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Groundwater Salinity in the Wind River and Bighorn Basins, Wyoming

Karl G. Taboga, James E. Stafford, James R. Rodgers, and Seth J. Wittke

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INTRODUCTION

This Wyoming State Geological Survey (WSGS) open file report investigated groundwater salinity in the deep (>1,000 feet below ground surface [ft bgs]) aquifers of the Wind River (WRB) and Bighorn (BHB) structural basins of northern Wyoming. Previous WSGS studies examined groundwater salinity in the Greater Green River (Taboga and others, 2020), Powder River (Taboga and others, 2018), and Denver-Julesburg structural basins (Taboga and others, 2016). In addition to these basin studies, the WSGS explored statistical relations between groundwater depth and salinity in selected aquifers throughout Wyoming (Taboga and Stafford, 2020). This and the previous reports focus on saline groundwaters suited to industrial uses to encourage the conservation of higher-quality waters for municipal, domestic, and agricultural uses.

Chemical Constituents of TDS

Salinity, or total dissolved solids (TDS), is "the measure of the total ionic concentration of dissolved minerals in water," (U.S. Bureau of Reclamation, 2006). In practice, TDS is the residue of dissolved salts, minerals, and metals that remains following laboratory evaporation of a filtered (2-micrometer filter) water sample (Howard, 1933). However, TDS is only a general predictor of water quality because it does not specify the particular chemical constituents that make up solids in the residue or their concentrations. Groundwater with low TDS levels can contain toxic concentrations of manufactured chemicals such as pesticides or naturally occurring heavy metals and radioactive elements. Still, salinity is a useful measure of general water quality, particularly when accompanied by a complete water-chemistry analysis conducted by an accredited water-quality laboratory. The terms "salinity" and "TDS" are used interchangeably in this report.

Occurrence of Saline Groundwater and Available Data

In Wyoming, most saline (TDS>5,000 milligrams per liter [mg/L]) groundwaters are produced from deep wells as a by-product of oil and gas development in the semi-arid energy-producing basins (table 1). Saline waters are rarely reported by domestic and agricultural users who want to access high-quality (TDS<5,000) groundwater from shallow wells (Taboga and others, 2014a,b, 2019). Additionally, there has never been an extensive deep aquifer drilling and water-sampling program conducted by the scientific community or any government agency in Wyoming. So, almost all water-quality data for the state's deep aquifers were obtained from reports filed by energy exploration and development companies.

In fact, salinity is the most available measure of general groundwater quality in Wyoming. TDS data are widely available from the United States Geological Survey (USGS, 2021), Wyoming Oil and Gas Conservation Commission (WOGCC, 2021a), Wyoming State Engineer's Office (WSEO, 2019), and Wyoming Department of Environmental Quality (WDEQ, 2020).

Table 1. Oil, gas, and associated water production levels (2019) compared to average annual precipitation and population in four Wyoming energy-producing basins. a) WOGCC, 2021b; b) PRISM Climate Group, 2017; c) Wyoming Department of Administration and Information Economic Analysis Division, 2019. [Abbreviations: bbls, barrels; mcf, 1,000 cubic feet; in, inches]

Basin	Oil (bbls) [a]	Gas (mcf) [a]	Water (bbls) [a]	Average annual precipitation (in)[b]	Estimated population [c]
Wind River	3,618,884	79,168,258	236,481,987	6–10	40,000
Bighorn	9,295,622	9,905,845	879,450,376	6–10	37,000
Greater Green River	13,134,097	1,003,068,976	146,023,818	6–15	62,000
Powder River	61,826,282	266,030,531	401,417,209	13–15	127,000

BACKGROUND

Water-Quality Standards, Groundwater Classification, and TDS Concentrations

Groundwater-quality standards in the state of Wyoming are established by the WDEQ, U.S. Environmental Protection Agency (EPA), and WOGCC. The WDEQ classifies groundwater suitability for domestic, agricultural, livestock, and industrial uses based on water-quality standards (WDEQ, 2020). The WDEQ specifies maximum TDS concentrations of 500 mg/L for Class I (domestic) use, 2,000 mg/L for Class II (irrigation) use, and 5,000 mg/L for Class III (livestock) use. Industrial-grade groundwaters are classified by TDS concentration as Class IV A (TDS≤10,000 mg/L) and Class IV B (TDS>10,000 mg/L). Chapter 8 of the WDEQ Water-quality Rules and Regulations, available at https://deq.wyoming.gov/water-quality/ contains current WDEQ water-quality standards.

Public water systems in Wyoming are regulated by the EPA Region 8 Office, headquartered in Denver, Colorado. The EPA standard for TDS in public drinking water is 500 mg/L (EPA, 2020). The TDS standard is a Secondary Maximum Contaminant Level, which is a non-enforceable guideline for contaminants that cause aesthetic problems such as degradation of odor, appearance, or appearance at higher concentrations. The current EPA drinking water standards (EPA, 2020) are available on the EPA's website, https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.

The WOGCC issues underground injection control (UIC) well permits for the disposal of wastewater coproduced during oil and gas development. The produced water in this case is not suitable for other beneficial uses. The WOGCC regulations require "Standard laboratory analysis of the water to be disposed and the water in the formation into which disposal is taking place" (chap. 4, sec. 5c [ix]) be included with any application for a Class II disposal well permit. A list of specified water-quality constituents, including TDS concentrations, must be provided in the laboratory analyses filed with the permit application. Current WOGCC regulations for the Class II UIC program are found at http://pipeline.wyo.gov/wogcchelp/commission.html.

Estimated Beneficial Uses of Saline Groundwater in Wyoming

The most recent USGS water-use report (Dieter and others, 2018) estimates that 96.8 million gallons of saline (TDS>1,000 mg/L) groundwater per day were used beneficially in Wyoming during 2015. The report states that all of the saline water was used by the mining industry, which includes oil and gas production by USGS definition (Dieter and others, 2018).

Industrial Applications for Saline Groundwater

Oil and gas development

The oil and gas industry uses substantial amounts of water to drill new wells during exploration while coproducing large volumes of saline groundwater during production (WOGCC, 2021b). In areas where exploration and production operations are both underway, it may be cost effective to use produced saline water for new well drilling and development. This method conserves freshwater resources while managing the often-substantial volumes of coproduced water, both of which are key components needed to obtain the requisite federal and state environmental permits. With these advantages in mind, the states of Texas and New Mexico will waive permits to inject produced saline waters downhole if certain water-quality standards are met.

In recent years, saline produced water has been used for secondary and tertiary oil recovery (water flooding), and hydraulic fracturing (American Geosciences Institute, 2015). Research in the use of saline water for hydraulic fracturing (American Geosciences Institute, 2015; Godsey, 2017; Scanlon and others, 2020) is driven by the cost and availability of freshwater. More than 10 million gallons of water may be required to fracture one well (Allison and Mandler, 2018). Freshwater resources are further limited in semi-arid western basins (Allison and Mandler, 2018; table 1 in this report) where surface-water flows are already (over) allocated to holders of existing water rights and groundwater from shallow aquifers may be saline. For example, at the time this report, WSGS hydrogeologists were receiving at least one call every month from energy industry consultants seeking to procure water for drilling wells in the tight-oil reservoirs of the Powder River Basin (National Energy Technology Laboratory, 2021).

Prior to reuse in fracturing fluid, saline water requires pre-treatment for microbial organisms, residual hydrocarbons, and total suspended solids. Additionally, some ions in saline groundwater may interact with additives in the hydraulic fracturing fluid, thereby limiting its efficacy (LeBas and others, 2013; American Geosciences Institute, 2015; Godsey, 2017). For example, divalent ions such as calcium, magnesium, and sulfate can precipitate as salts and cause scale buildup, high iron concentrations can inhibit chemical flocculation formers, and boron can disrupt cross-link additives. In practice, an experienced hydraulic fracturing contractor can often remedy these problems by adjusting the types and amounts of fracturing fluid additives. In spite of these challenges, the use of saline water for hydraulic fracturing is expected to grow as further technical and economic obstacles are resolved (Allison and Mandler, 2018).

The American Geosciences Institute provides a free short online course, "Making Produced Water More Productive," on its Geoscience Online Learning Initiative platform (American Geosciences Institute, 2015) at https://goli.americangeosciences.org. Course modules explore the environmental, legal, and economic issues that arise from reusing saline produced water.

Other industrial applications

In Wyoming, saline waters have been used in the coal, aggregate, and ore mining industries for quarrying and processing operations, equipment wash-down, and on-site dust suppression (WDEQ, 2020). Untreated or minimally treated saline waters can also be used in manufacturing for fabricating, processing, washing, or cooling, but whether these applications are currently employed by Wyoming manufacturers is unknown.

METHODS

The WSGS used TDS measurements obtained from almost 36,000 Wyoming chemical analyses provided by the USGS (Blondes and others, 2018; USGS, 2021) and WOGCC (2021a) water-quality databases. The water-chemistry analyses were processed using the USGS quality-control procedure adapted from Hitchon and Brulotte, (1994). Taboga and others (2018) provide an explanation of the manner used to process the USGS/WOGCC water-quality data. The resultant dataset used in this report provides water-quality analyses for 3,240 qualified wells in the Wind River (WRB) and Bighorn (BHB) basins.

The WSGS also estimated groundwater TDS levels from oil and gas well logs using the Static Spontaneous Potential (SSP) method (Schlumberger Well Services, 1989; Bassiouni, 1994; Schnoebelen and others, 1995). Petra® 4.3.0 geologic interpretation software was used to identify more than 2,700 candidate wells with SSP and gamma ray logs from 11,514 oil and gas wells in the WRB and BHB. Candidate wells were then subjected to a three-part qualifying process. First, geophysical log headers were reviewed to select wells drilled with water-based muds that had recorded borehole bottom temperatures and mud-filtrate resistivity values. Second, gamma ray logs were examined to identify known sandstone strata (Lynds, 2013) that are more than 20 ft thick. Lastly, SSP deflections in sandstone strata located at depths of more than 1,000 ft were quantified. A set of fitted mathematical algorithms (Brown and others, 1980) programmed into Petra® 4.3.0 was used to estimate TDS levels from the observed SSP deflections. The final SSP dataset consisted of 2,098 calculated TDS levels from 588 wells. The combined dataset contains 5,338 qualified water-quality analyses and SSP salinity estimates in total.

The WSGS has taken the following steps to present this large amount of data effectively:

- Results are presented by 1,000-ft intervals from 1,000 to 12,000 ft bgs, and by depth of first encountered industrial-grade (TDS>5,000 mg/L) saline groundwater. In depth intervals that contained more than one observed SP deflection or water-quality analysis, the least saline groundwater is shown.

- Water-quality samples and SSP estimates (collectively referred to as samples in this report) with salinities less than 1,000 mg/L are not considered.

- In this report, groundwater salinities have been categorized by WDEQ (2020) classes of use:

    - Slightly saline water (1,000–2,000 mg/L TDS) is suitable for Class II agricultural use

    - Moderately saline water (2,000–5,000 mg/L TDS) is suitable for Class III livestock use

    - Industrial-grade groundwaters are rated as Class IVA (5,000–10,000 mg/L TDS) or Class IVB (>10,000 mg/L TDS).

- The WSGS determined stratigraphic units for selected wells from geologic markers records obtained from Petra® 4.3.0 records or WOGCC gamma ray logs (WOGCC, 2021b). Formation symbols (table 2) are shown in the maps when the depth of occurrence could be correlated to a Wyoming stratigraphic unit listed by Love and others (1993). Qualifying wells that could not be assigned to a stratigraphic unit, referred to as "undesignated" in the text, are shown without formation symbols on map figures.

- Results for the WRB and BHB are presented in separate sections.

Table 2. Geologic units and corresponding symbols examined in this study (geological symbols modified from Love and Christiansen, 1985).

Formation	Symbol	Formation	Symbol
Wind River Formation	Twdr	Sundance Formation	Js
Fort Union Formation	Tfu	Nugget Sandstone	JŦn
Lance Formation	Kl	Chugwater Group	Ŧc
Meeteetse Formation	Km	Dinwoody Formation	Ŧd
Lewis Shale	Kle	Phosphoria Formation	Pp
Mesaverde Group	Kmv	Tensleep Sandstone	PIPMa
Cody Shale	Kc	Amsden Formation	PIPMa
Frontier Formation	Kf	Madison Limestone	Mm
Mowry Shale	Kmt	Bighorn Dolomite	MDO
Muddy Sandstone	Kmd	Gros Ventre Formation	OꞒ
Cloverly Formation	Kcv	Flathead Sandstone	Ꞓf
Morrison Formation	Jm		

RESULTS AND DISCUSSION

Wind River Basin

Qualified oil and gas wells are broadly distributed across the WRB except for the area around the Granite Mountains (fig. 1). Generally, these wells target oil-bearing Paleozoic formations in the west and southwest, Mesozoic oil and gas reservoirs in the central basin, and Cenozoic gas-bearing units in the north (Toner and others, 2021). A notable exception is the Madden Gas Field, shown on figure 1 as a large cluster of wells about 25 miles east-northeast of Shoshoni. Wells in the Madden Field extract natural gas from multiple Paleozoic, Mesozoic, and Cenozoic reservoirs (Toner and others, 2021).

Variations in salinity with depth

Table 3 provides summary statistics for saline waters in the Wind River Basin by depth interval. Mean and median TDS concentrations generally increase with depth-of-burial (fig. 2), consistent with groundwater salinity trends observed in other North American (Kharaka and Hanor, 2003) and Wyoming (Taboga and Stafford, 2020) sedimentary basins. The median values form a smoother curve than the means because the medians are more robust against outliers. Also, mean TDS concentrations exceed the corresponding medians at each depth interval, reflecting the sensitivity of the means to the high maximum TDS values (table 3) and the constraint placed on low value outliers (<1,000 mg/L). Many of the maximum values shown are four to five times higher than the levels shown at the 75th percentile, suggesting that samples with these extreme salinities occur infrequently.

Mean and median salinities (fig. 2) increase very rapidly at depth intervals exceeding 7,000 ft bgs. This appears to be related to the "regional anomalous pressure surface" present in Rocky Mountain Laramide basins at depths of 6,000–8,000 ft bgs (Surdam and others, 2006). The properties of fluids (natural gas, water, and oil) differ markedly above and below this depth range (Law and Dickinson, 1985; Surdam and others 2006). Generally, groundwater pressure above this boundary is determined by the weight of the water column, tracking the hydrostatic gradient (~0.43 pounds per square inch per foot [psi/ft]). However, below the boundary, fluids in low-permeability sandstone and shale reservoir rocks are typically anomalously pressured (either under or over pressured). Law and Dickinson (1985) attribute the development of anomalously pressured reservoirs to the balance between thermogenic gas generation and gas loss. In over-pressured zones, the rate of gas generation exceeds that of loss and gas pressure builds, forcing much of the groundwater out of the pore space in reservoir rocks into overlying normally pressured rocks.

The remnant water is bound with oil and gas into complex multi-phase fluids with very low flow characteristics effectively isolating these reservoirs from meteoric groundwater in adjacent aquifers. Dissolution of host rock minerals continues in the over-pressured reservoirs, however, and salinity levels rise.

Under-pressured reservoirs develop when faults or fractures breach an over-pressured zone during basin uplift. Gas-charged fluid suddenly leaks into the fault, causing a sudden drop in pressure followed by the rapid precipitation of silicate and calcite cements that seal the fault before meteoric groundwater from adjacent aquifers can flush the anomalously pressured zone. The affected reservoir remains hydrologically isolated, and salinity levels usually stay elevated (Surdam and others 2006).

Figure 22 in Surdam and others (2006) documents a sudden increase in salinity in the Muddy Sandstone of the Powder River Basin at the 7,000–8,000-ft depth interval. Papers by Law and Dickinson (1985), Swarbrick and Osbourne (1998), and Surdam and others (2003, 2006) provide complete explanations of the interactions between hydrocarbons, groundwater, and rock that generate abnormal pressures in hydrocarbon reservoirs.

Table 4 and figure 3 show frequency percentages for saline groundwater by WDEQ class-of-use. In the shallowest interval (1,000–2,000 ft bgs), industrial-grade (TDS>5,000 mg/L) groundwaters occur in about 25 percent of samples. Industrial-grade waters occur with about 40–50 percent frequency at depths of 2,000–6,000 ft bgs and more than 50 percent frequency at depths greater than 6,000 ft bgs.

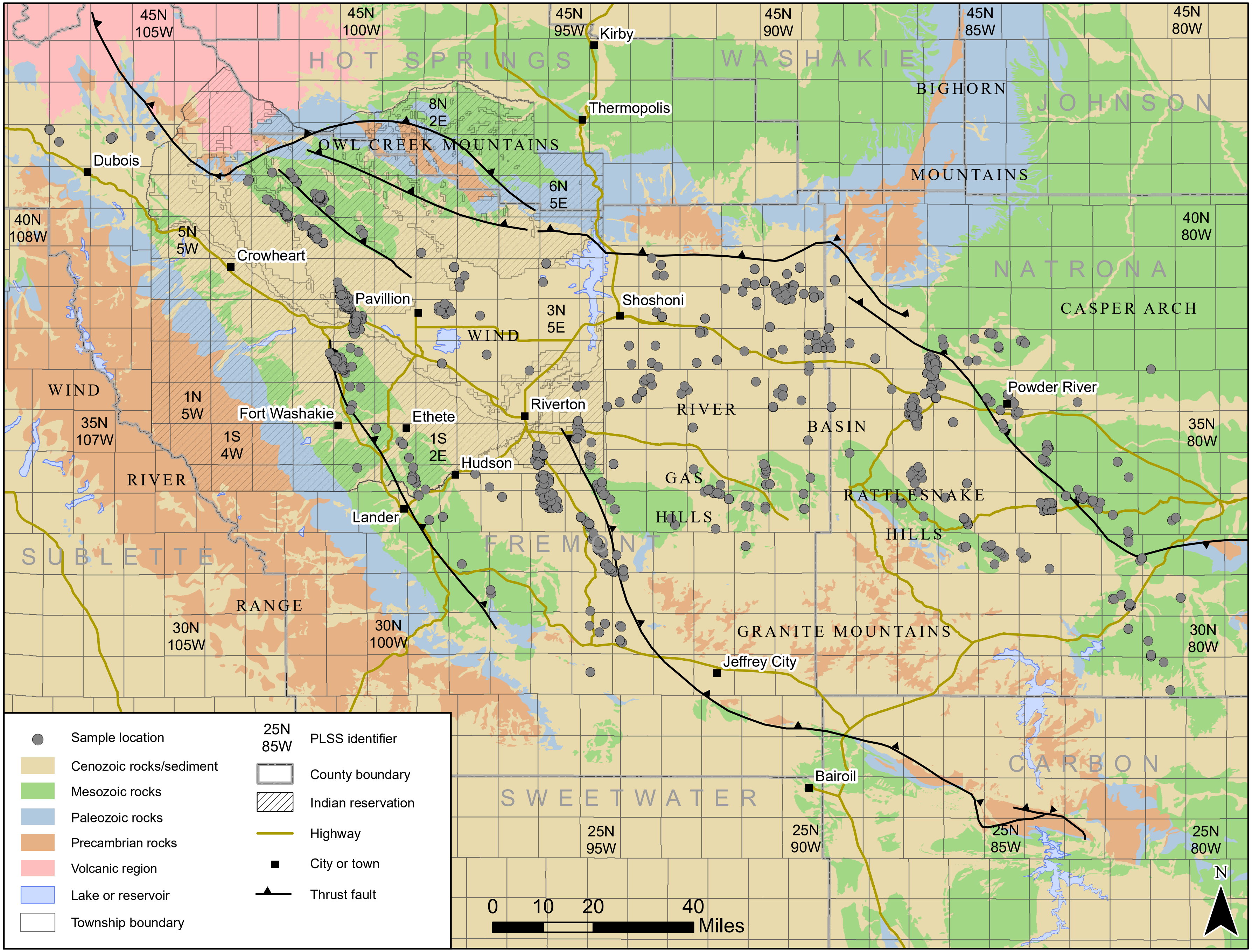

Figure 1. Qualified wells in the Wind River Basin used in this study. TDS concentrations were estimated using the Static Spontaneous Potential (SSP) Method (Schlumberger Well Services, 1989; Schnoebelen and others, 1995) or obtained as water-quality analyses from Engle and others (2019), the USGS (2021), and the WOGCC (2021b). Surface geologic units adapted from Love and Christiansen (1985), faults adapted from Blackstone (1993). [Abbreviations: PLSS, Public Land Survey System; N, north; W, west.]

