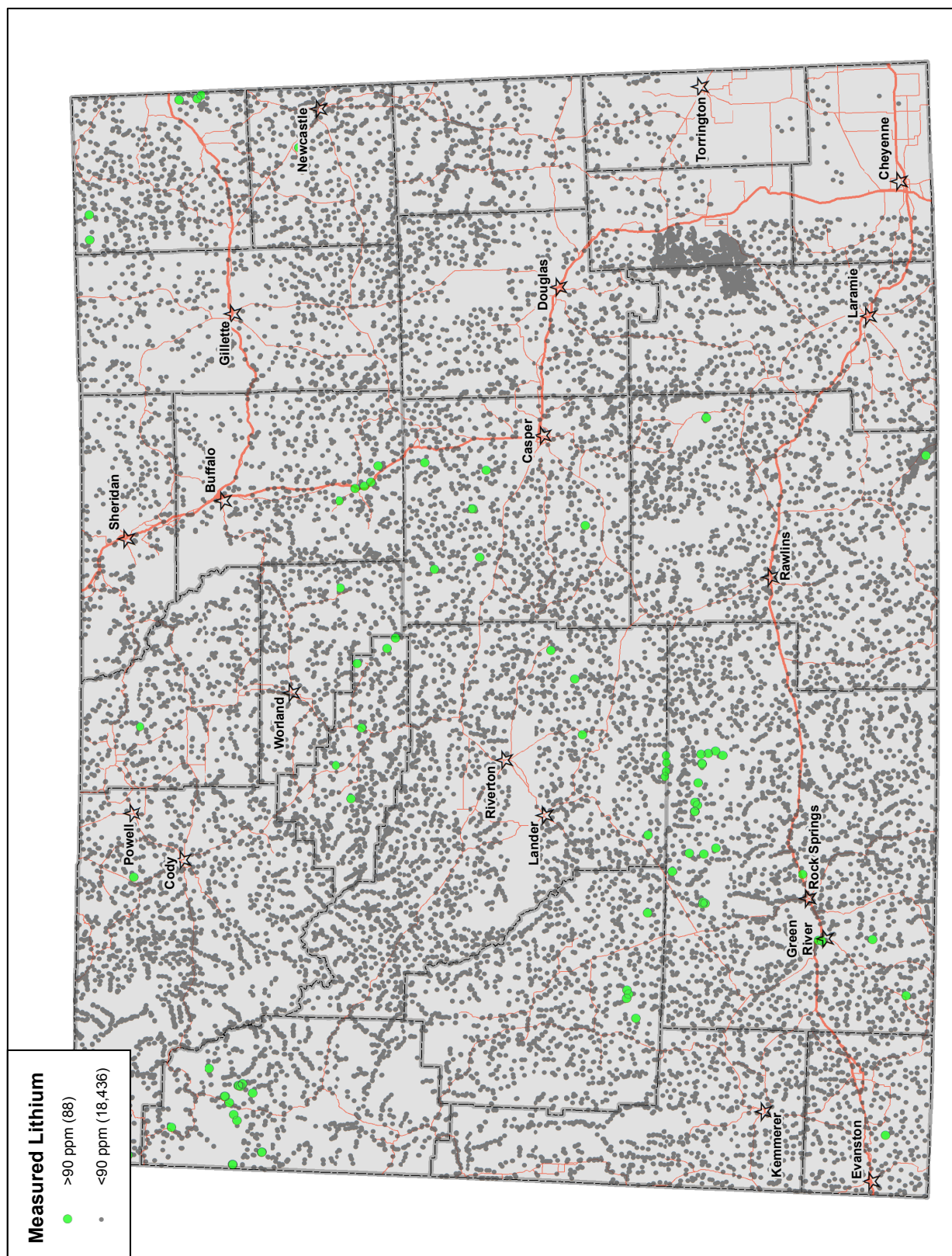


Figure 8. NURE sediment samples with lithium concentration data (Smith, 1997).