Table 3. Summary statistics for salinity levels in the Wind River Basin by depth intervals. Only TDS values greater than 1,000 mg/L were used. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Depth interval (ft bgs)	Salinity as TDS (mg/L)								Sample size
	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum	Mean	
1,000–2,000	1,028	1,543	2,004	2,855	4,713	8,071	27,936	4,170	59
2,000–3,000	1,061	1,696	2,195	3,680	6,883	9,562	16,932	4,886	66
3,000–4,000	1,034	1,488	3,072	4,735	7,484	11,415	30,221	6,087	67
4,000–5,000	1,020	1,762	2,826	4,108	7,082	11,594	41,353	6,020	68
5,000–6,000	1,059	2,237	3,280	5,265	9,493	13,036	28,049	6,910	58
6,000–7,000	1,299	2,139	2,754	5,204	8,470	13,294	40,222	7,704	51
7,000–8,000	1,346	1,722	2,747	5,174	7,915	17,345	33,534	7,649	59
8,000–9,000	1,085	1,642	3,575	5,666	7,465	13,149	23,801	6,804	46
9,000–10,000	1,237	3,597	4,747	6,571	8,181	15,654	30,440	8,352	32
10,000–11,000	1,733	3,749	6,051	8,240	16,149	30,462	46,894	12,721	33
11,000–12,000	1,200	2,274	3,547	8,504	15,704	23,303	33,026	11,031	16
>12,000	1,271	1,469	3,332	8,036	28,243	42,998	127,111	19,951	23

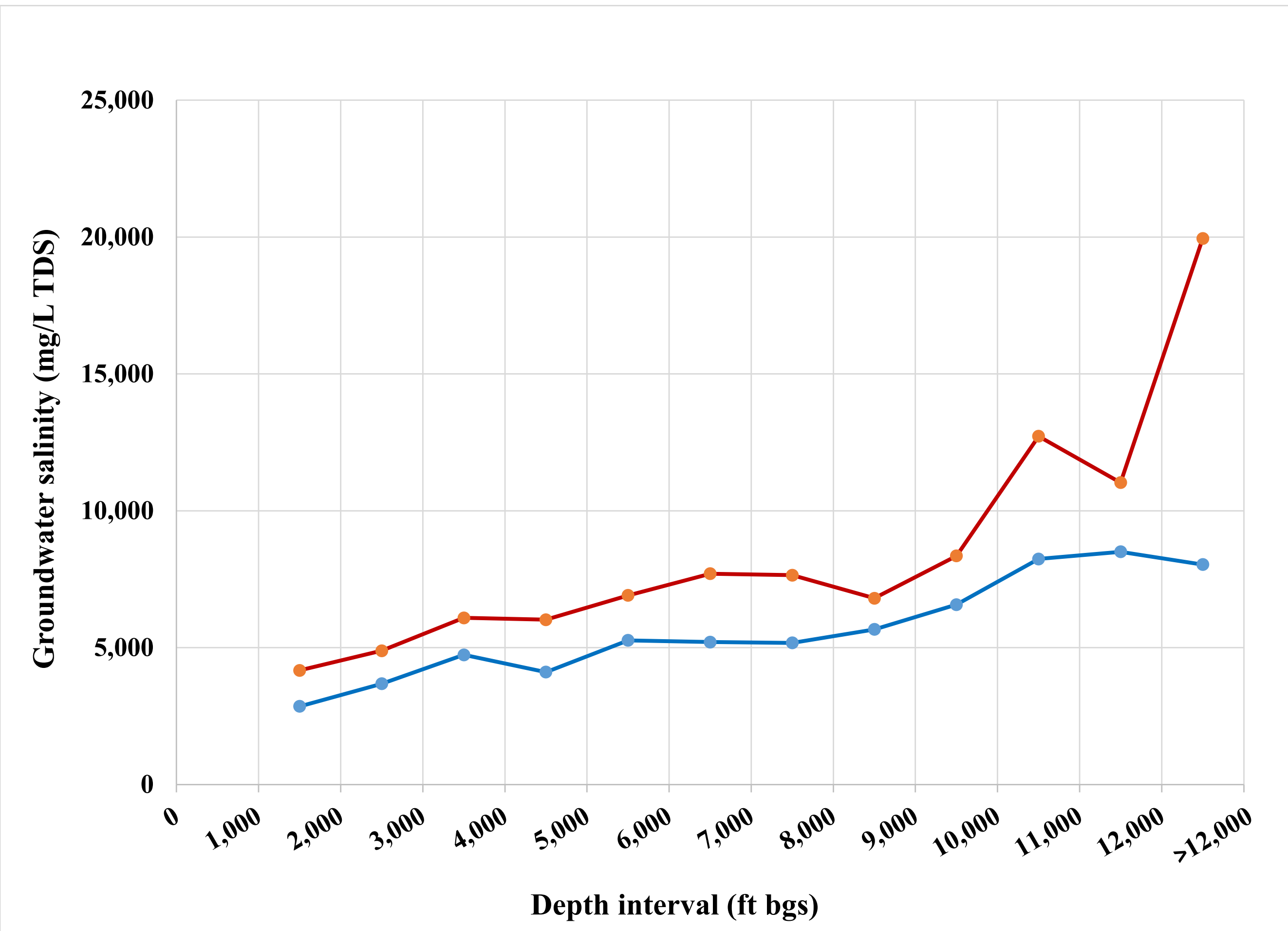

Figure 2. Mean (in red) and median (in blue) groundwater TDS concentrations (mg/L) versus depth of sample in the Wind River Basin. Note the rapid increase in salinity at depth intervals greater than 8,000–9,000 ft bgs. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Table 4. Prevalence of saline groundwater, as WDEQ class-of-use, by depth interval in the Wind River Basin. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Depth interval (ft bgs)	Number of samples	Class II agricultural 1,000–2,000 (mg/L TDS)	Class III livestock 2,000–5,000 (mg/L TDS)	Class IV-A industrial 5,000–10,000 (mg/L TDS)	Class IV-B industrial >10,000 (mg/L TDS)	Class IV-A&B Combined industrial >5,000 (mg/L TDS)
		Percent				
1,000–2,000	59	25	51	17	7	24
2,000–3,000	66	23	39	29	9	38
3,000–4,000	67	15	37	30	18	48
4,000–5,000	68	13	47	27	13	40
5,000–6,000	58	9	40	27	24	51
6,000–7,000	51	10	33	37	20	57
7,000–8,000	59	17	32	31	20	51
8,000–9,000	46	13	28	44	15	59
9,000–10,000	32	9	19	53	19	72
10,000–11,000	33	3	15	46	36	82
11,000–12,000	16	13	25	12	50	62
>12,000	23	22	13	17	48	65

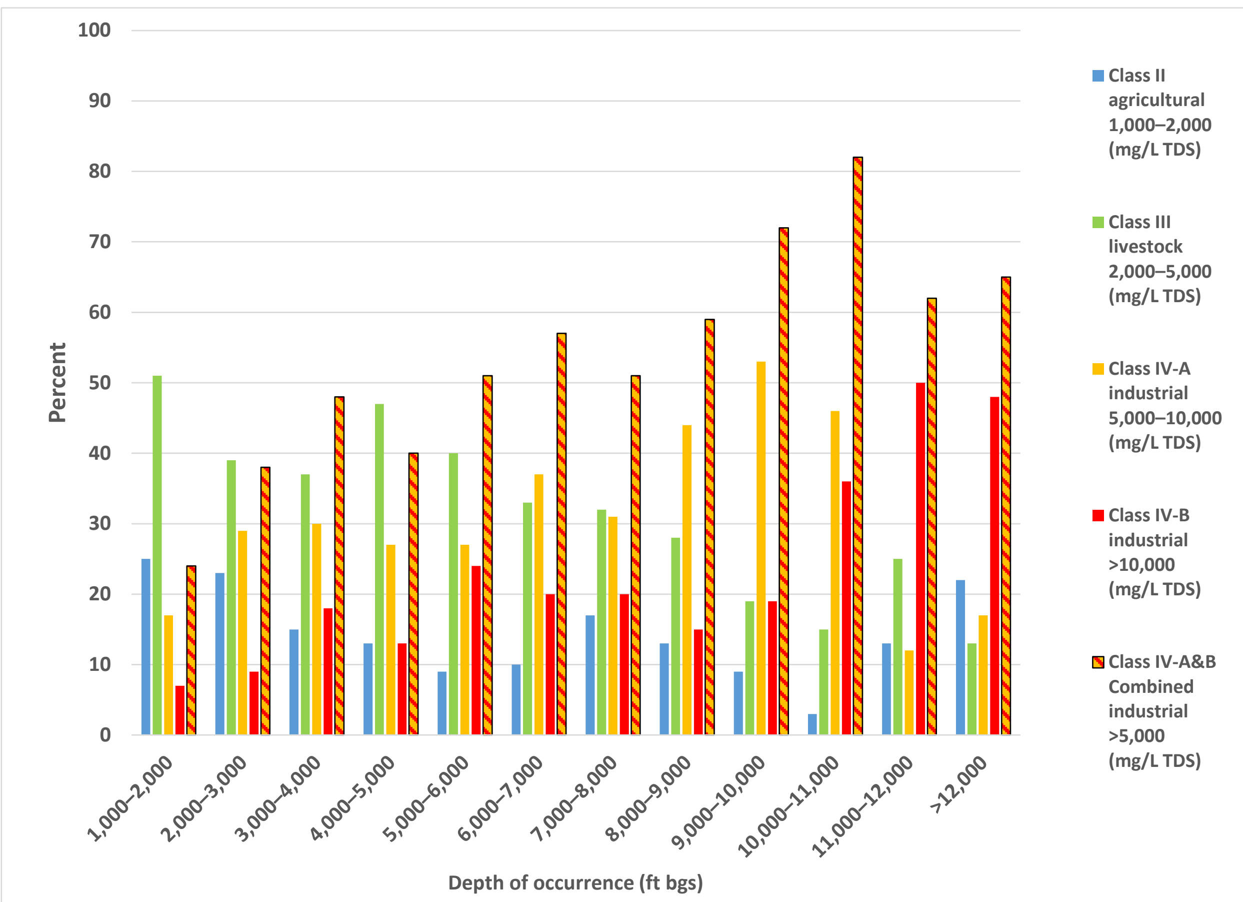

Figure 3. Frequency of occurrence of saline groundwater, by WDEQ class-of-use, in 1,000-ft depth intervals in the Wind River Basin. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Geographic distributions of saline groundwaters

Appendix figures A1-1–A1-12 show the geographic distribution of saline wells in the WRB by 1,000-ft intervals from 1,000 ft bgs to more than 12,000 ft bgs. Generally, industrial-grade (TDS>5,000 mg/L) groundwaters are somewhat more prevalent in the basin interior and across its northern margin, south of the Owl Creek and Bighorn Mountains, and Casper Arch. The location of wells with industrial-grade water is less straightforward than in other Wyoming structural basins (Taboga and others, 2016, 2018, 2020), likely due to the complicated geologic structure of the WRB.

Environmental and geologic controls on the distribution of saline groundwaters

<u>Precipitation and potential recharge</u>

The magnitude of fresher water inputs flowing from nearby recharge areas affects groundwater salinity (Taboga and others, 2020). Richter (1981) posited that basinward aquifers in the WRB received recharge from upland areas in the Granite and Owl Creek Mountains, the Absaroka and Wind River ranges, and the Casper Arch. Potential recharge inputs, however, are largely determined by precipitation and soil permeability. Based on these factors, Hammerlinck and Arneson (1998) estimated that potential annual recharge to the Granite Mountains, Casper Arch, and the basin interior is less than one inch. In contrast, the bordering flanks of the Wind River Range and Owl Creek Mountains and the southern Absaroka Range receive more than 6 inches of potential recharge annually (Hammerlinck and Arneson, 1998).

<u>Geologic structure and recharge</u>

Geologic structure controls the direction and magnitude of groundwater flow, enhancing or limiting the delivery of recharge and its freshening effect on groundwater in basinward aquifers. Dr. Peter Huntoon and his graduate students recognized the role that Laramide basin foreland structures, specifically large displacement thrust faults (Huntoon, 1993), have on groundwater availability and quality. The large thrust faults that bound about half of all structural basin margins in Wyoming (fig. 2 in Huntoon [1993]) sever hydraulic continuity between upland recharge areas and basin interior aquifers. Generally, groundwater on the upland side of the fault is less saline than on the basinward side. This is not readily observed in the structurally complex WRB, (figs. A1-1–A1-12). One exception might be seen, however, along the southwestern edge of the Casper Arch in the 3,000–4,000-ft and 4,000–5,000-ft intervals where industrial-grade (TDS>5,000 mg/L) groundwaters occur most frequently on the basinward side of the fault but are encountered less frequently on the hanging wall side.

Salinity variations in geologic units

The Paleozoic Tensleep Sandstone and Madison Limestone show markedly lower mean and median levels of salinity than do Cenozoic or Mesozoic units (table 5). Taucher and others (2012) describe these major limestone aquifers as, "… well known for producing high volumes of groundwater at and near the flanks of the Laramide uplifts surrounding the basins where permeability has been structurally enhanced by solution-enlarged fractures." The lower salinities observed in the Tensleep Sandstone and Madison Limestone extend into deeper intervals. Moderately saline waters (2,000–5,000 mg/L TDS) occur in the Tensleep Sandstone to a depth of 10,000 ft bgs (fig. A1-10). Slightly saline groundwaters (1,000–2,000 mg/L TDS) are commonly observed in the small number of samples obtained from the Madison Limestone at depths exceeding 10,000 ft bgs (figs. A1-10–A1-12). Powley (1987) noted that a normally pressured Paleozoic carbonate-dominated sequence that includes the Tensleep Sandstone and the Madison Limestone underlies an anomalously pressured Mesozoic zone in the southern WRB. This allows these Paleozoic aquifers to receive recharge from hydraulically connected surface exposures along the flanks of the Wind River Range and Rattlesnake Hills.

Table 5. Summary statistics and prevalence of saline groundwater by geologic formation in the Wind River Basin. [Abbreviations: mg/L, milligrams per liter]

Formation	Sample size	Salinity as TDS (mg/L)								Samples TDS>5,000 mg/L	
		Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum	Mean	Number	Percent
Wind River Fm	28	1,148	1,804	2,827	4,522	9,918	29,460	35,299	8,889	13	46%
Fort Union Fm	119	1,113	2,423	3,611	6,048	7,580	12,691	127,111	8,111	73	61%
Lance Fm	53	1,679	3,433	4,990	6,412	10,302	21,934	46,894	9,787	39	74%
Mesaverde Fm	42	1,237	2,664	3,714	4,839	7,255	11,875	21,237	6,281	20	48%
Cody Shale	10	1,033	1,817	3,540	4,421	5,350	11,495	16,225	5,651	3	30%
Frontier Fm	37	1,271	3,190	5,375	8,081	13,877	21,764	35,675	10,872	30	79%
Muddy Ss	27	1,217	2,614	2,890	5,686	8,564	10,382	43,789	7,257	15	56%
Cloverly Fm	26	1,117	1,629	2,028	4,956	7,203	12,220	27,614	6,077	13	50%
Sundance Fm	6	1,070	1,817	2,723	3,601	5,715	14,103	21,920	6,507	2	33%
Nugget Ss	13	1,152	1,346	2,539	6,896	19,000	28,847	41,353	11,870	8	57%
Chugwater Fm	7	3,512	5,785	7,761	8,805	13,081	15,820	15,836	9,977	6	86%
Dinwoody Fm	10	2,181	3,248	3,635	5,180	8,250	9,801	10,742	6,020	6	60%
Phosphoria Fm	52	1,034	1,759	2,642	5,300	9,117	16,487	58,338	8,782	26	50%
Tensleep Ss	68	1,028	1,223	1,571	2,284	3,516	5,474	10,388	2,932	8	12%
Madison Ls	25	1,020	1,131	1,440	1,881	2,341	2,983	7,771	2,209	2	8%

The elevated salinity levels typical of the other geologic units listed in table 5 are likely the result of a combination of lithology (units containing limited shale, evaporite, and siltstone strata) and poor groundwater circulation in anomalously pressured fine-grained Mesozoic reservoirs.

First encountered industrial-grade groundwaters (TDS>5,000 mg/L)

Figure 4 shows the depth interval where industrial-grade saline groundwater (TDS>5,000 mg/L) is first observed at the WRB well sites, as shown in figures A1-1–A1-12. Figure 4 does not include wells with salinity levels below 5,000 mg/L.

Generally, industrial-grade groundwaters are first encountered at less than 5,000 ft bgs along the northwestern, western, and eastern margins of the WRB. In comparison, industrial-grade waters first occur at deeper intervals in two clusters of basinward well sites. The first group is a broad band of wells that extends from Ocean Lake eastward across the northern half of the WRB to the town of Powder River along the drainages of Badwater and Poison Creeks. The first occurrence of saline groundwater at greater depths in these wells is likely due to the data available in the geophysical logs. Frequently, gamma ray and resistivity logging was conducted in borehole intervals from 6,000 ft bgs to the total depth, particularly in Tertiary Wind River and Fort Union Formation wells.

A second group of deep saline wells is present below the northeastern flank of the Rattlesnake Hills where Precambrian through Tertiary units are exposed from the crest of the uplift basinward. In this area, recharge from direct precipitation to nearby exposures of Upper Cretaceous rocks along the base of the Rattlesnake Hills probably refreshes groundwater in the shallow geologic units of deep saline wells located less than 6 miles to the northeast.

Bighorn Basin

Oil and gas fields are generally located around the basin's margins (Toner and others, 2021), and are largely absent from the basin's interior (fig. 5). Most fields in the Bighorn Basin target oil reservoirs in the Paleozoic Phosphoria Formation, Tensleep Sandstone, and Madison Limestone. However, many Paleozoic wells are also completed in Mesozoic oil and gas reservoirs (Toner and others, 2021; WOGCC, 2021).

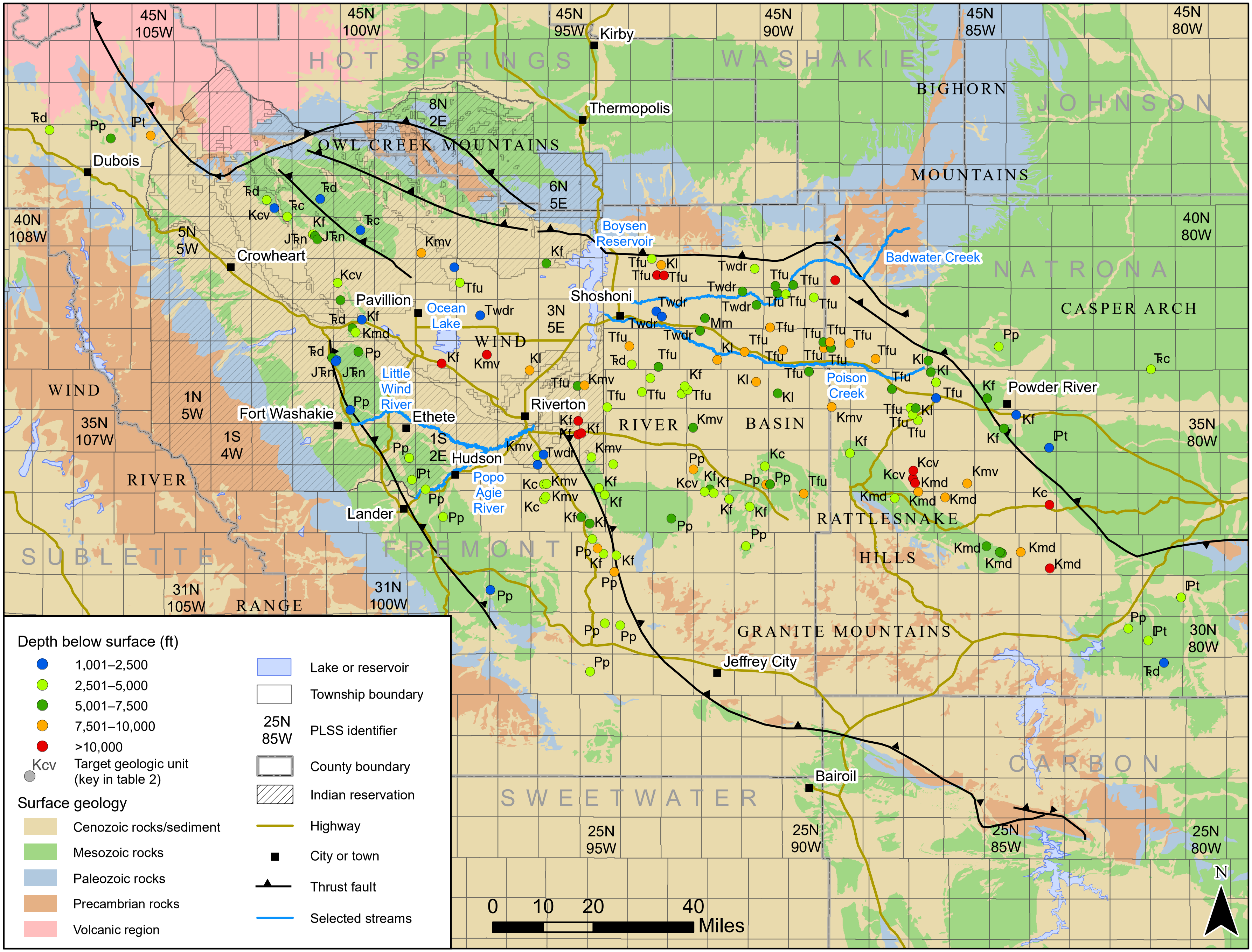

Figure 4. Depth to first industrial-grade (TDS>5,000 mg/L) groundwater in the Wind River Basin. Geologic units adapted from Love and Christiansen (1985), faults adapted from Blackstone (1993). [Abbreviations: PLSS, Public Land Survey System; N, north; W, west.]

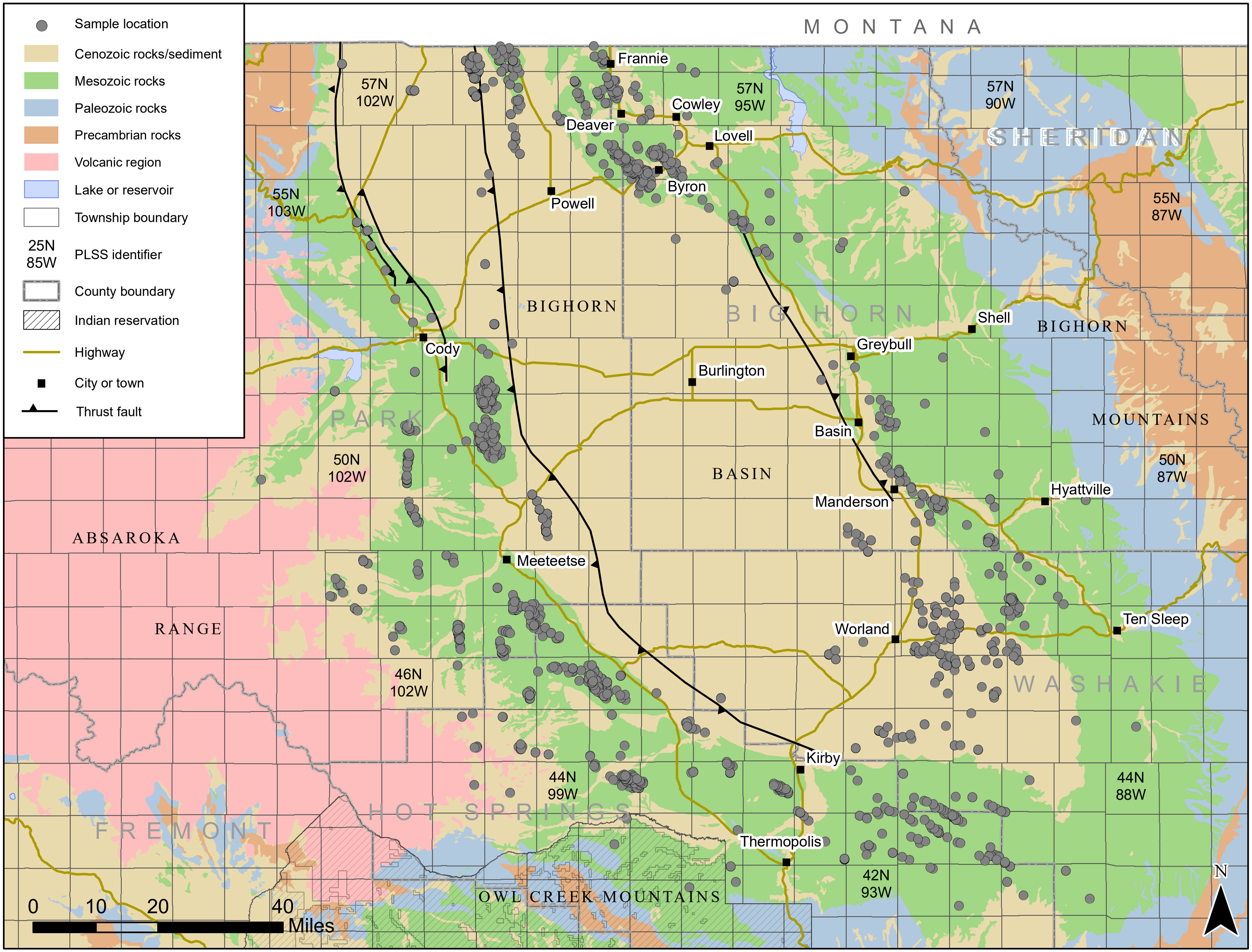

Figure 5. Qualified wells in the Bighorn Basin used in this study. TDS concentrations were estimated using the Static Spontaneous Potential (SSP) Method (Schlumberger Well Services, 1989; Schnoebelen and others, 1995) or obtained as water-quality analyses from the USGS (2021a) and WOGCC (2021). Surface geologic units adapted from Love and Christiansen (1985, faults adapted from Blackstone (1993). [Abbreviations: PLSS, Public Land Survey System; N, north; W, west.]

Variations in salinity with depth

Summary statistics for saline waters by depth interval are shown on table 6. As in the WRB, mean and median TDS concentrations generally increase with depth-of-burial (fig. 6) and the median values are lower than the means. Again, the means at each depth interval exceed the corresponding median value, largely due to the 1,000-mg/L constraint placed on minimum TDS levels in this report. The large differences between maximum TDS values compared to those at the 75th percentile indicates that extremely high salinities also occur infrequently in the BHB.

Mean and median salinities (fig. 6) increase more rapidly in intervals deeper than 6,000–7,000 ft bgs, coincident with the depth range of the "regional anomalous pressure surface" in Rocky Mountain Laramide basins (Surdam and others, 2006).

Industrial-grade groundwaters occur with less than 45 percent frequency (table 7, fig. 7) at depths less than 7,000 ft bgs and at 70–80 percent frequency at depths greater than 8,000 ft bgs. In addition, there is a slight decrease in the incidence of saline water in the two deepest intervals (11,000–12,000 ft bgs and >12,000 ft bgs) where samples were obtained from Paleozoic units (tables A2-1–A2-12).

Geographic distributions of saline groundwaters

The geographic distribution of saline wells is shown by 1,000-ft depth intervals in appendix figures A2-1–A2-12. At depths of 1,000–3,000 ft bgs, industrial-grade (TDS>5,000 mg/L) groundwaters occur more frequently along the western margin of the basin. However, industrial-grade waters are found more often along the basin's eastern margin at depths below 3,000 ft. Small clusters of industrial-grade waters occur east of Thermopolis, Worland, Manderson, and Powell.

Environmental and geologic controls on the distribution of saline groundwaters

Precipitation and potential recharge

Libra and others (1981) noted that Mesozoic and Paleozoic aquifers in the BHB receive recharge, "chiefly by the direct infiltration of precipitation at the outcrop." In contrast, Tertiary aquifers, such as the Fort Union, are recharged by direct precipitation to outcrops and by seepage from Quaternary gravel and alluvial deposits (Libra and others, (1981).

Based on annual precipitation and soil permeability, Hammerlinck and Arneson (1998) estimated that annual recharge is more than 6 inches along the adjacent flanks of the Absaroka Range and Bighorn Mountains, and western part of the Owl Creek Mountains, and less than one inch elsewhere.

Geologic structure and recharge

Much of the research done by Dr. Peter Huntoon's group to develop his conceptual model of the permeability architecture in Laramide basin foreland structures (Huntoon, 1993) was conducted in the BHB. The research concluded that the large thrust faults present along Laramide basin margins interrupt the flow of groundwater from upland recharge areas, such as the Absaroka Range and Bighorn Mountains (Huntoon, 1993), resulting in elevated groundwater salinities in basinward (footwall) aquifers.

However, most of the oil and gas wells used in this study are sited in areas that are unaffected by the large thrust faults (figs. A2-1–A2-12). Generally, wells on the western margin adjacent to the Absaroka Range are located on the hanging walls of the large thrust faults where groundwater flows from upland recharge areas unimpeded. In a similar way, most wells on the eastern margin are sited at either end or in the hanging wall of the thrust fault that extends from Byron to Manderson (figs. 8 and A2-1–A2-12).

Table 6. Summary statistics for salinity levels in the Bighorn Basin by depth intervals. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Depth Interval (ft bgs)	Salinity as TDS (mg/L)								Sample size
	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum	Mean	
1,000–2,000	1,078	1,495	2,165	4,882	9,265	15,946	38,862	7,570	52
2,000–3,000	1,062	1,404	2,408	4,284	9,286	13,109	41,683	7,213	70
3,000–4,000	1,022	1,884	2,654	4,585	8,027	12,505	62,163	6,631	92
4,000–5,000	1,081	1,974	2,715	3,855	8,608	13,860	52,680	6,643	79
5,000–6,000	1,183	1,823	2,843	4,289	10,573	18,297	54,513	8,609	59
6,000–7,000	1,101	2,069	2,677	4,507	9,579	16,177	115,997	9,361	49
7,000–8,000	1,017	1,534	2,965	6,334	12,845	22,234	66,676	9,991	48
8,000–9,000	1,604	1,893	2,807	4,640	8,487	17,715	22,461	7,257	30
9,000–10,000	1,050	1,626	2,232	3,752	6,041	17,448	38,111	6,817	25
10,000–11,000	2,052	2,512	5,771	13,397	17,579	20,653	55,482	14,820	24
11,000–12,000	1,810	2,838	3,376	6,615	14,005	22,678	22,911	9,664	11
>12,000	3,080	3,763	6,057	8,377	12,640	17,235	18,275	9,589	7

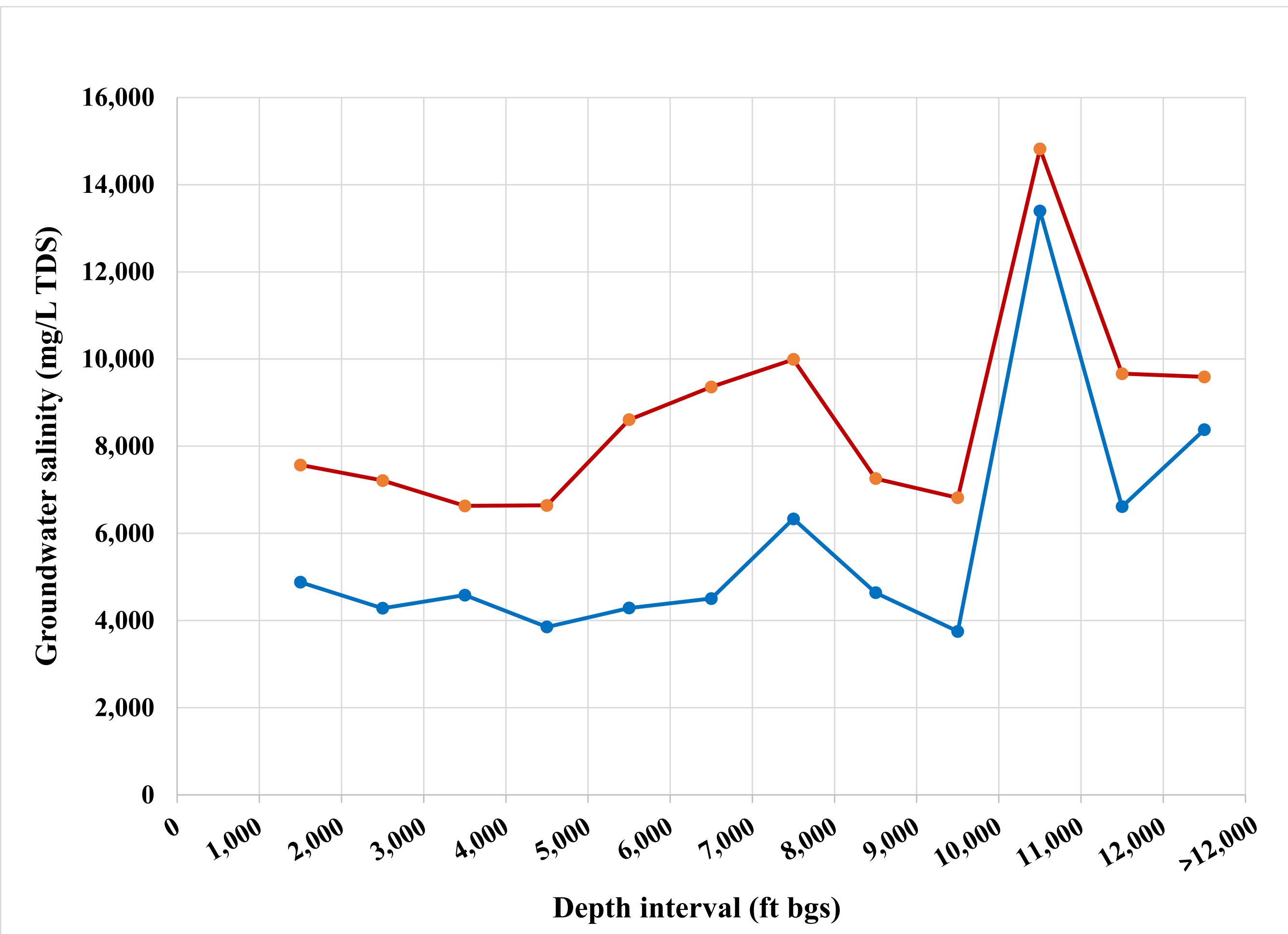

Figure 6. Mean (in red) and median (in blue) groundwater TDS concentrations (mg/L) versus depth of sample in the Bighorn Basin. Note the increase in the slope of the trendline for both at depth intervals exceeding 6,000–7,000 ft bgs. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Table 7. Prevalence of saline groundwater, as WDEQ class-of-use, by depth interval in the Bighorn Basin. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

Depth interval (ft bgs)	Number of samples	Class II agricultural 1,000–2,000 (mg/L TDS)	Class III livestock 2,000–5,000 (mg/L TDS)	Class IV-A industrial 5,000–10,000 (mg/L TDS)	Class IV-B industrial >10,000 (mg/L TDS)	Class IV-A&B Combined industrial >5,000 (mg/L TDS)
		Percent				
1,000–2,000	52	19	35	29	17	45
2,000–3,000	70	16	47	13	24	38
3,000–4,000	92	16	42	19	23	42
4,000–5,000	79	20	55	11	14	26
5,000–6,000	59	15	49	26	10	36
6,000–7,000	49	10	55	14	21	38
7,000–8,000	48	6	40	19	35	55
8,000–9,000	30	0	23	37	40	77
9,000–10,000	25	8	12	36	44	80
10,000–11,000	24	4	17	17	62	80
11,000–12,000	11	9	18	18	55	73
>12,000	7	14	14	29	43	70

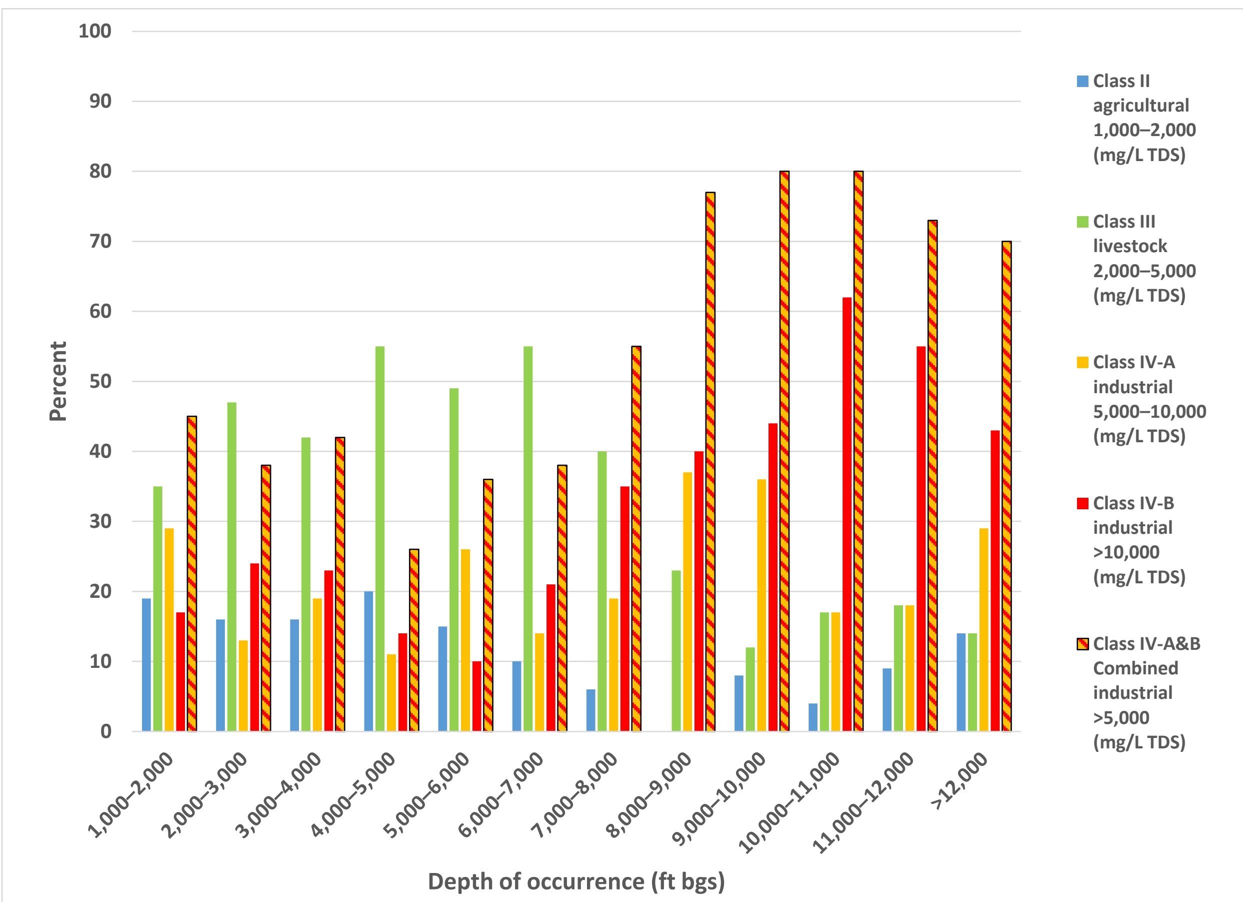

Figure 7. Frequency of occurrence of saline groundwater, by WDEQ class-of-use, in 1,000-ft depth intervals in the Bighorn Basin. [Abbreviations: mg/L, milligrams per liter; ft bgs, feet below ground surface]

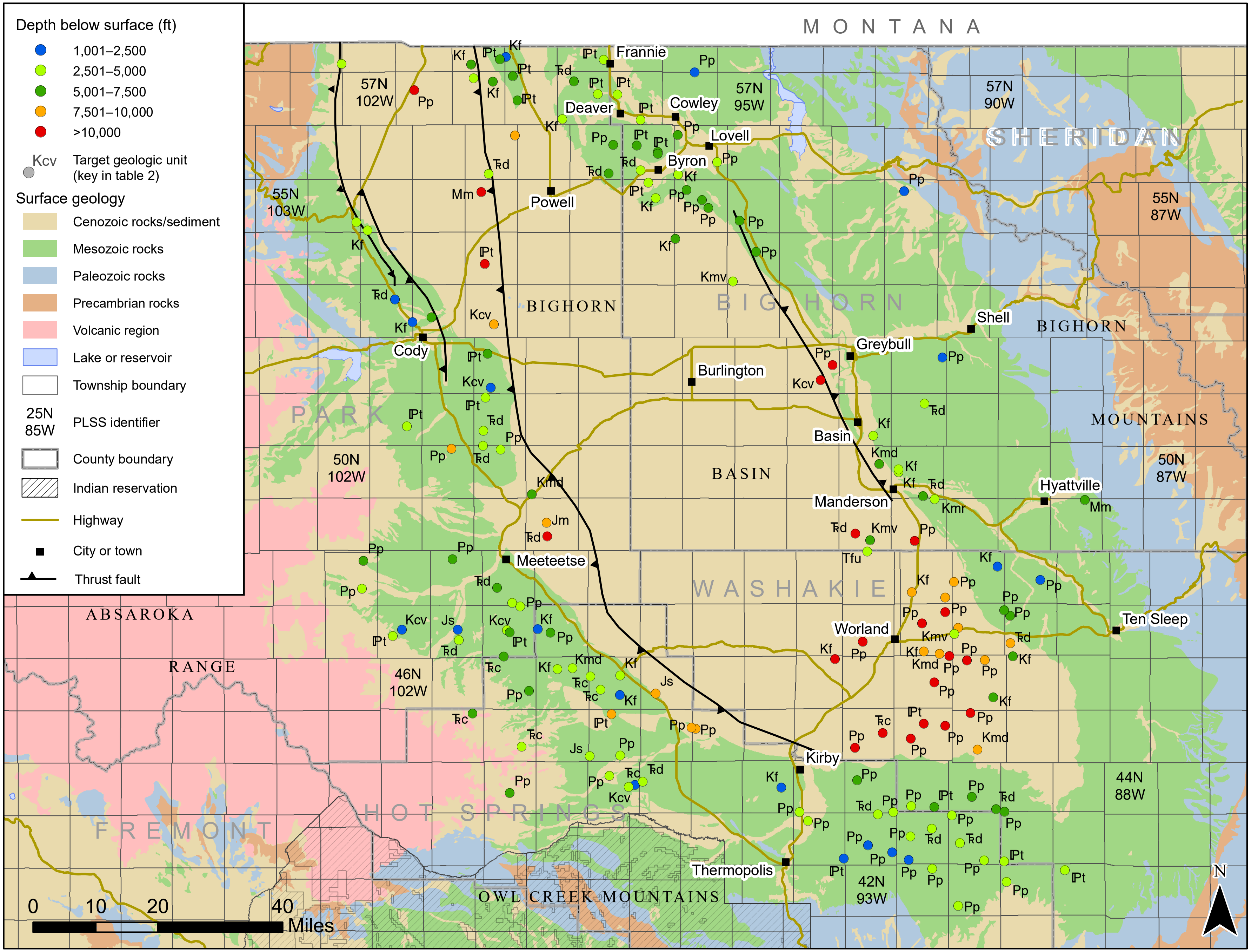

Figure 8. Depth to first industrial-grade (TDS>5,000 mg/L) groundwater in the Bighorn Basin. Geologic units adapted from Love and Christiansen (1985) faults adapted from Blackstone (1993). [Abbreviations: PLSS, Public Land Survey System; N, north; W, west.]

Salinity variations in geologic units

In the BHB, industrial-grade waters occur less frequently in the Paleozoic Tensleep Sandstone, Amsden Formation, Madison Limestone, and Flathead Sandstone than overlying Cenozoic or Mesozoic formations (table 8). The Madison Limestone, in particular, exhibits markedly low salinity levels with only 7 percent of samples/estimates exceeding 5,000 mg/L. Slightly saline groundwaters (TDS<2,000 mg/L) are seen in the Madison Limestone at all depth intervals with the exception of the 10,000–11,000-ft interval. Both the Tensleep Sandstone and Madison Limestone receive recharge from hydraulically connected surface exposures along the flanks of the Bighorn Mountains (Plates XII–XV in Taucher and others, 2012).

The elevated occurrence of industrial-grade groundwaters observed in the Phosphoria Formation as well as the Mesozoic and Cenozoic formations shown in table 8 is likely due to a combination of lithology (containing shale, evaporite, and siltstone strata) and poor groundwater circulation.

First encountered industrial-grade groundwaters (TDS>5,000 mg/L)

Depth intervals where industrial-grade saline groundwater (TDS>5,000 mg/L) is first encountered are shown in figure 8. Well sites with salinity levels below 5,000 mg/L are not shown in figure 8.

Industrial-grade waters are first observed at less than 7,500 ft bgs in most BHB wells (fig. 8). The large cluster of deeper salinity wells around Worland is within a focus area where recharge inputs from Mesozoic and Paleozoic exposures converge from the south, southeast, and east (Jarvis, 1986; Spencer, 1986). Most samples in this deep salinity area are taken from the Paleozoic Phosphoria Formation, which contains numerous evaporite facies (Inden and Coalson, 2012).

Table 8. Summary statistics and prevalence of saline groundwater by geologic formation in the Bighorn Basin. [Abbreviations: mg/L, milligrams per liter]

		Salinity as TDS (mg/L)								Samples TDS>5,000 mg/L	
Formation	Sample size	Minimum	10th percentile	25th percentile	Median	75th percentile	90th percentile	Maximum	Mean	Sample size	Percent
Fort Union Fm	5	1,611	1,957	2,476	3,249	5,752	7,544	8,738	4,365	2	40%
Lance Fm	9	1,101	1,691	2,238	3,502	6,510	6,593	6,827	3,989	4	44%
Mesaverde Fm	24	2,062	2,525	2,828	4,243	6,917	13,847	22,911	6,246	9	38%
Frontier Fm	62	1,288	2,108	3,686	7,098	10,988	14,243	32,425	8,130	36	58%
Muddy Ss	25	1,229	1,788	4,617	6,050	7,813	13,618	36,215	7,678	17	68%
Cloverly Fm	32	1,657	2,362	2,989	6,221	11,230	15,915	25,539	8,234	21	66%
Morrison Fm	7	1,387	1,917	2,704	8,478	9,688	11,242	12,984	6,805	4	57%
Sundance Fm	31	1,485	3,888	5,952	10,459	17,222	21,865	54,513	13,493	26	79%
Chugwater Fm	24	2,804	4,441	7,810	11,448	15,067	22,454	43,398	13,438	20	83%
Dinwoody Fm	34	1,078	2,536	3,202	4,698	9,317	15,897	62,163	9,297	15	44%
Phosphoria Fm	77	1,105	2,461	3,619	6,931	16,112	30,241	115,997	13,580	45	58%
Tensleep Ss	118	1,050	1,287	1,985	3,025	4,550	9,783	23,440	4,247	21	18%
Amsden Fm	5	1,022	1,330	1,791	1,877	2,867	9,386	13,732	4,258	1	20%
Madison Ls	44	1,017	1,319	1,779	2,445	3,623	4,439	15,557	3,067	3	7%
Flathead Ss	6	2,729	3,012	3,329	3,528	4,222	8,655	12,889	5,065	1	17%

SUMMARY

The WSGS examined groundwater salinity in the deep geological formations (>1,000 ft bgs) of the Wind River (WRB) and the Bighorn (BHB) structural basins of northern Wyoming. Salinity data were obtained from USGS water-quality analyses and spontaneous potential (SP) measurements from borehole geophysical logs. The resultant salinity dataset contains more than 5,000 qualified water-quality analyses and SP salinity estimates in total.