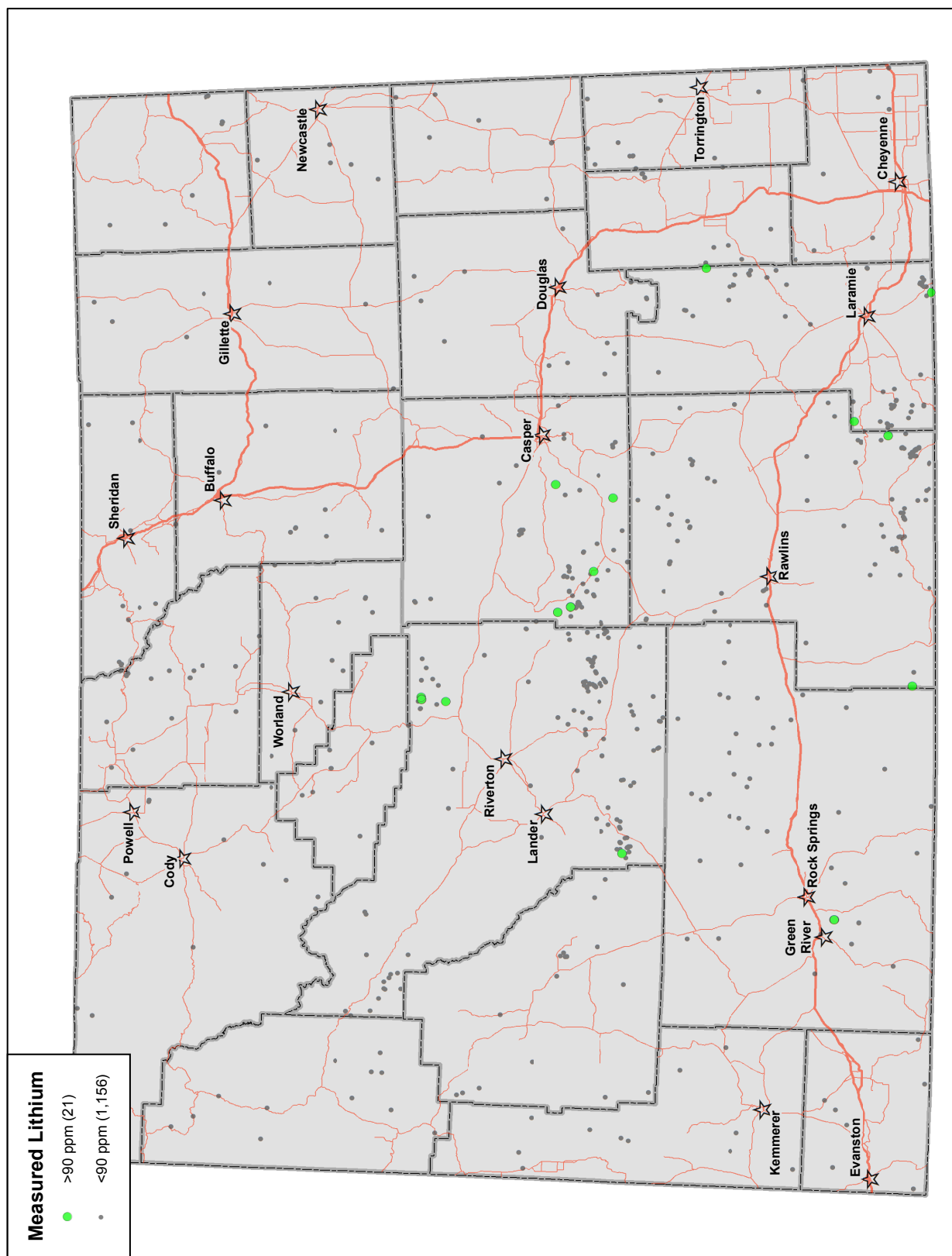