In the WRB, groundwater salinity generally increases with depth with the exception of the Tensleep Sandstone and Madison Formation. Industrial-grade waters (TDS>5,000 mg/L) comprise more than 50 percent of groundwaters at depths greater than 5,000 ft bgs but are less prevalent at shallower depths. At all depths, the Fort Union, Lance, Frontier, Chugwater, Dinwoody, and Phosphoria formations as well as the Muddy and Nugget sandstones produce groundwaters with median TDS levels exceeding 5,000 mg/L at more than 50 percent frequency. Using the same median and frequency criteria, the Mesaverde, Frontier, and Chugwater formations are the most promising sources of industrial-grade water from shallow wells (<5,000 ft bgs). In contrast to these saline formations, only 8 percent of groundwater samples from the Madison Limestone and 12 percent of samples from the Tensleep Sandstone had TDS levels exceeding 5,000 mg/L.

Areas along the northwestern, western, southern, and eastern margins of the WRB are most likely to produce saline water from shallow wells (<5,000 ft bgs). In these areas, it may be economically feasible to repurpose once-productive oil and gas wells to provide saline groundwater for industrial uses. On the other hand, saline waters are first encountered in deeper intervals (>5,000 ft bgs) along a broad area that stretches across the north-central basin from Ocean Lake to the eastern edge of the Rattlesnake Hills.

The relation between salinity and depth is not as clear in the BHB (fig. 7). Industrial-grade waters occur with about 40 percent frequency at depth intervals of 1,000–4,000 ft bgs and then fall to about 30 percent frequency in the 4,000–6,000 ft intervals. Thereafter, salinity levels generally increase with depth. Industrial-grade waters constitute more than 50 percent of samples at depths greater than 7,000 ft bgs. The frequency with which industrial-grade waters occur is related to the proportion of relatively low-salinity Paleozoic samples compared to those collected from higher salinity Mesozoic formations (tables A2-1–A2-12).

High salinity (median TDS>5,000 mg/L) units in the BHB are the Mesozoic Frontier, Muddy, Cloverly, Morrison, Sundance, and Chugwater formations and the Paleozoic Phosphoria Formation. In comparison, the Paleozoic Tensleep Sandstone, Amsden Formation, Madison Limestone, and Flathead Sandstone are characterized by median salinity levels of 3,038 mg/L or less. It is worth noting that samples from these lower salinity formations appear in every depth interval examined. Shallow wells (<5,000 ft bgs) in the Frontier, Cloverly, Sundance, and Chugwater formations are likely to provide supplies of industrial-grade water. Industrial-grade groundwaters in the BHB are first encountered at depths of less than 7,500 ft bgs, with the notable exception of a large cluster of deeper saline wells located east of Worland.

DISCLAIMER

Despite the large number of WOGCC well logs and USGS water-quality analyses examined during the course of this project, this report does not constitute a comprehensive examination of saline waters in the Wind River and Bighorn structural basins. The locations and geologic units of sites that produce saline waters were largely determined by the potential of those sites to yield economically recoverable reserves of oil and gas.

This document was prepared as a WSGS Open File Report that will be supplemented as new information becomes available. It is expected that the WOGCC will continue to release new groundwater-quality data for the WRB and BHB periodically. This report is intended to provide a preliminary approximation of salinity levels to depths exceeding 12,000 ft bgs in the Wind River and Bighorn structural basins of northern Wyoming. The WSGS makes no guarantees regarding the accuracy of the data contained herein and encourages readers of this report to consult other reports, publications, and data sources, and to seek information from other qualified groundwater professionals before seeking to develop groundwater resources in this or any other area of the state. Additional information about the hydrogeology of these Wyoming basins can be found in technical memoranda contained in Wyoming Water Development river basin planning reports (Taucher and others, 2012) https://waterplan.state.wy.us/plan/bighorn/bighorn-plan.html and in USGS publications (https://pubs.er.usgs.gov/).

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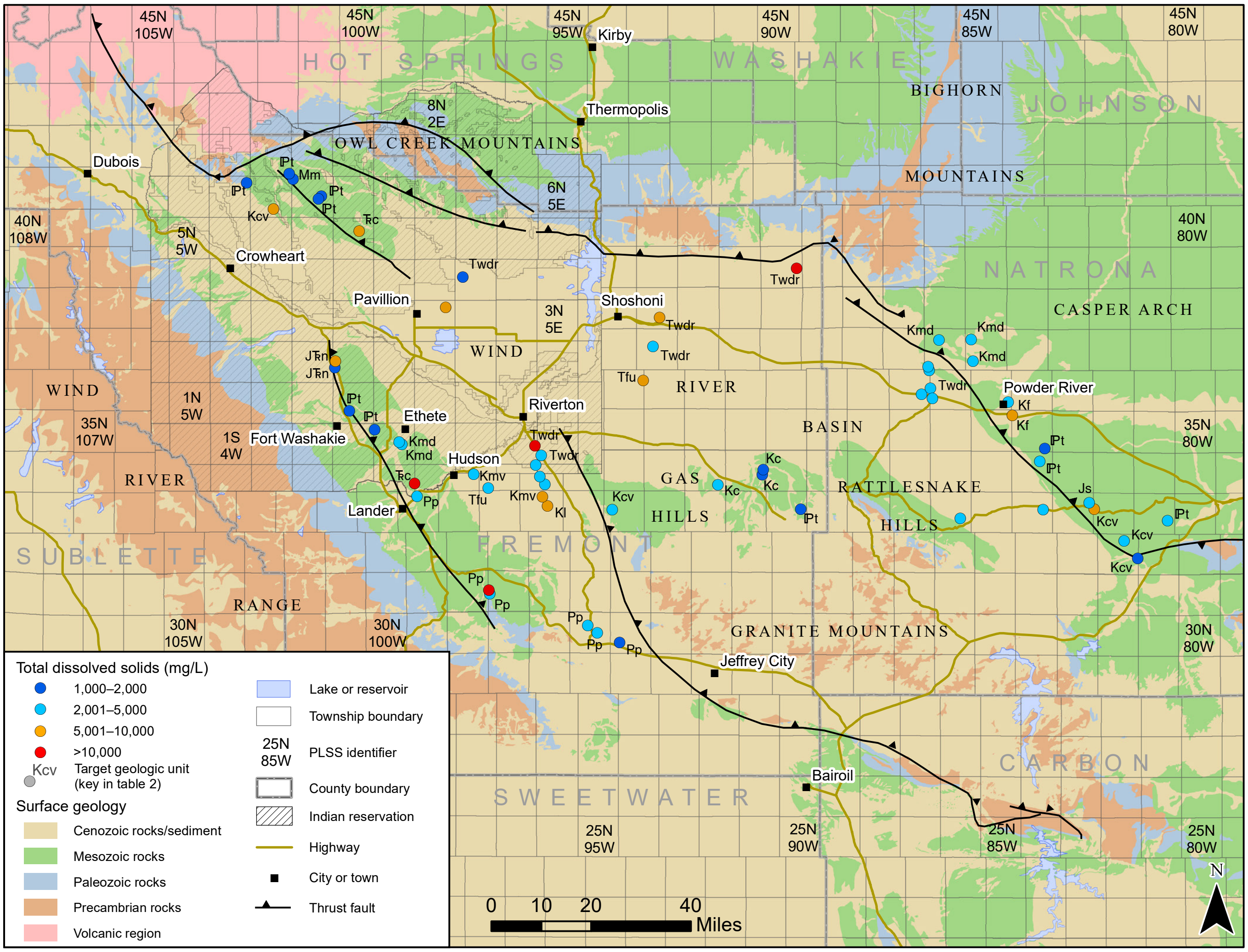
Appendices

Appendix 1

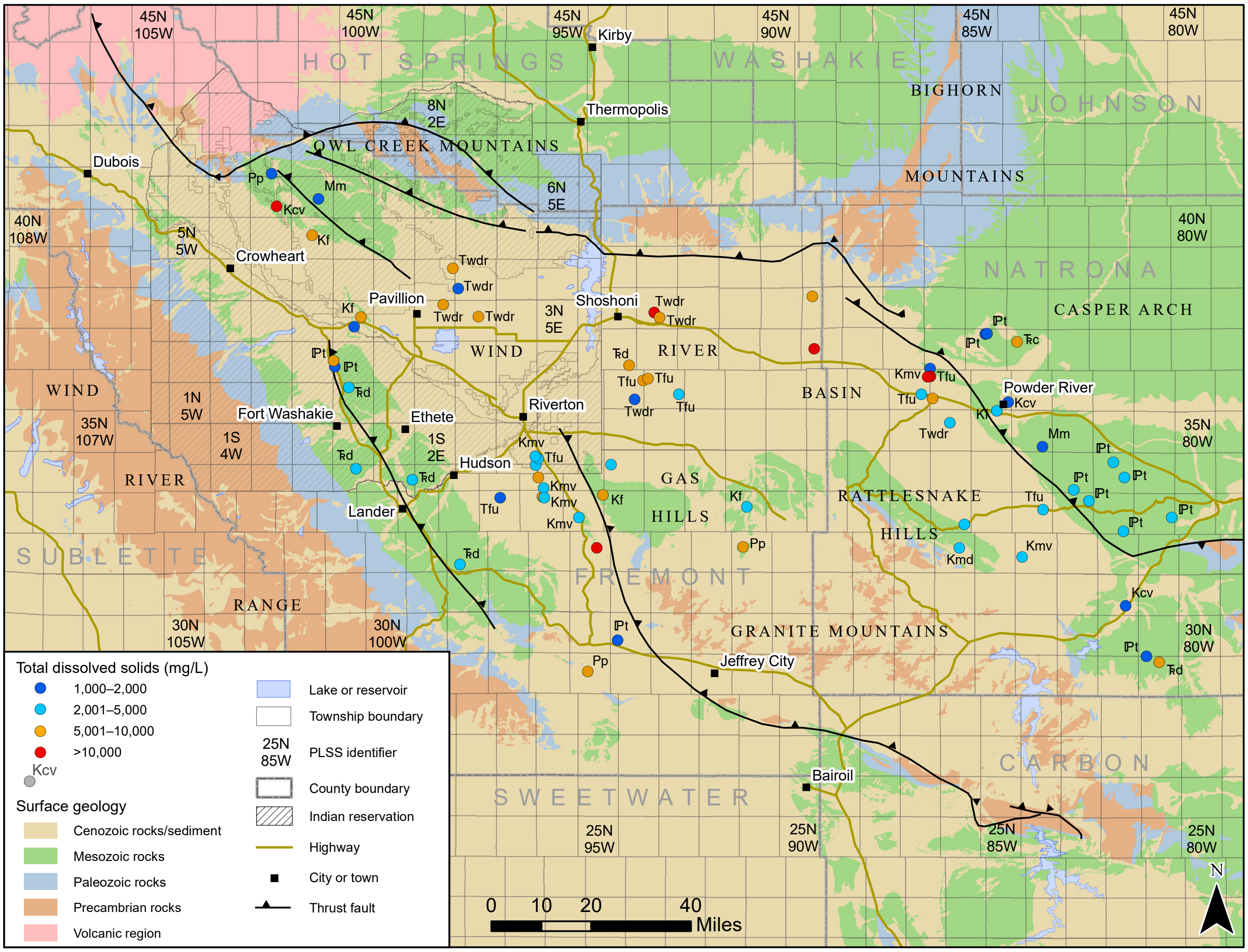
Wind River Basin

Figure/Table A1–1. Figure and table show saline waters in the 1,000–2,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



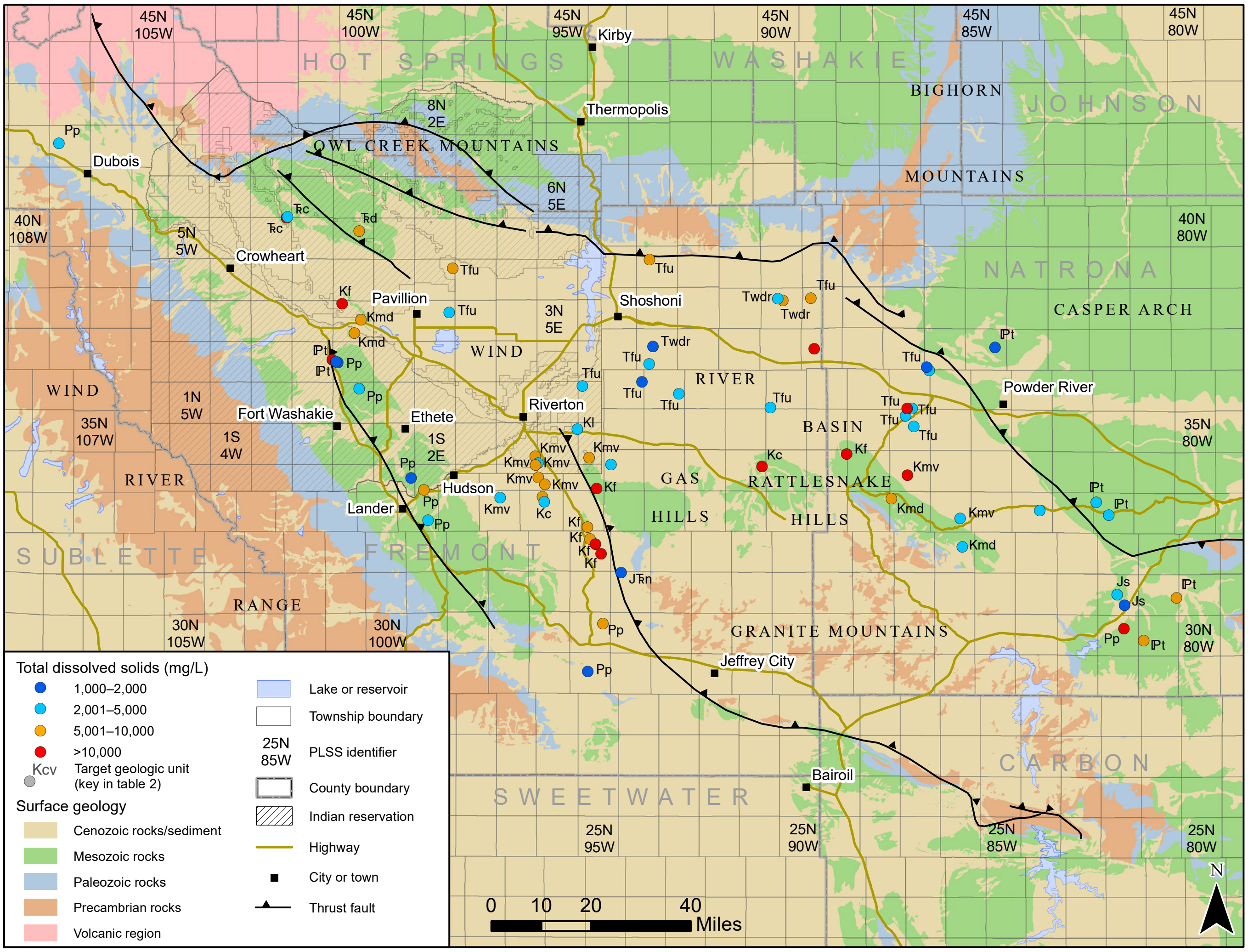
Subsurface geologic unit	Geologic age	Number of samples	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	7	1,471	7,867	27,936	3
Fort Union Fm	Tertiary	2	2,336	4,578	6,819	1
Lance Fm	Cretaceous	1	6,265	6,265	6,265	1
Mesaverde Fm	Cretaceous	2	2,643	5,443	8,242	1
Cody Shale	Cretaceous	3	1,033	2,476	4,491	0
Frontier Fm	Cretaceous	2	2,883	4,285	5,687	1
Muddy Ss	Cretaceous	5	2,612	3,002	3,680	0
Cloverly Fm	Cretaceous	5	1,202	4,246	8,028	2
Sundance Fm	Jurassic	1	2,564	2,564	2,564	0
Nugget Ss	Triassic/Jurassic	2	1,588	4,242	6,896	1
Chugwater Fm	Triassic	2	8,805	9,578	10,351	2
Phosphoria Fm	Permian	6	1,759	4,609	13,989	1
Tensleep Ss	Pennsylvanian	10	1,028	1,743	3,734	0
Madison Ls	Mississippian	1	1,885	1,885	1,885	0
Unspecified unit	Unspecified	10	2,189	3,527	6,648	1

Figure/Table A1–2. Figure and table show saline waters in the 2,000–3,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



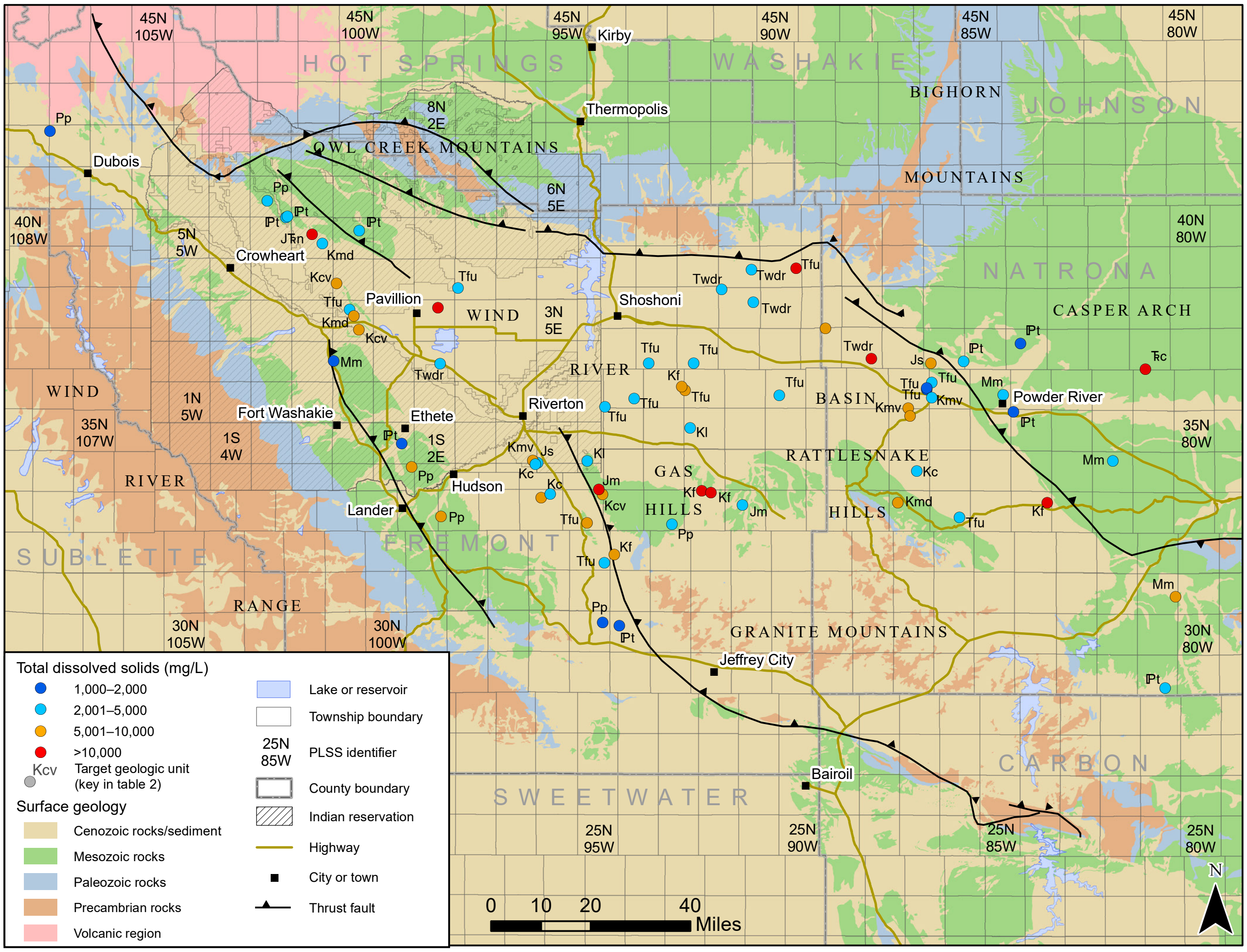
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	8	1,244	6,000	12,760	5
Fort Union Fm	Tertiary	8	1,976	5,628	12,507	3
Mesaverde Fm	Cretaceous	6	2,188	4,228	11,132	1
Frontier Fm	Cretaceous	5	4,418	6,476	9,815	3
Muddy Ss	Cretaceous	1	2,217	2,217	2,217	0
Cloverly Fm	Cretaceous	3	1,826	4,728	10,467	1
Chugwater Fm	Triassic	1	7,300	7,300	7,300	1
Dinwoody Fm	Triassic	6	2,181	4,394	7,960	2
Phosphoria Fm	Permian	3	1,170	4,806	7,135	2
Tensleep Ss	Pennsylvanian	12	1,061	2,589	6,067	1
Madison Ls	Mississippian	2	1,881	1,910	1,938	0
Unspecified unit	Unspecified	11	1,348	6,577	16,932	6

Figure/Table A1–3. Figure and table show saline waters in the 3,000–4,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