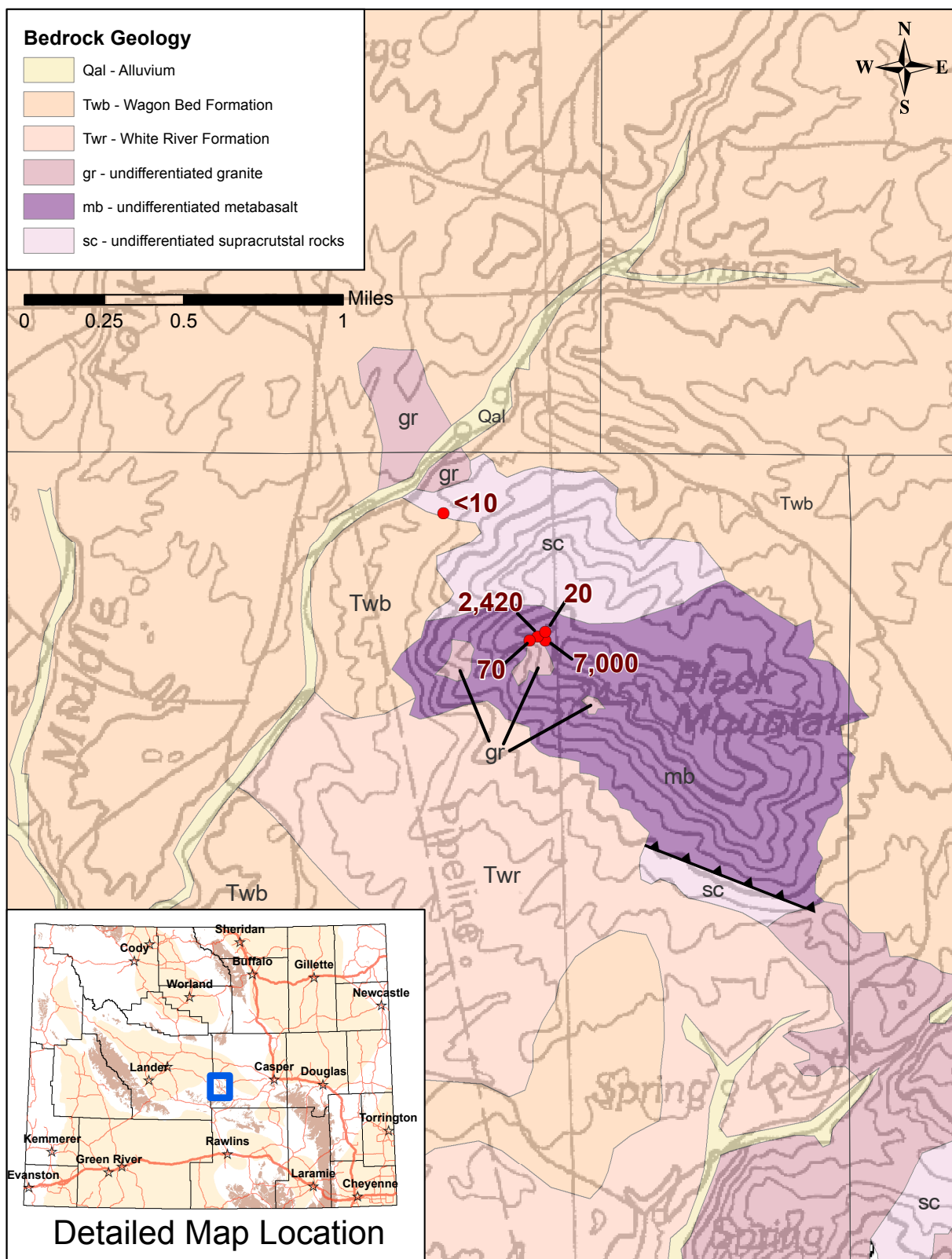


Figure 9. WSGS rock and playa samples and USGS soil samples with lithium data (Smith and others, 2014)

Table 6. WSGS hard rock samples with lithium concentrations greater than 90 ppm.

| Sample number | Lithium (ppm) | Latitude | Longitude | Unit Age | Rock Type | Unit Name (Love and Christiansen, 1985) |
|---------------|---------------|----------|-----------|----------------------------------|------------------------------------|--|
| 20150609LC-1 | 7000 | 42.7729 | -107.4453 | Late Archean | Metavolcanic rock | Metamorphosed mafic/ultramafic rocks |
| 20150609LC-3 | 2420 | 42.7731 | -107.4458 | Late Archean | Metavolcanic rock | Metamorphosed mafic/ultramafic rocks |
| 20121011JC-F | 480 | 43.4105 | -107.9891 | Middle Archean-Late Archean | Metasedimentary/metavolcanic rocks | Metasedimentary/metavolcanic rocks |
| 20150804LC-4B | 270 | 43.4081 | -108.0021 | Middle Archean-Late Archean | Metasedimentary/metavolcanic rocks | Metasedimentary/metavolcanic rocks |
| 20150804LC-2C | 130 | 43.4083 | -108.0063 | Eocene | Claystone/conglomerate | Wagon Bed Formation |
| 20121031WS-C | 129.5 | 42.7139 | -107.4099 | Miocene | Sandstone/conglomerate | Miocene rocks |
| RSWS92501-2 | 124 | 42.6073 | -107.1885 | Miocene | Sandstone/conglomerate | Miocene rocks |
| 20121031WS-F | 120 | 42.7135 | -107.4133 | Miocene | Sandstone/conglomerate | Miocene rocks |
| 20121031JC-A | 120 | 42.7787 | -106.635 | Upper Cretaceous | Sandstone/shale | Frontier Formation |
| 20150714LC-7A | 120 | 42.4623 | -108.972 | Late Archean | Metasedimentary rock | Metasedimentary rocks |
| 20120928JC-D | 110 | 41.4652 | -109.3612 | Eocene | Mixed clastic/carbonate | Wilkins Peak Member/Tipton Shale Member of Green River Formation |
| 20120928JC-E | 110 | 41.464 | -109.361 | Eocene | Mixed clastic/carbonate | Wilkins Peak Member/Tipton Shale Member of Green River Formation |
| 20150818LC-8B | 110 | 41.2201 | -106.3532 | Archean | Tectonite | Shear zone |
| 20150823WS-A | 110 | 41.3817 | -106.2625 | Pleistocene-Holocene | Glacial drift | Glacial deposits |
| PC3-96 | 104.5 | 42.0567 | -105.286 | Late Archean | Granitic gneiss | Granite gneiss |
| 20121114JC-E | 100 | 41.0086 | -105.4724 | Early Proterozoic | Metasedimentary/metavolcanic rock | Granite gneiss/pelitic schist |
| 20121023JC-B | 100 | 42.5103 | -106.7241 | Middle Jurassic-Lower Cretaceous | Fine-grained mixed clastic | Cloverly Formation/Morrison Formation/Sundance Formation |
| 20150818LC-8A | 100 | 41.2201 | -106.3532 | Archean | Tectonite | Shear zone |
| 20150804LC-6B | 100 | 43.2973 | -108.0168 | Eocene | Claystone/siltstone | Wind River Formation |
| 20150917LC-6 | 160 | 41.2748 | -107.0909 | Late Archean | Granitic gneiss | Granite gneiss |
| 20150928LC-1 | 120 | 41.5326 | -109.3767 | Eocene | Mixed clastic/carbonate | Wilkins Peak Member/Tipton Shale Member of Green River Formation |
| 20150929LC-7A | 90 | 41.3254 | -109.3536 | Eocene | Mixed clastic/carbonate | Wilkins Peak Member/Tipton Shale Member of Green River Formation |
| 20150929LC-7B | 160 | 41.3254 | -109.3536 | Eocene | Mixed clastic/carbonate | Wilkins Peak Member/Tipton Shale Member of Green River Formation |



in 208 samples from core holes to average from 2.6 to 3.8 ppm lithium.

Trace elements, including metals within coal vary considerably both regionally and within individual coal beds as shown in various studies (Stricker and Flores, 2003; Hower and others, 2013; Hower and others, 2015; Deonarine and others, 2015). The greatest concentrations of trace elements are generally found within zones of higher ash, in association with clay/shale partings, and within or near sediments at the tops and bottoms of some coal seams (Stricker and others, 2007; Hower and others, 2015). A small number of multi-element analyses on WSGS coal and related samples suggest that lithium may concentrate in the same coal bed environments as other trace elements, particularly rare earth elements (REE).

Jones (2010) noted that Wyoming coals have ash contents varying widely from only a few percent to more than 50 percent. However, he showed that a typical, persistent, Wyoming coal of mineable thickness generally contains less than 10 percent ash. Assuming that a Wyoming coal bed contains 20 ppm Li and the lowest average amount of ash, as cited by Jones (2010), of about 5 percent, then the coal combustion products could, most efficiently, concentrate the trace element, or Li, content by a factor of about 20 times. That would increase the Li concentration from 20 ppm in the highly uniform and fictitious coal to 400 ppm in the coal combustion products (an unlikely prospect). If the Li was recovered at 60 percent, as in the Chinese extraction experiment, then approximately 240 ppm could be recovered from the ash product. If beneficiation and or blending occurred to bring the coal into specification for a particular power plant, then the lithium concentration could be significantly lower. If the coal was an average Wyoming coal at 4.6 ppm, concentrated in the ash 20x to 92 ppm, then recovery would be closer to 55 ppm.

Beneficiation often removes undesirable (for power plant use) rock and high ash material from the coal, which may also remove REE; blending coals from other areas may have a similar effect (Hower and others, 2015). As the REE are removed or diluted, so also may be the lithium content.