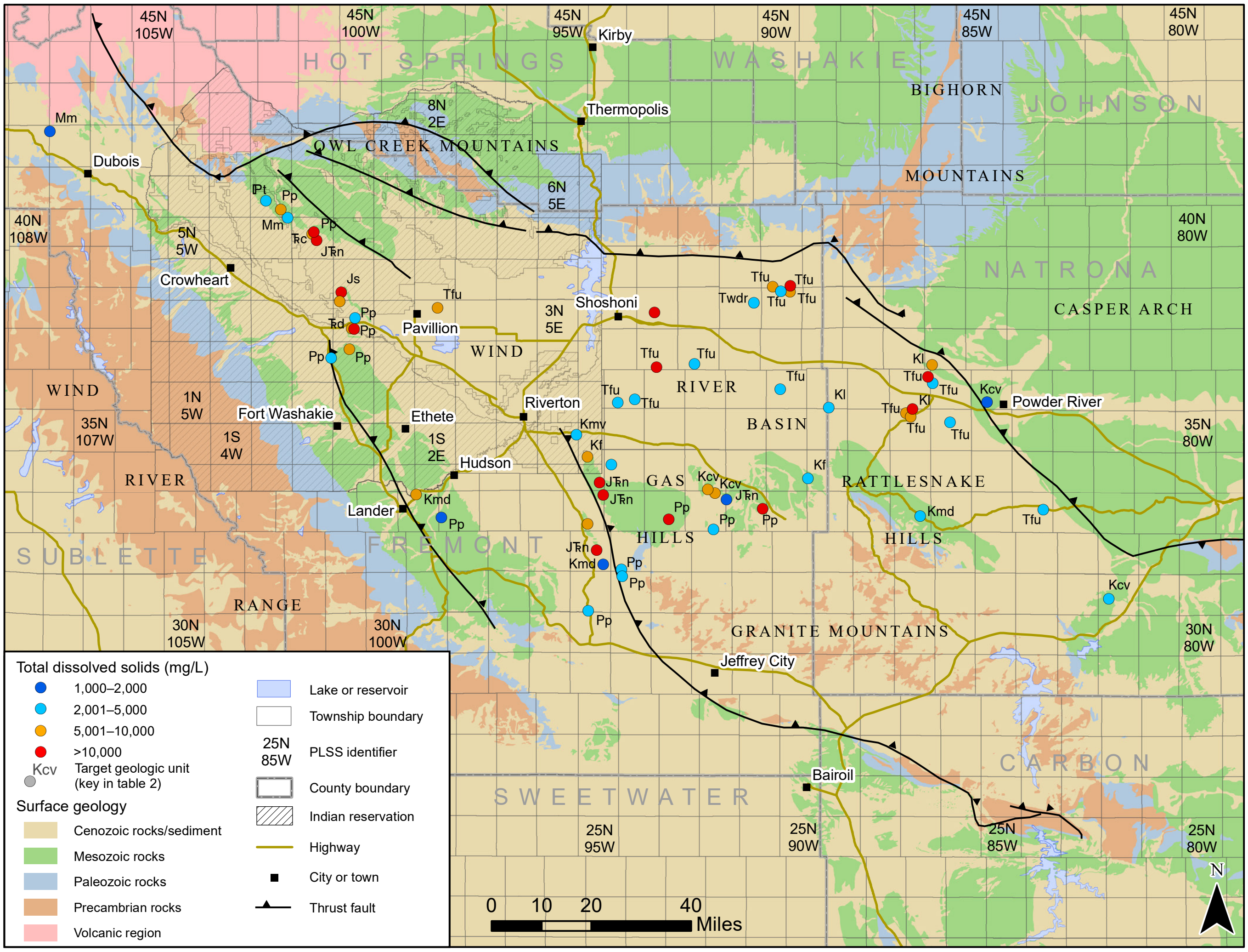
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	3	1,148	3,539	5,029	1
Fort Union Fm	Tertiary	14	1,113	4,339	10,200	4
Lance Fm	Cretaceous	1	3,776	3,776	3,776	0
Mesaverde Fm	Cretaceous	9	3,853	6,410	17,399	6
Cody Shale	Cretaceous	2	3,475	7,222	10,969	1
Frontier Fm	Cretaceous	7	6,412	13,104	30,221	7
Muddy Ss	Cretaceous	4	4,203	6,709	8,920	3
Sundance Fm	Jurassic	2	1,070	2,134	3,198	0
Nugget Ss	Triassic Jurassic	1	1,152	1,152	1,152	0
Chugwater Fm	Triassic	2	3,512	9,661	15,810	1
Dinwoody Fm	Triassic	1	5,055	5,055	5,055	1
Phosphoria Fm	Permian	9	1,034	5,462	20,087	3
Tensleep Ss	Pennsylvanian	7	1,040	4,221	10,388	3
Unspecified unit	Unspecified	5	2,956	6,698	16,645	2

Figure/Table A1–4. Figure and table show saline waters in the 4,000–5,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



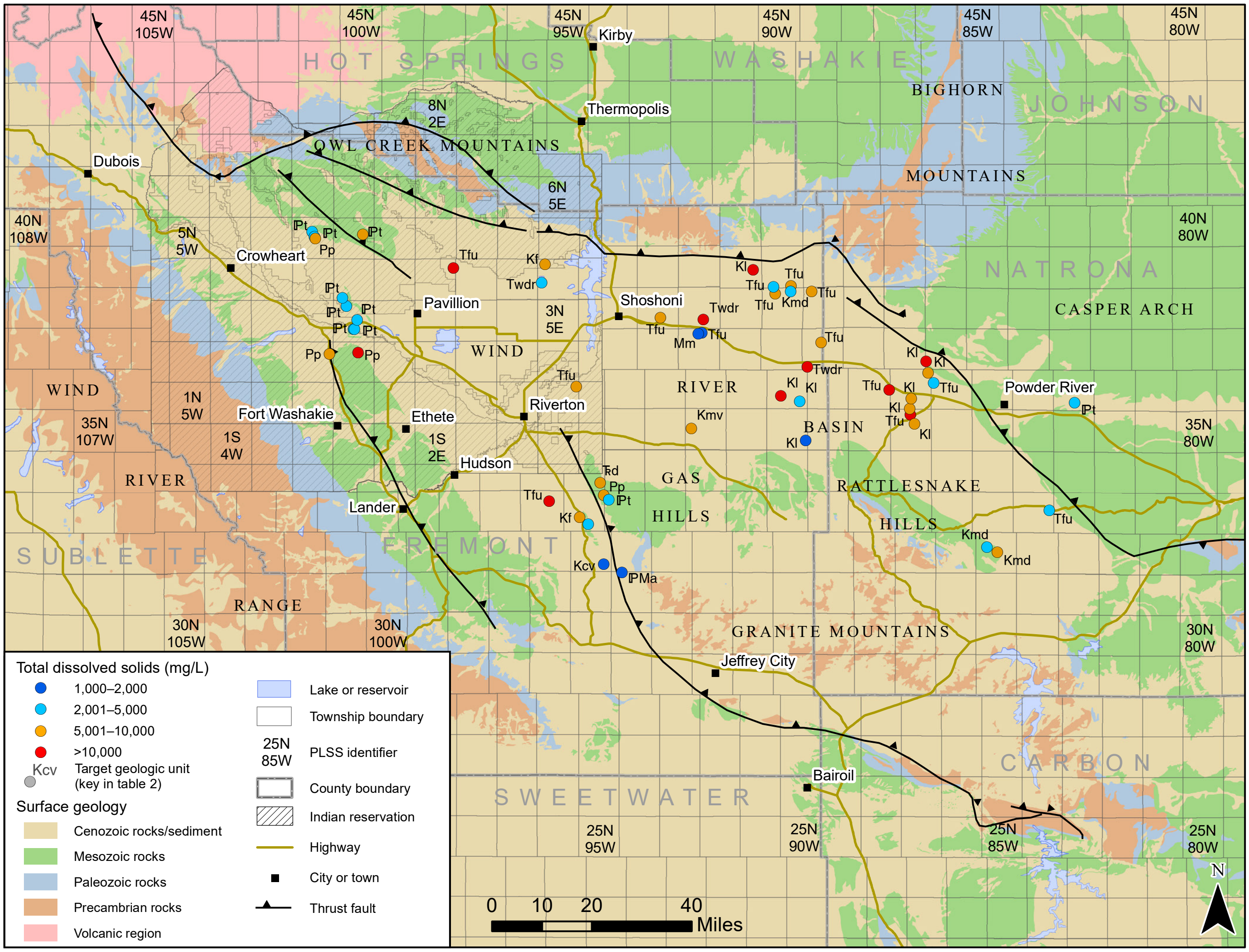
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	5	2,349	5,118	11,746	1
Fort Union Fm	Tertiary	16	1,762	5,351	16,868	5
Lance Fm	Cretaceous	2	2,619	3,070	3,520	0
Mesaverde Fm	Cretaceous	3	3,426	5,770	7,209	2
Cody Shale	Cretaceous	3	3,736	4,688	5,537	1
Frontier Fm	Cretaceous	5	7,040	11,613	15,734	5
Muddy Ss	Cretaceous	3	4,338	5,222	5,686	2
Cloverly Fm	Cretaceous	3	4,543	6,616	8,347	2
Morrison Fm	Jurassic	2	4,687	7,635	10,582	1
Sundance Fm	Jurassic	2	4,003	5,144	6,285	1
Nugget Ss	Triassic Jurassic	1	41,353	41,353	41,353	1
Phosphoria Fm	Permian	6	1,293	3,770	8,642	2
Tensleep Ss	Pennsylvanian	9	1,138	2,391	4,067	0
Madison Ls	Mississippian	4	1,020	3,471	7,771	1
Unspecified unit	Unspecified	4	4,905	10,531	22,990	3

Figure/Table A1–5. Figure and table show saline waters in the 5,000–6,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



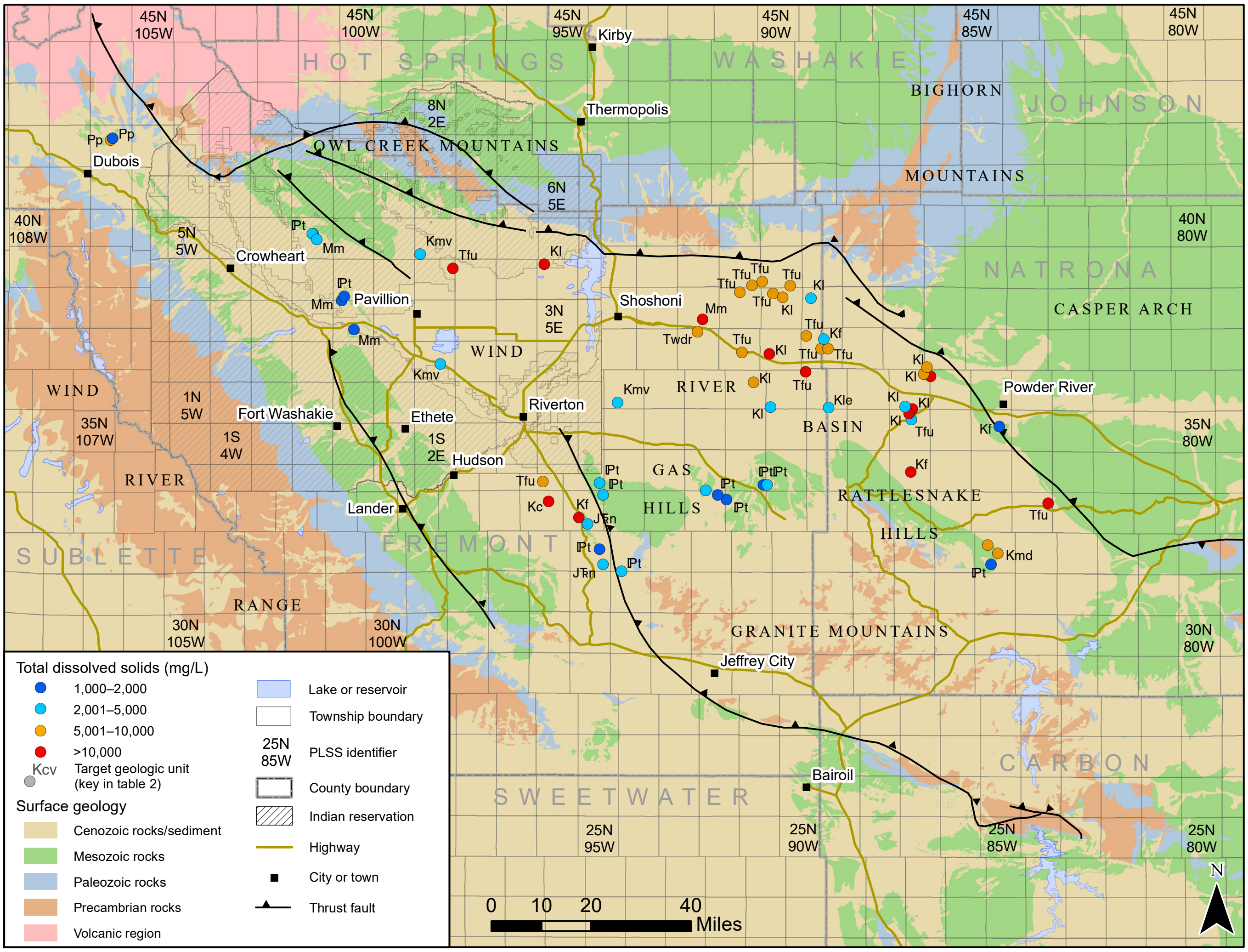
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	1	4,423	4,423	4,423	0
Fort Union Fm	Tertiary	16	2,280	6,796	28,049	8
Lance Fm	Cretaceous	3	2,792	6,092	10,325	2
Mesaverde Fm	Cretaceous	1	3,082	3,082	3,082	0
Frontier Fm	Cretaceous	2	3,394	5,101	6,808	1
Muddy Ss	Cretaceous	3	1,217	4,012	8,205	1
Cloverly Fm	Cretaceous	4	1,994	4,169	7,030	2
Sundance Fm	Jurassic	1	21,920	21,920	21,920	1
Nugget Ss	Triassic Jurassic	5	1,286	12,176	19,000	4
Chugwater Fm	Triassic	1	8,222	8,222	8,222	1
Dinwoody Fm	Triassic	1	9,696	9,696	9,696	1
Phosphoria Fm	Permian	13	1,415	7,033	16,765	6
Tensleep Ss	Pennsylvanian	1	4,080	4,080	4,080	0
Madison Ls	Mississippian	2	1,059	1,598	2,136	0
Unspecified unit	Unspecified	4	3,704	6,976	12,887	3

Figure/Table A1–6. Figure and table show saline waters in the 6,000–7,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



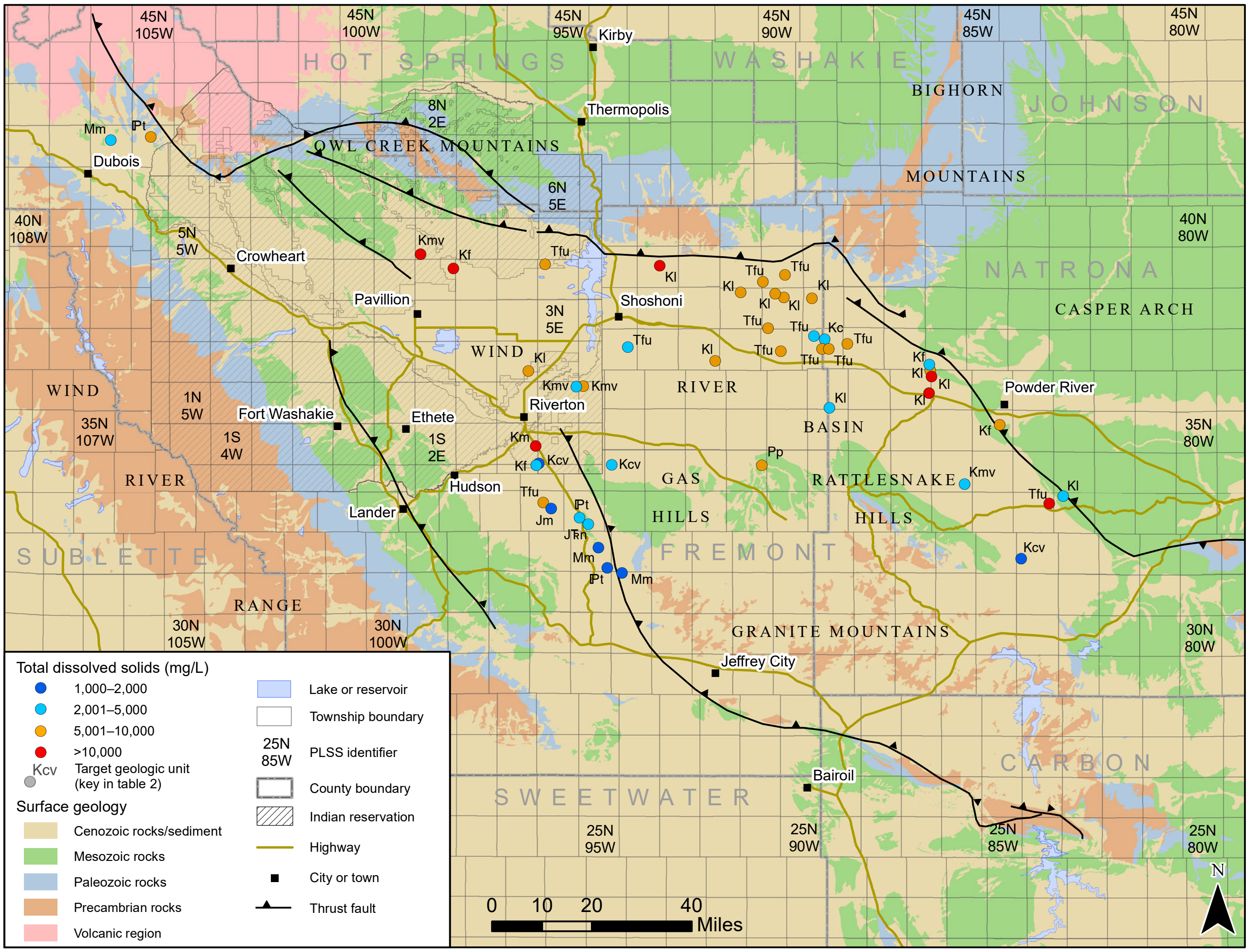
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	3	3,342	23,886	35,299	2
Fort Union Fm	Tertiary	14	1,340	7,968	19,637	10
Lance Fm	Cretaceous	9	1,679	10,247	40,222	7
Mesaverde Fm	Cretaceous	1	9,291	9,291	9,291	1
Frontier Fm	Cretaceous	2	5,204	6,212	7,220	2
Muddy Ss	Cretaceous	3	2,732	4,700	8,593	1
Cloverly Fm	Cretaceous	1	1,558	1,558	1,558	0
Dinwoody Fm	Triassic	1	8,347	8,347	8,347	1
Phosphoria Fm	Permian	4	4,645	7,867	11,335	3
Tensleep Ss	Pennsylvanian	10	2,139	3,416	7,852	2
Amsden Fm	Pennsylvanian/Mississippian	1	1,299	1,299	1,299	0
Madison Ls	Mississippian	1	1,785	1,785	1,785	0
Unspecified unit	Unspecified	1	3,033	3,033	3,033	0

Figure/Table A1–7. Figure and table show saline waters in the 7,000–8,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



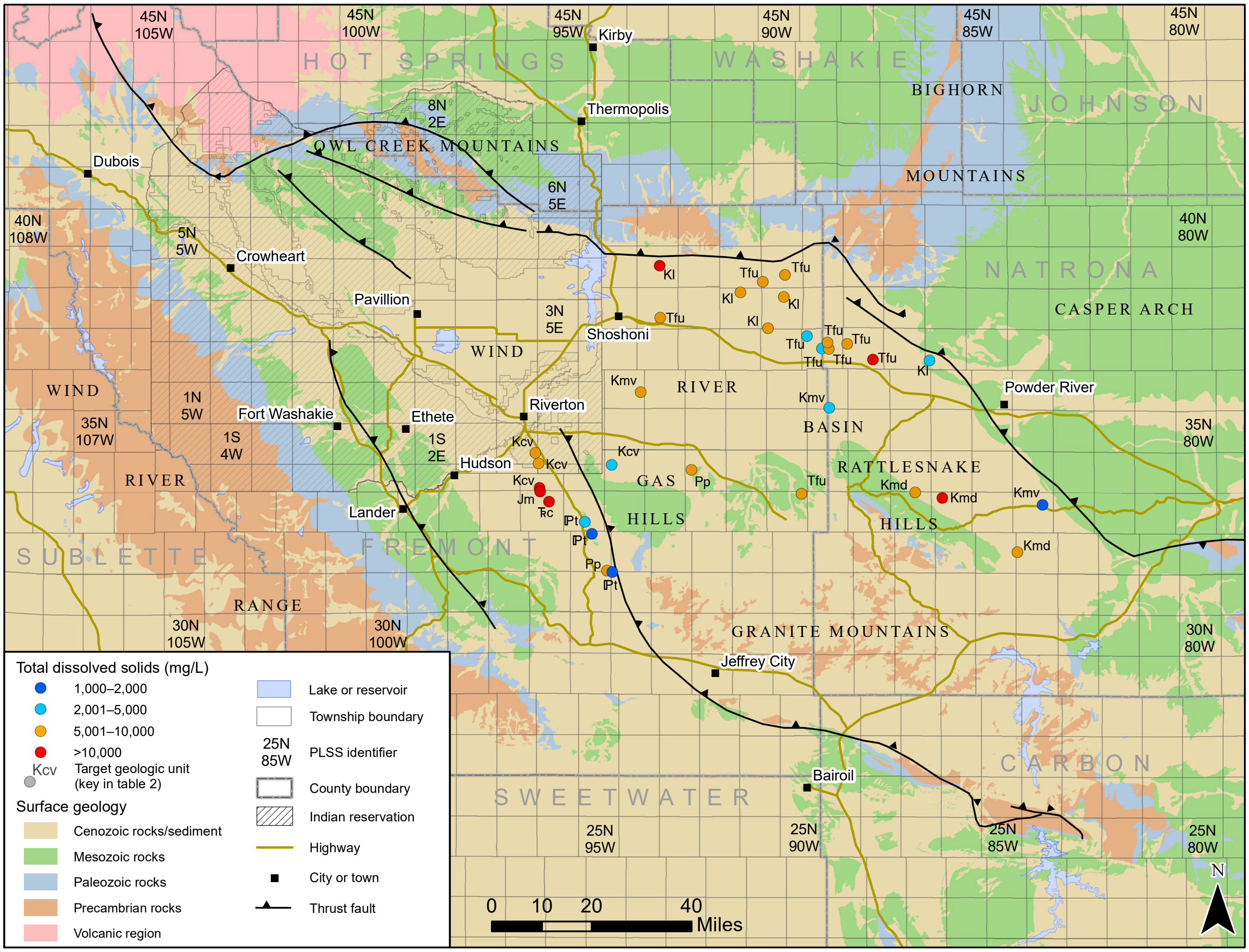
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	1	33,534	33,534	33,534	1
Fort Union Fm	Tertiary	14	4,782	10,235	31,819	13
Lance Fm	Cretaceous	11	2,338	9,772	27,234	8
Lewis Shale	Cretaceous	1	4,020	4,020	4,020	0
Mesaverde Fm	Cretaceous	3	3,498	3,758	4,107	0
Cody Shale	Cretaceous	1	16,225	16,225	16,225	1
Frontier Fm	Cretaceous	4	1,629	6,593	10,554	2
Muddy Ss	Cretaceous	1	8,535	8,535	8,535	1
Nugget Ss	Triassic Jurassic	2	2,539	2,852	3,165	0
Phosphoria Fm	Permian	2	1,437	4,119	6,801	1
Tensleep Ss	Pennsylvanian	11	1,346	2,537	4,630	0
Madison Ls	Mississippian	4	1,720	3,011	5,409	1
Unspecified unit	Unspecified	4	2,451	11,659	33,451	2

Figure/Table A1–8. Figure and table show saline waters in the 8,000–9,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



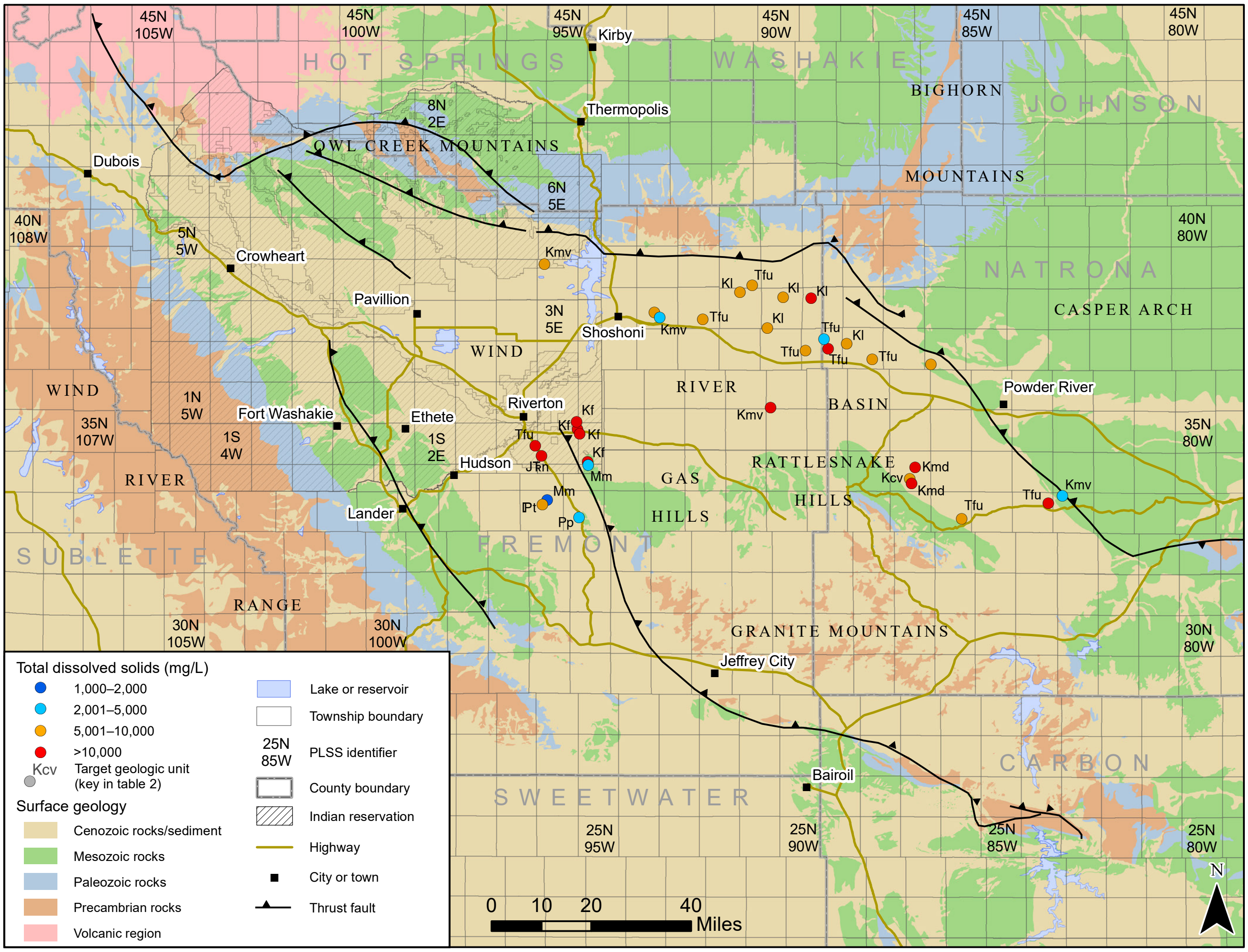
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	12	2,338	6,323	13,705	10
Lance Fm	Cretaceous	12	3,411	8,804	23,007	9
Meeteetse Fm	Cretaceous	1	18,598	18,598	18,598	1
Mesaverde Fm	Cretaceous	4	4,190	7,366	12,593	2
Cody Shale	Cretaceous	1	4,350	4,350	4,350	0
Frontier Fm	Cretaceous	4	2,638	10,292	23,801	3
Cloverly Fm	Cretaceous	3	1,117	1,778	2,519	0
Morrison Fm	Jurassic	1	1,584	1,584	1,584	0
Nugget Ss	Triassic Jurassic	1	4147	4147	4147	0
Phosphoria Fm	Permian	1	7,820	7,820	7,820	1
Tensleep Ss	Pennsylvanian	3	1370	4464	9555	1
Madison Ls	Mississippian	3	1,085	1,863	3,001	0

Figure/Table A1–9. Figure and table show saline waters in the 9,000–10,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



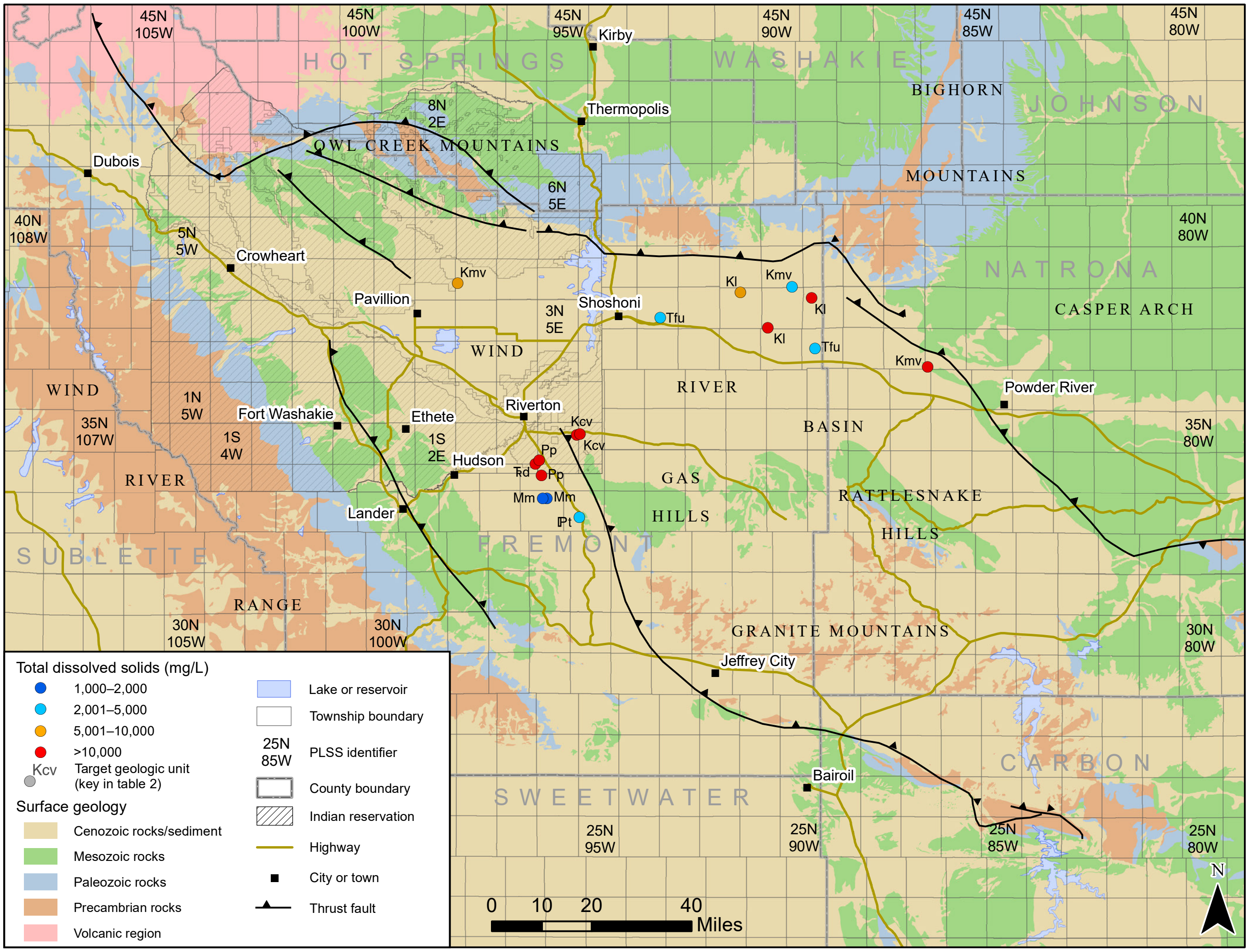
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	10	3,555	6,731	14,016	8
Lance Fm	Cretaceous	5	4,117	8,724	19,943	4
Mesaverde Fm	Cretaceous	3	1,237	4,357	7,270	1
Muddy Ss	Cretaceous	3	7,788	9,140	10,271	3
Cloverly Fm	Cretaceous	4	3,976	11,123	27,614	3
Morrison Fm	Jurassic	1	30,440	30,440	30,440	1
Chugwater Fm	Triassic	1	15,836	15,836	15,836	1
Phosphoria Fm	Permian	2	7,232	8,526	9,820	2
Tensleep Ss	Pennsylvanian	3	1,416	2,676	4,808	0

Figure/Table A1–10. Figure and table show saline waters in the 10,000–11,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



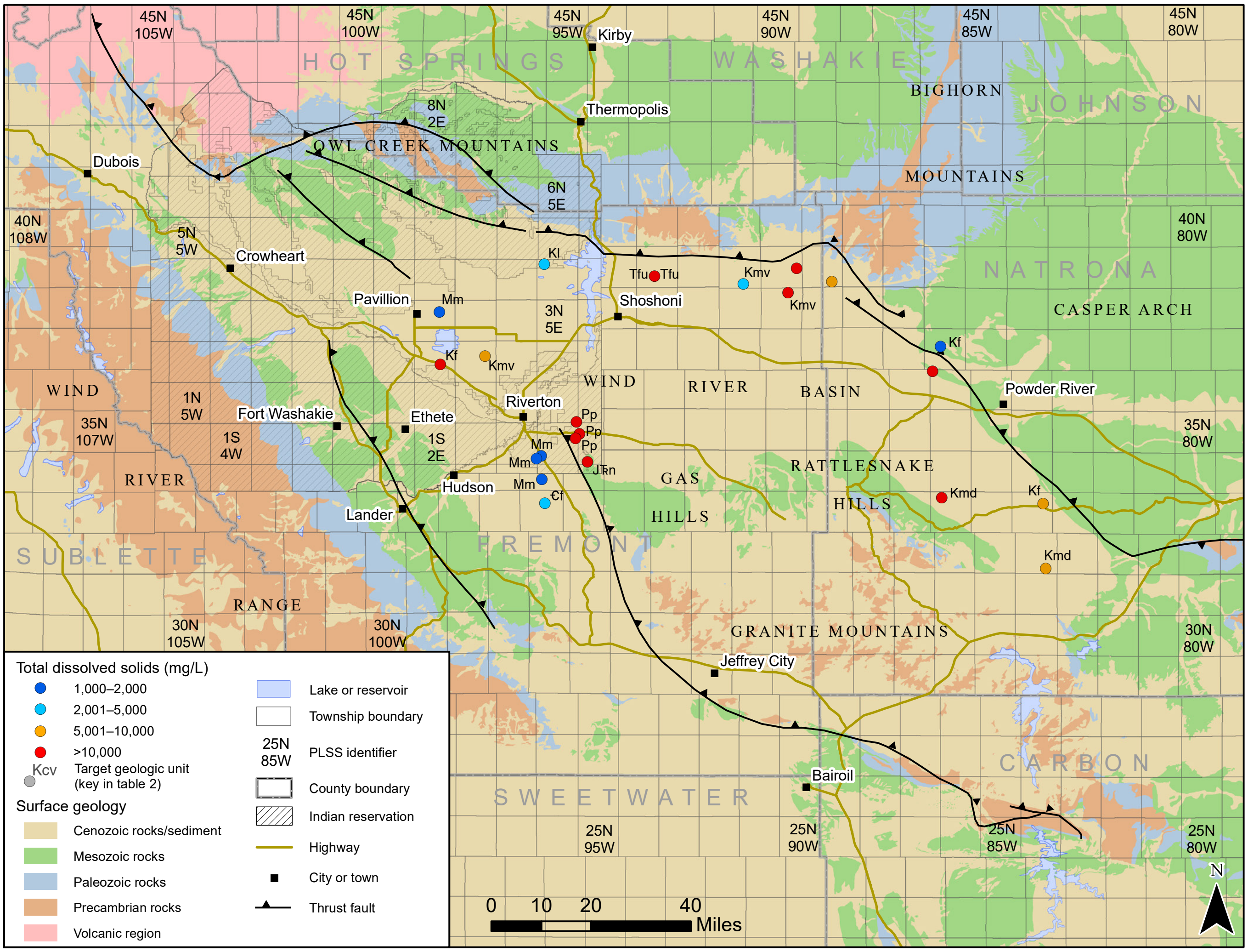
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Wind River Fm	Tertiary	10	3,733	11,286	32,768	9
Fort Union Fm	Cretaceous	5	6,777	15,489	46,894	5
Lance Fm	Cretaceous	4	2,883	8,769	21,237	2
Mesaverde Fm	Cretaceous	4	16,149	22,426	33,658	4
Muddy Ss	Cretaceous	2	13,652	28,721	43,789	2
Cloverly Fm	Cretaceous	1	5,484	5,484	5,484	1
Nugget Ss	Triassic Jurassic	1	11,877	11,877	11,877	1
Phosphoria Fm	Permian	1	3,815	3,815	3,815	0
Tensleep Ss	Pennsylvanian	1	8,848	8,848	8,848	1
Madison Ls	Mississippian	2	1,733	2,037	2,341	0
Unspecified unit	Unspecified	2	6,051	6,586	7,120	2

Figure/Table A1–11. Figure and table show saline waters in the 11,000–12,000-ft depth interval in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	2	3,118	3,365	3,611	0
Lance Fm	Cretaceous	3	6,698	17,768	24,730	3
Mesaverde Fm	Cretaceous	3	4,796	9,072	17,190	2
Cloverly Fm	Cretaceous	2	13,973	14,591	15,209	2
Dinwoody Fm	Triassic	1	10,742	10,742	10,742	1
Phosphoria Fm	Permian	2	10,310	21,668	33,026	2
Tensleep Ss	Pennsylvanian	1	3,356	3,356	3,356	0
Madison Ls	Mississippian	2	1,200	1,315	1,430	0

Figure/Table A1–12. Figure and table show saline waters at depths greater than 12,000 ft in the Wind River Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]

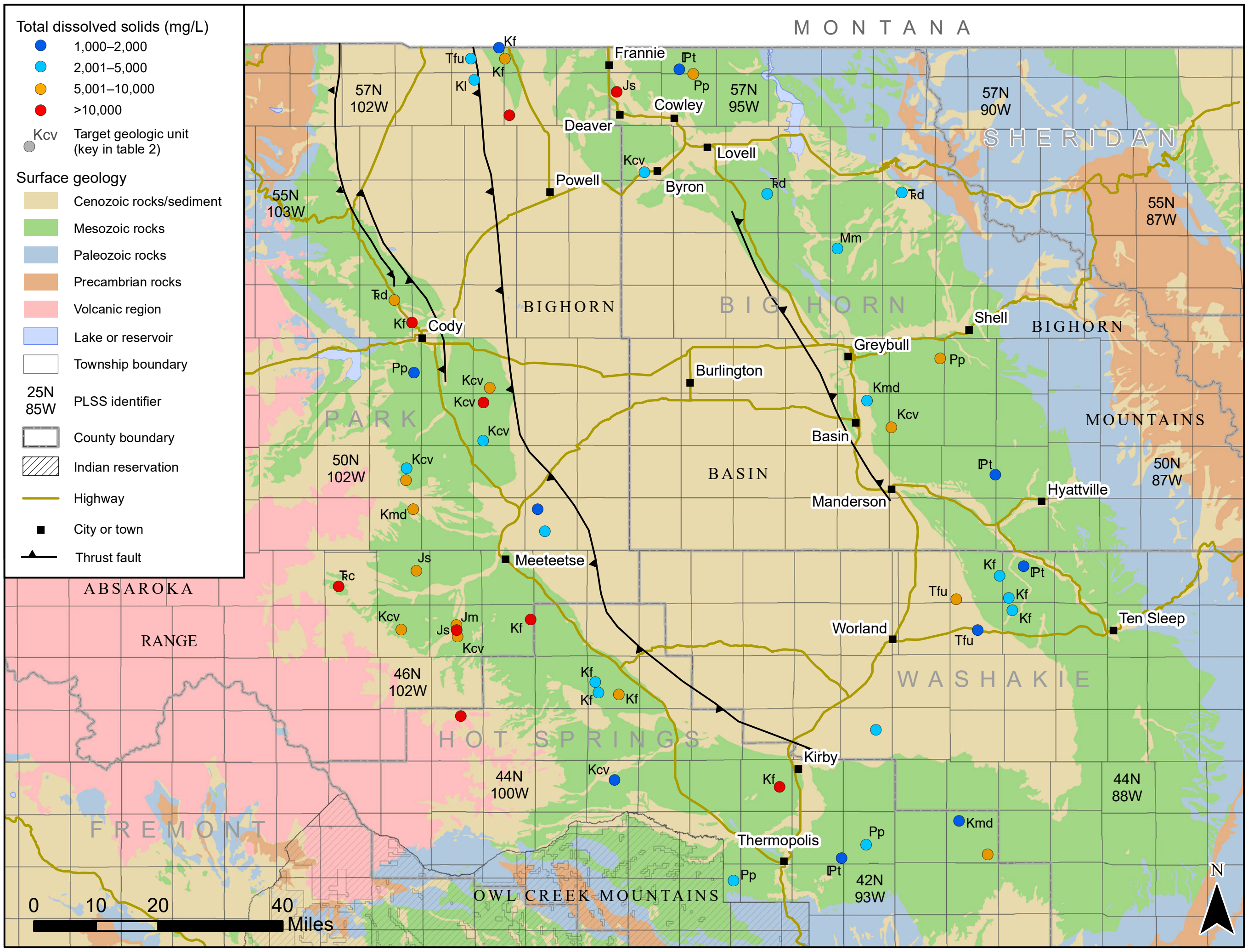


Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	2	25,177	76,144	127,111	2
Lance Fm	Cretaceous	1	4,511	4,511	4,511	0
Mesaverde Fm	Cretaceous	3	4,071	8,021	11,957	2
Frontier Fm	Cretaceous	3	1,271	14,107	35,675	2
Muddy Ss	Cretaceous	2	6,117	8,333	10,548	2
Nugget Ss	Triassic Jurassic	1	31,309	31,309	31,309	1
Phosphoria Fm	Permian	3	36,735	46,546	58,338	3
Madison Ls	Mississippian	4	1,411	1,583	1,897	0
Flathead Ss	Cambrian	1	2,593	2,593	2,593	0
Unspecified unit	Unspecified	3	6,404	13,055	16,646	3

Appendix 2

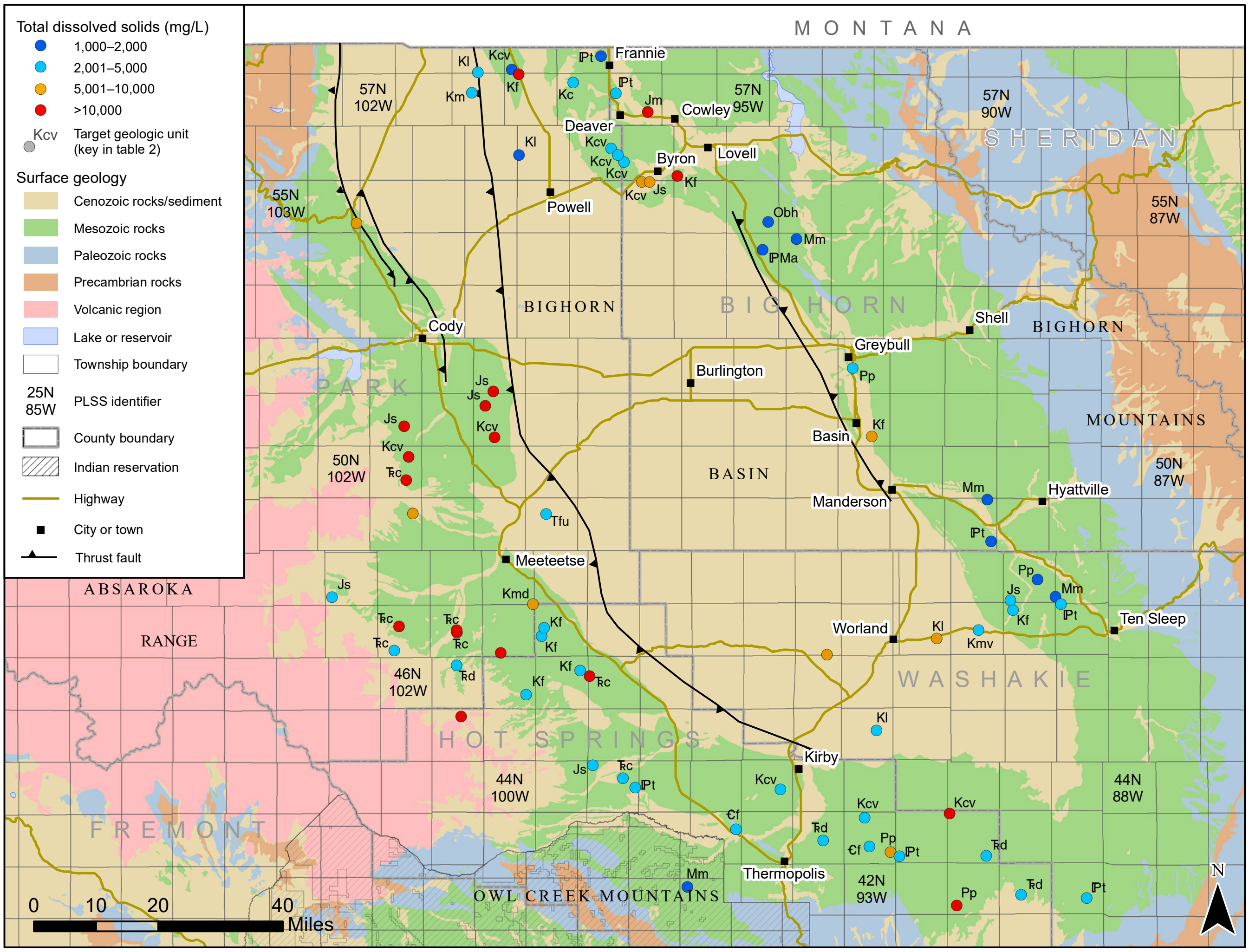
Bighorn Basin

Figure/Table A2–1. Figure and table show saline waters in the 1,000–2,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	3	1,611	4,275	8,738	1
Lance Fm	Cretaceous	1	2,258	2,258	2,258	0
Frontier Fm	Cretaceous	11	1,633	8,137	26,624	5
Muddy Ss	Cretaceous	3	1,350	4,061	6,216	1
Cloverly Fm	Cretaceous	9	1,905	6,418	19,527	6
Morrison Fm	Jurassic	1	9,295	9,295	9,295	1
Sundance Fm	Jurassic	3	8,580	12,539	16,966	3
Chugwater Fm	Triassic	1	14,151	14,151	14,151	1
Dinwoody Fm	Triassic	3	2,727	4,408	5,840	1
Phosphoria Fm	Permian	5	1,818	4,361	8,658	2
Tensleep Ss	Pennsylvanian	4	1,050	1,578	1,992	0
Madison Ls	Mississippian	1	2,197	2,197	2,197	0
Unspecified unit	Unspecified	7	1,851	6,069	13,821	3