In attempting to assess the economics of extraction of relatively low lithium concentrations from coal combustion products, other factors should be considered. As the coal beds vary widely in their chemistries and lithium contents, the design of any lithium chemical processing facility must consider these variabilities for efficiency of recovery. In addition, shipping of coal ash from widely disbursed power plants to a central processing plant is another expense.

The low lithium concentrations typically found in Wyoming coal combined with other factors do not appear to indicate any economic potential for lithium extraction from coal combustion products.

Lithium in Yellowstone Geothermal Waters (Ball and others, 2010; Ball and others, 2002; Ball and others, 2001; Ball and others, 1998a; Ball and others, 1998b; McCleskey and others, 2004)

The review of the USGS soils data (Smith and others, 2014) indicated the presence of elevated (<90 ppm) lithium levels in several soil samples in Yellowstone National Park (YNP). Furthermore, geologic conditions in those parts of YNP where geothermal activity has been documented appear to be conducive to the deposition of lithium brines (Bradley and others 2013). Although, brine extraction would not be possible within the park's boundaries, in the interest of conducting a complete investigation, WSGS geologists reviewed lithium concentrations for 426 samples collected from YNP's geothermal waters by USGS geologists.

Lithium concentrations ranged from 0.001 – 11.40 mg/L in the collected samples; the average concentration for all samples is 1.94 mg/L which is about 1 percent of the minimum brine concentration being extracted at lithium producing facilities currently in operation.

CONCLUSIONS

The Wyoming State Geological Survey reviewed lithium concentration data for 26,385 samples of geomaterials in Wyoming from eight geochemical databases managed by federal and state agencies to assess the occurrence of lithium enriched waters and mineral ores in Wyoming. One mineral sample obtained from a small spodumene bearing pegmatite located in central Wyoming was found to have a lithium content of 7,000 ppm. This occurrence of spodumene, on Black Mountain in the Rattlesnake Hills of central Wyoming, was first documented by WSGS in 1959. By comparison, larger spodumene deposits of this concentration were actively extracted in the King's Mountain district of North Carolina until 1998. Substantial documented lithium reserves still exist at King's Mountain but the mines there cannot compete with lithium salts extracted from high grade brines produced in the Atacama Desert in Argentina, Chile, and Bolivia. Extraction of lithium from the small Black Mountain deposit is therefore highly unlikely. Neither is it likely that other hard rock or sedimentary occurrences of significantly lower lithium concentrations can compete economically with any currently mined lithium deposits around the world.

A review of produced water data indicates that lithium levels were elevated in brines produced from ten Wyoming oil wells. Unfortunately, none of those analyses can be independently confirmed at this time. Four of the wells have been plugged and abandoned, two records appear to be duplicates, one well showed lithium concentration of 0.00 ppm during a retest and the existence of the two wells that had no API numbers could not be confirmed. The remaining well, completed in the Bear River and Frontier formations has a lithium concentration of 204 ppm. The well was tested in 2012 but has not been retested since then. Six water samples collected in 2011 and 2012 from the Paleozoic Weber and Madison formations at the 12,810 foot deep RSU-#1 well in the Rock Springs Uplift had lithium concentrations that range between 90.5 – 105 mg/L (ppm). In contrast, the South American brines that currently produce most of the world's lithium contain more than 200 ppm and are pumped from shallow wells less than 130 feet deep (Meridian International Research, 2008). Additionally, South American production costs are kept low by processing the brines in passive lined pits where the Atacama Desert's high evaporation rates (about 125 inches/year) and low precipitation rates (less than 1 inch/year) allow for the rapid concentration of lithium salts (SQM, 2015). Lithium concentrations of 200 ppm are seen also in the brines extracted at the only active lithium operation in the U.S. at Chemtall Foote's Silver Peak facility in Clayton Valley, Nevada. However, production costs

there are likely lower because facility infrastructure has been in place since the plant began producing lithium in 1967. Given the higher lithium concentrations and lower production costs, it is unlikely that any Wyoming brine deposit can compete economically with the Nevada and South American facilities.

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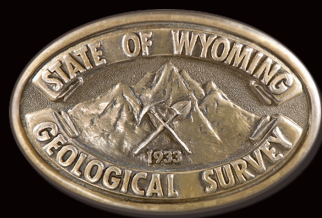
All maps were compiled using data from the following sources, USGS, the Wyoming Geographic Information Science Center, and the WSGS. We appreciate the use of this data.

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