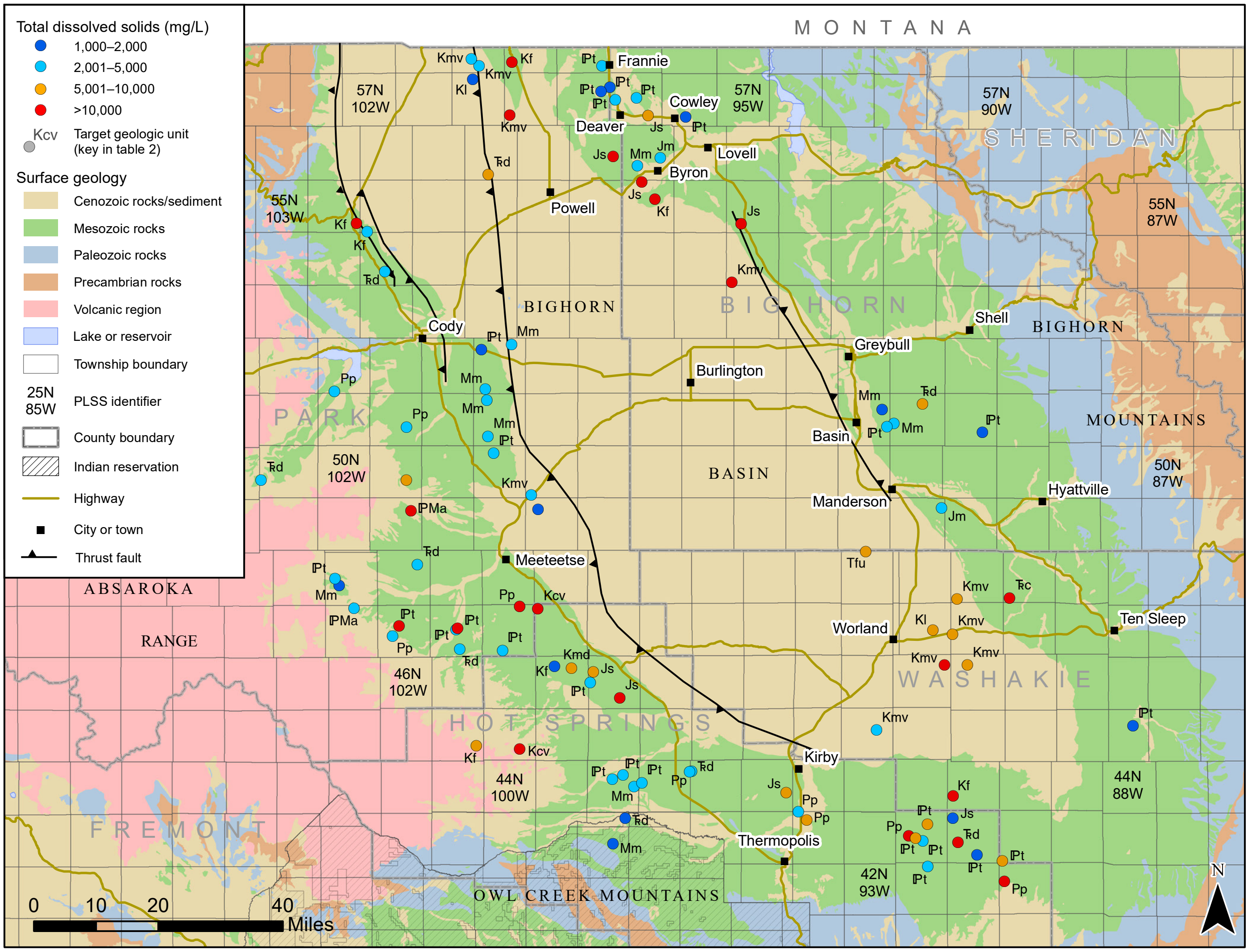
Figure/Table A2–2. Figure and table show saline waters in the 2,000–3,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



Figure/Table A2–2 continued.

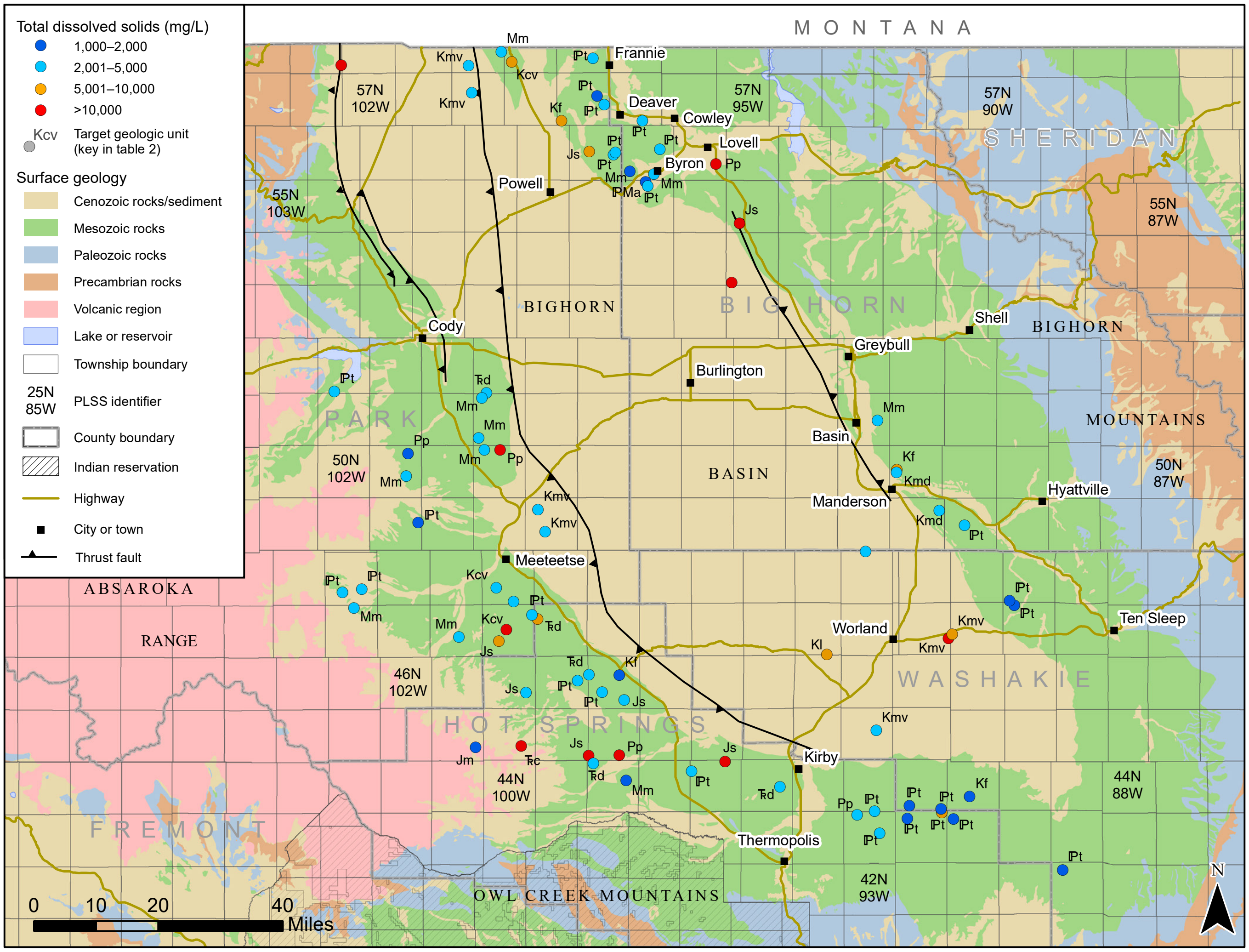
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	1	3,249	3,249	3,249	0
Lance Fm	Cretaceous	4	1,101	2,984	5,093	1
Meeteetse Fm	Cretaceous	1	2,473	2,473	2,473	0
Mesaverde Fm	Cretaceous	1	2,792	2,792	2,792	0
Cody Shale	Cretaceous	1	2,941	2,941	2,941	0
Frontier Fm	Cretaceous	8	2,254	6,018	12,663	3
Muddy Ss	Cretaceous	1	7,203	7,203	7,203	1
Cloverly Fm	Cretaceous	10	1,657	7,523	21,185	4
Morrison Fm	Jurassic	1	10,080	10,080	10,080	1
Sundance Fm	Jurassic	7	2,278	10,108	18,973	4
Chugwater Fm	Triassic	7	2,804	16,675	43,398	5
Dinwoody Fm	Triassic	4	3,195	3,861	4,921	0
Phosphoria Fm	Permian	4	1,105	7,184	17,884	2
Tensleep Ss	Pennsylvanian	7	1,279	3,377	4,634	0
Amsden Fm	Pennsylvanian	1	1,022	1,022	1,022	0
Madison Ls	Mississippian	4	1,281	1,618	1,780	0
Bighorn Dm	Ordovician	1	1,178	1,178	1,178	0
Flathead Ss	Cambrian	2	2,729	3,012	3,294	0
Unspecified unit	Unspecified	5	5,414	11,332	21,826	5

Figure/Table A2–3. Figure and table show saline waters in the 3,000–4,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



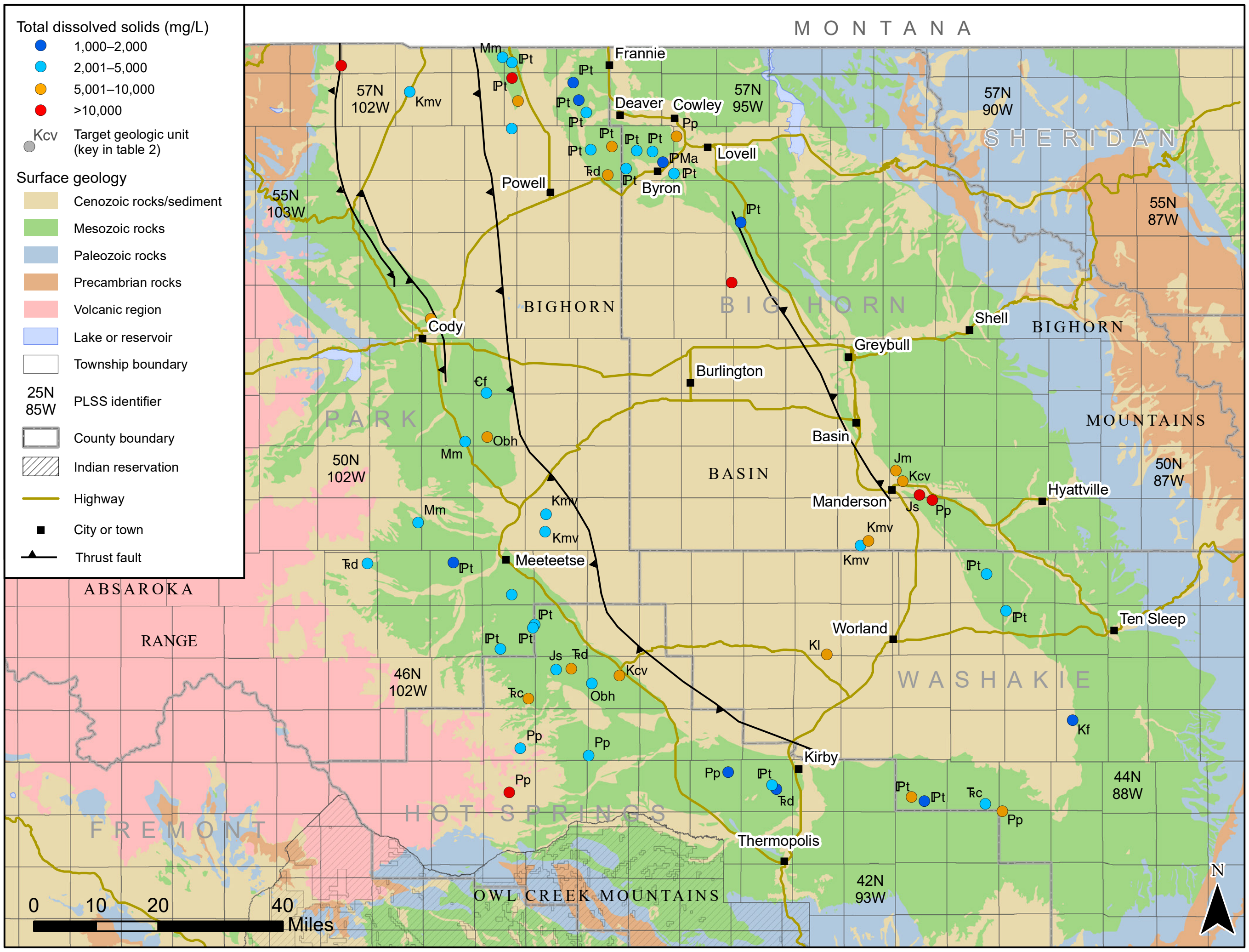
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Fort Union Fm	Tertiary	1	5,752	5,752	5,752	1
Lance Fm	Cretaceous	2	1,839	4,187	6,534	1
Mesaverde Fm	Cretaceous	10	2,062	8,963	22,911	6
Frontier Fm	Cretaceous	7	1,823	8,165	12,705	5
Muddy Ss	Cretaceous	1	5,008	5,008	5,008	1
Cloverly Fm	Cretaceous	2	11,117	11,751	12,384	2
Morrison Fm	Jurassic	2	2,271	2,704	3,137	0
Sundance Fm	Jurassic	8	1,485	16,280	54,513	7
Chugwater Fm	Triassic	1	19,858	19,858	19,858	1
Dinwoody Fm	Triassic	9	1,078	10,782	62,163	3
Phosphoria Fm	Permian	9	2,525	8,296	18,935	4
Tensleep Ss	Pennsylvanian	26	1,287	4,675	19,486	5
Amsden Fm	Pennsylvanian	2	2,867	8,300	13,732	1
Madison Ls	Mississippian	10	1,017	2,393	3,805	0
Unspecified unit	Unspecified	2	1,810	5,188	8,565	1

Figure/Table A2–4. Figure and table show saline waters in the 4,000–5,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



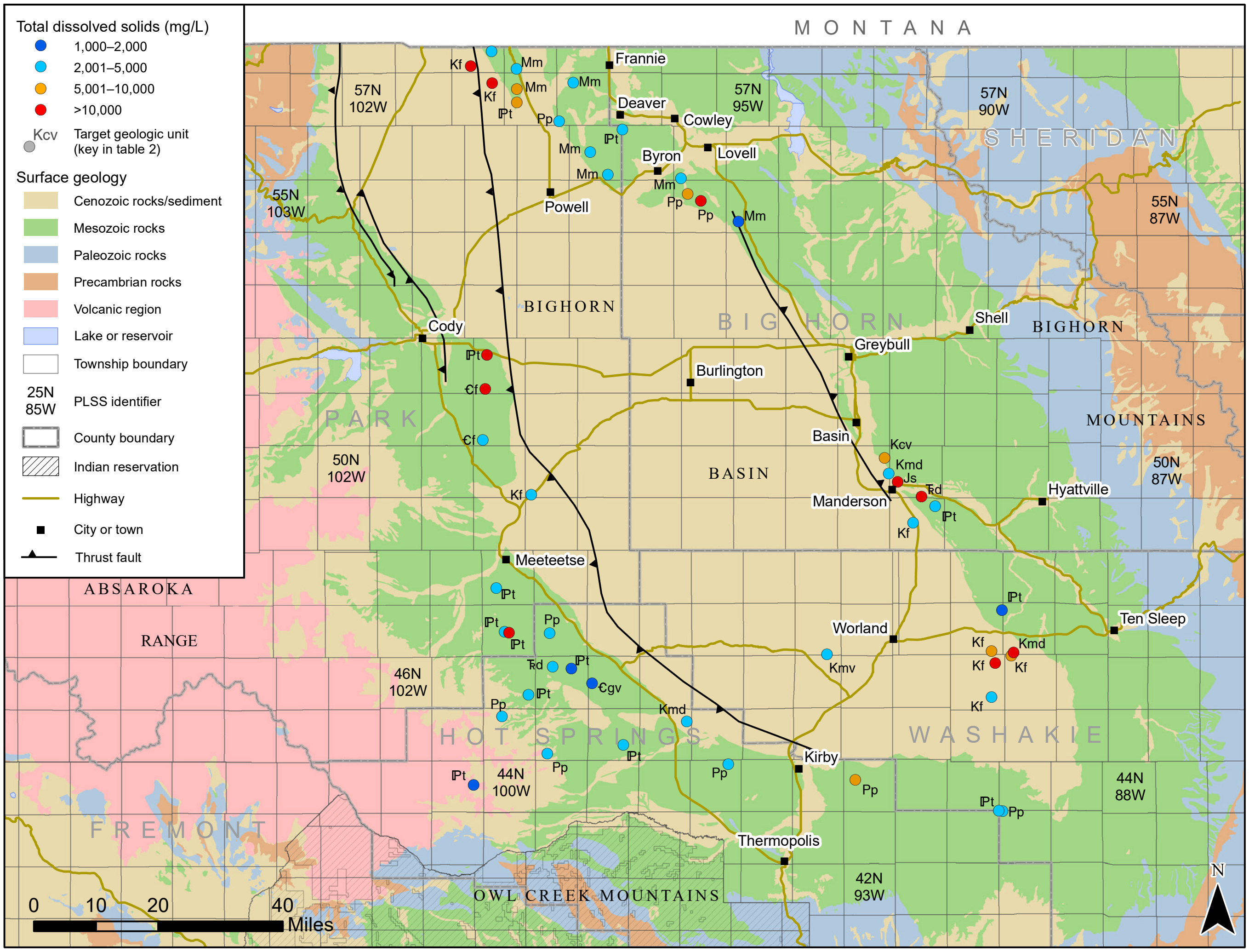
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Lance Fm	Cretaceous	1	6,510	6,510	6,510	1
Mesaverde Fm	Cretaceous	7	2,501	4,847	10,483	2
Frontier Fm	Cretaceous	4	1,288	4,291	7,070	2
Muddy Ss	Cretaceous	2	2,206	2,442	2,678	0
Cloverly Fm	Cretaceous	3	2,232	12,097	25,539	2
Morrison Fm	Jurassic	1	1,387	1,387	1,387	0
Sundance Fm	Jurassic	7	3,888	8,790	14,642	5
Chugwater Fm	Triassic	1	21,818	21,818	21,818	1
Dinwoody Fm	Triassic	5	2,909	4,050	5,441	1
Phosphoria Fm	Permian	5	1,554	10,436	20,548	3
Tensleep Ss	Pennsylvanian	27	1,066	2,570	5,820	1
Amsden Fm	Pennsylvanian	1	1,877	1,877	1,877	0
Madison Ls	Mississippian	11	1,140	2,753	4,693	0
Unspecified unit	Unspecified	4	3,688	11,697	22,729	2

Figure/Table A2–5. Figure and table show saline waters in the 5,000–6,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



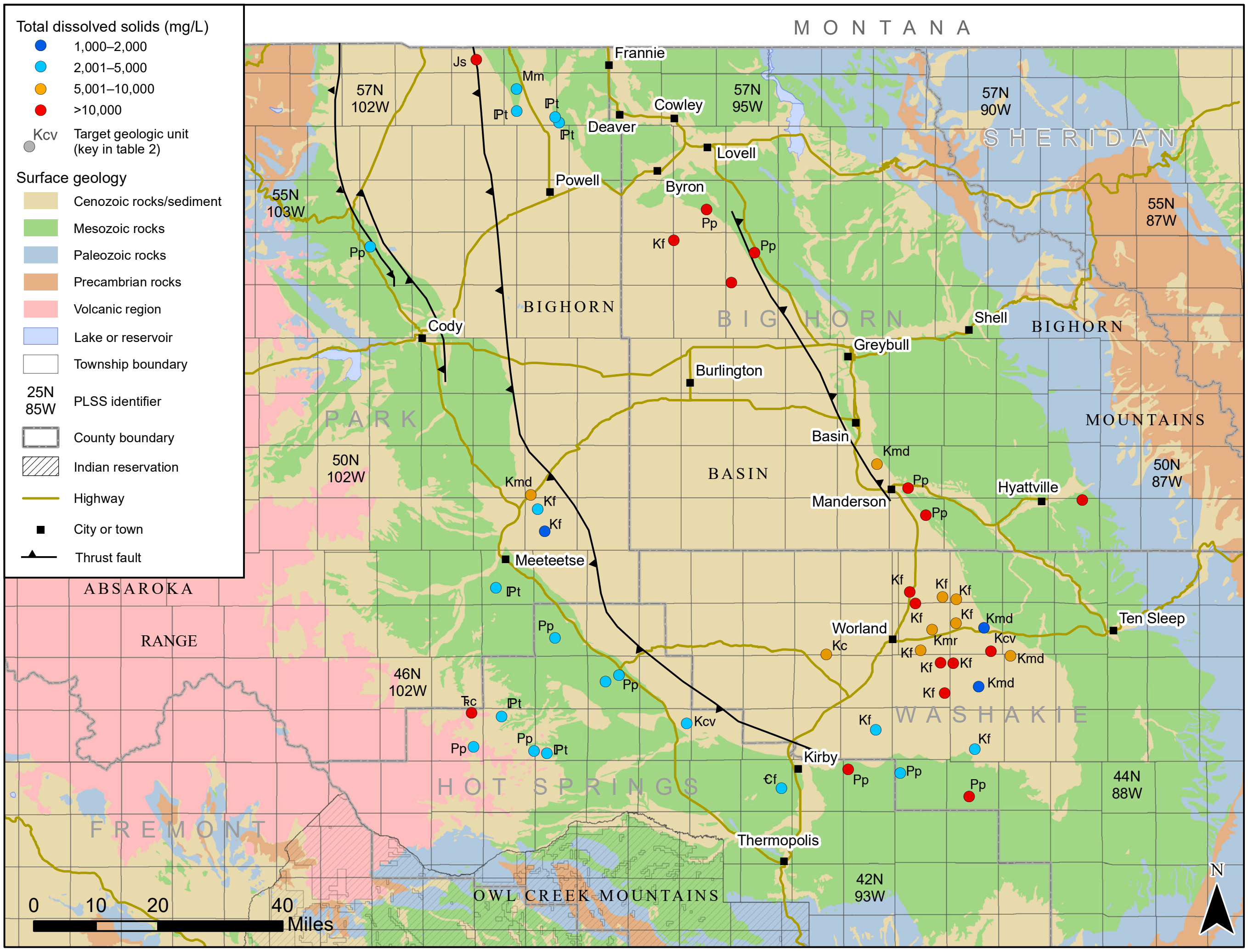
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Lance Fm	Cretaceous	1	6,827	6,827	6,827	1
Mesaverde Fm	Cretaceous	5	2,840	3,736	6,013	1
Frontier Fm	Cretaceous	1	1,676	1,676	1,676	0
Cloverly Fm	Cretaceous	2	5,678	6,003	6,328	2
Morrison Fm	Jurassic	1	8,478	8,478	8,478	1
Sundance Fm	Jurassic	2	4,947	14,895	24,842	1
Chugwater Fm	Triassic	2	4,635	5,004	5,373	1
Dinwoody Fm	Triassic	4	1,205	4,337	8,055	2
Phosphoria Fm	Permian	7	1,192	8,947	21,182	4
Tensleep Ss	Pennsylvanian	21	1,198	3,463	11,403	3
Amsden Fm	Pennsylvanian	1	1,791	1,791	1,791	0
Madison Ls	Mississippian	3	3,720	4,140	4,574	0
Bighorn Dm	Ordovician	2	2,892	6,088	9,284	1
Flathead Ss	Cambrian	1	4,421	4,421	4,421	0
Unspecified unit	Unspecified	6	3,548	12,081	26,956	4

Figure/Table A2–6. Figure and table show saline waters in the 6,000–7,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



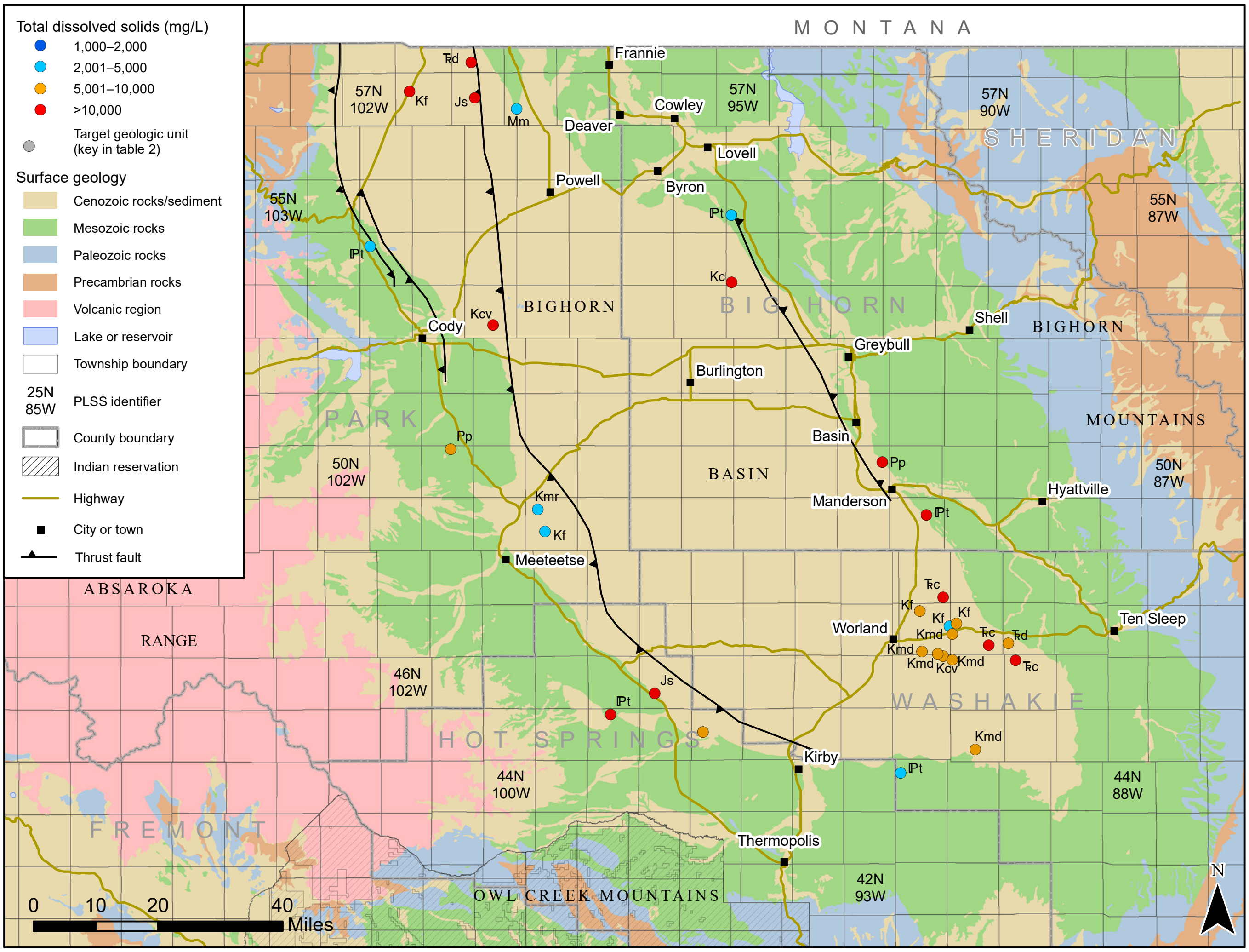
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Mesaverde Fm	Cretaceous	1	4,882	4,882	4,882	0
Frontier Fm	Cretaceous	8	2,097	8,179	17,107	5
Muddy Ss	Cretaceous	3	2,700	6,244	11,219	1
Cloverly Fm	Cretaceous	1	8,964	8,964	8,964	1
Sundance Fm	Jurassic	1	19,333	19,333	19,333	1
Dinwoody Fm	Triassic	2	4,690	10,457	16,223	1
Phosphoria Fm	Permian	9	2,075	5,362	11,769	3
Tensleep Ss	Pennsylvanian	13	1,062	5,438	23,440	3
Madison Ls	Mississippian	7	1,406	3,336	6,354	1
Gros Ventre Fm	Cambrian	1	1,869	1,869	1,869	0
Flathead Ss	Cambrian	2	3,432	8,161	12,889	1
Unspecified unit	Unspecified	1	3673	3673	3673	0

Figure/Table A2–7. Figure and table show saline waters in the 7,000–8,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



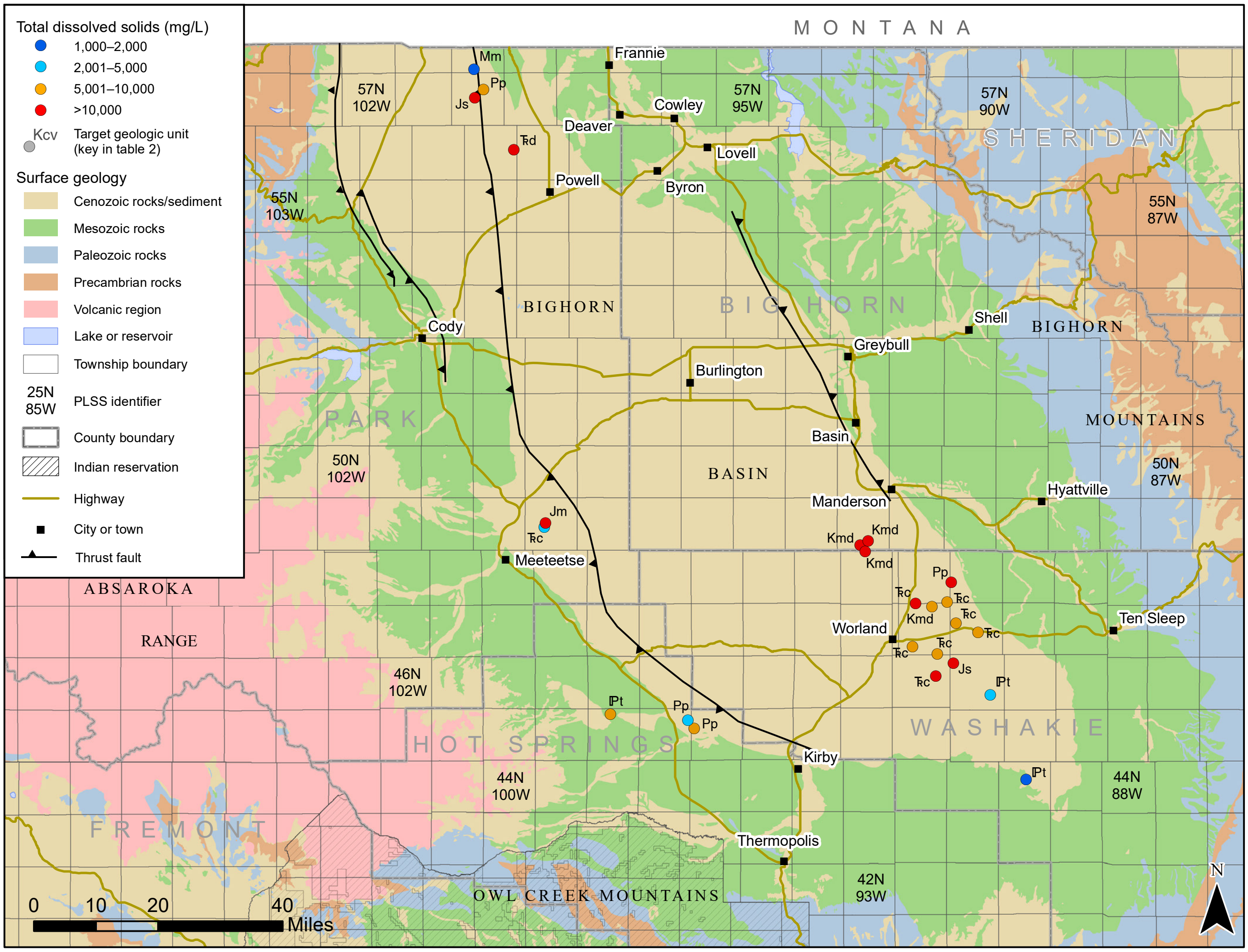
Subsurface geologic unit	Geologic age	Count	TDS (mg/L) Minimum	TDS (mg/L) Mean	TDS (mg/L) Maximum	Count TDS>5,000 mg/L
Cody Shale	Cretaceous	1	8,312	8,312	8,312	1
Frontier Fm	Cretaceous	14	1,896	8,936	18,070	10
Mowry Shale	Cretaceous	1	8,145	8,145	8,145	1
Muddy Ss	Cretaceous	5	1,229	4,506	7,813	3
Cloverly Fm	Cretaceous	2	3,344	6,981	10,617	1
Sundance Fm	Jurassic	1	10,338	10,338	10,338	1
Chugwater Fm	Triassic	1	32,750	32,750	32,750	1
Phosphoria Fm	Permian	12	2,734	10,625	22,678	6
Tensleep Ss	Pennsylvanian	6	2,085	3,023	3,871	0
Madison Ls	Mississippian	1	3,080	3,080	3,080	0
Flathead Ss	Cambrian	1	3,624	3,624	3,624	0
Unspecified unit	Unspecified	3	3,872	12,083	20,480	2

Figure/Table A2–8. Figure and table show saline waters in the 8,000–9,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



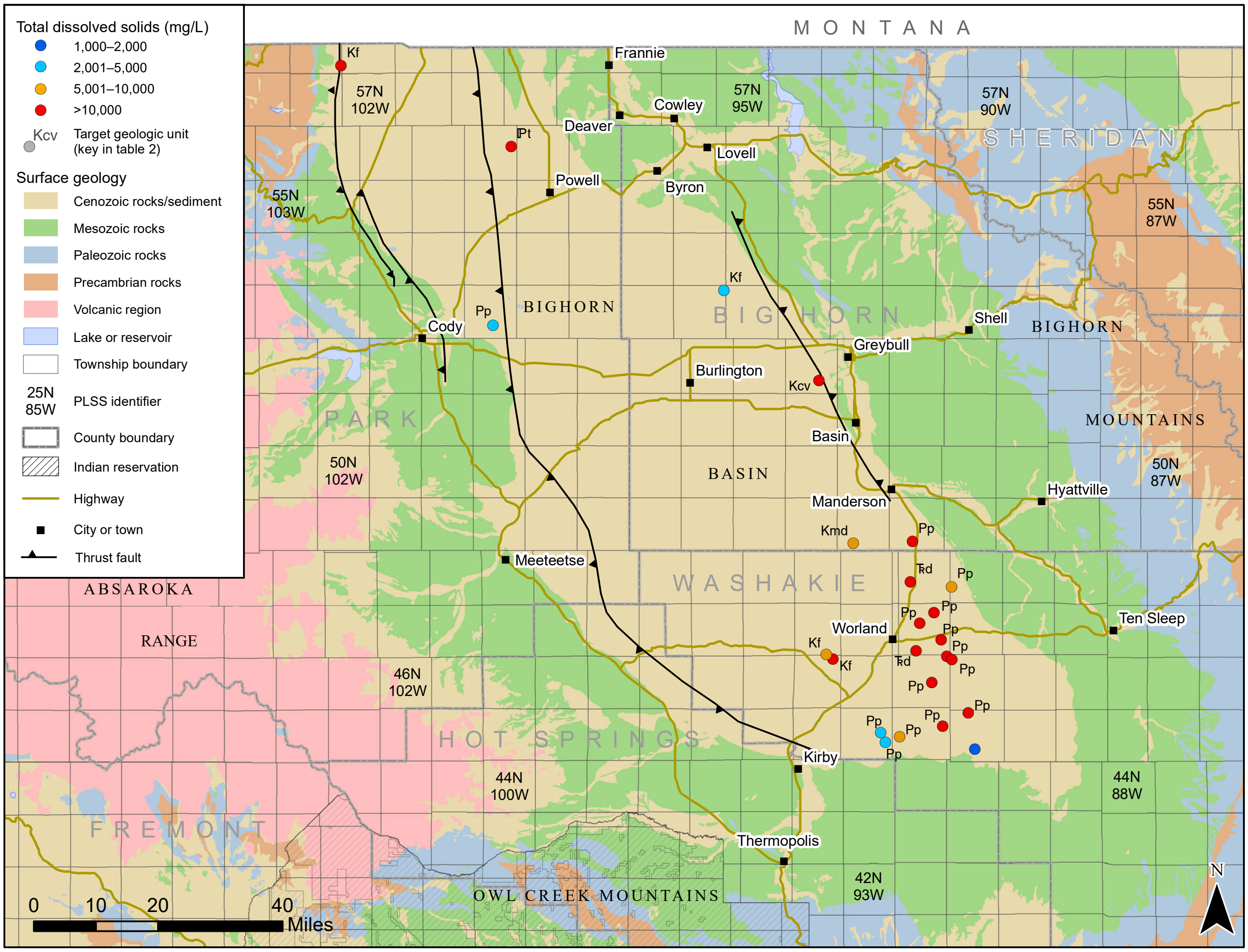
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Cody Shale	Cretaceous	1	26,327	26,327	26,327	1
Frontier Fm	Cretaceous	5	3,645	9,373	22,461	3
Mowry Shale	Cretaceous	1	4,053	4,053	4,053	0
Muddy Ss	Cretaceous	5	5,074	6,710	9,957	5
Cloverly Fm	Cretaceous	2	9,391	10,479	11,567	2
Sundance Fm	Jurassic	2	19,305	29,084	38,862	2
Chugwater Fm	Triassic	3	11,260	12,536	13,275	3
Dinwoody Fm	Triassic	2	9,533	11,999	14,465	2
Phosphoria Fm	Permian	2	5,961	30,722	55,482	2
Tensleep Ss	Pennsylvanian	5	3,229	6,935	11,502	2
Madison Ls	Mississippian	1	2,052	2,052	2,052	0
Unspecified unit	Unspecified	1	7,853	7,853	7,853	1

Figure/Table A2–9. Figure and table show saline waters in the 9,000–10,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



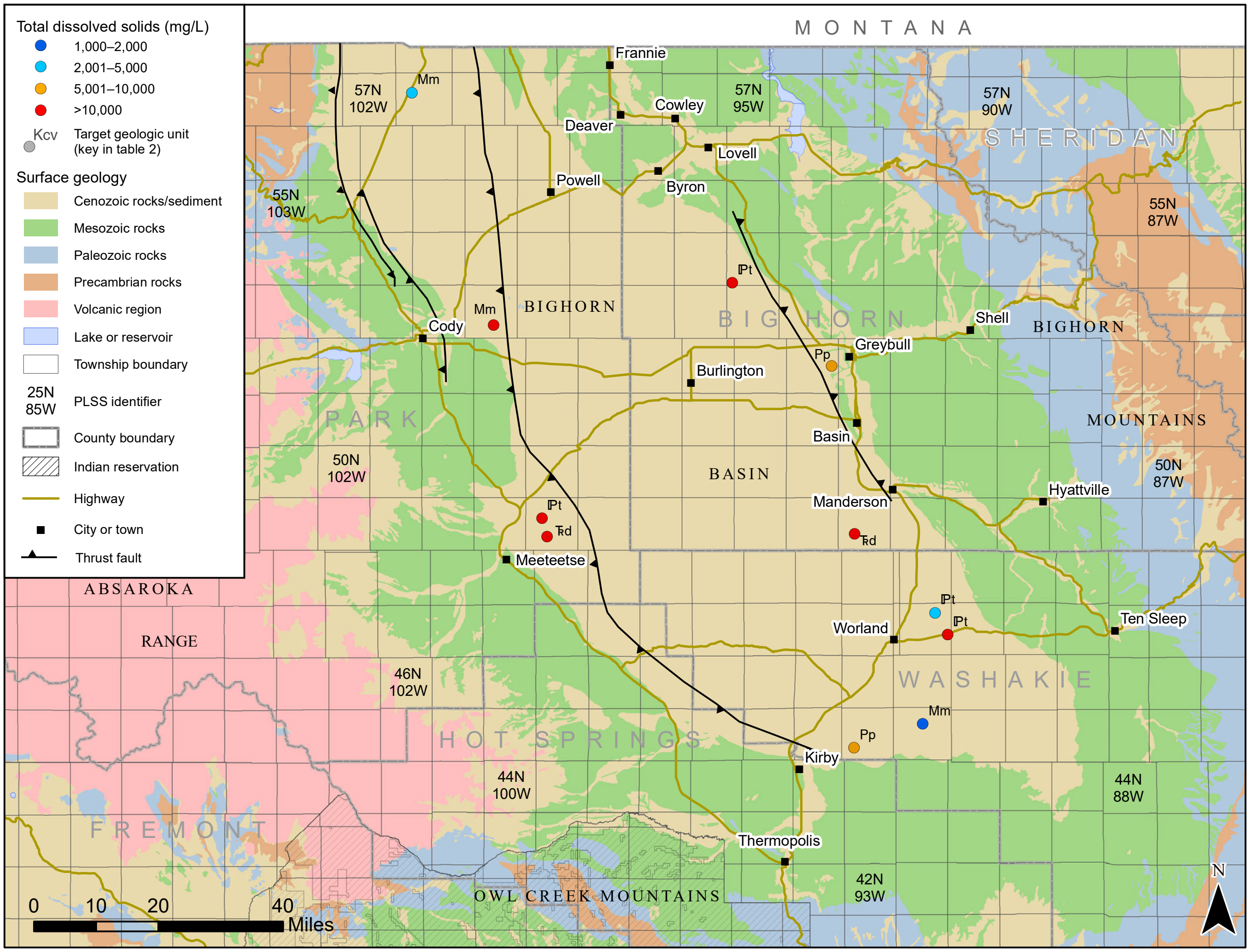
Subsurface geologic unit	Geologic age	Count	TDS (mg/L) Minimum	Mean	Maximum	Count TDS>5,000 mg/L
Muddy Ss	Cretaceous	4	7,945	20,293	36,215	4
Morrison Fm	Jurassic	1	12,984	12,984	12,984	1
Sundance Fm	Jurassic	2	15,299	15,777	16,255	2
Chugwater Fm	Triassic	8	3,558	8,698	11,773	7
Dinwoody Fm	Triassic	1	13,104	13,104	13,104	1
Phosphoria Fm	Permian	5	3,071	40,378	115,997	4
Tensleep Ss	Pennsylvanian	3	1,183	5,307	9,912	1
Madison Ls	Mississippian	1	1,869	1,869	1,869	0

Figure/Table A2–10. Figure and table show saline waters in the 10,000–11,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



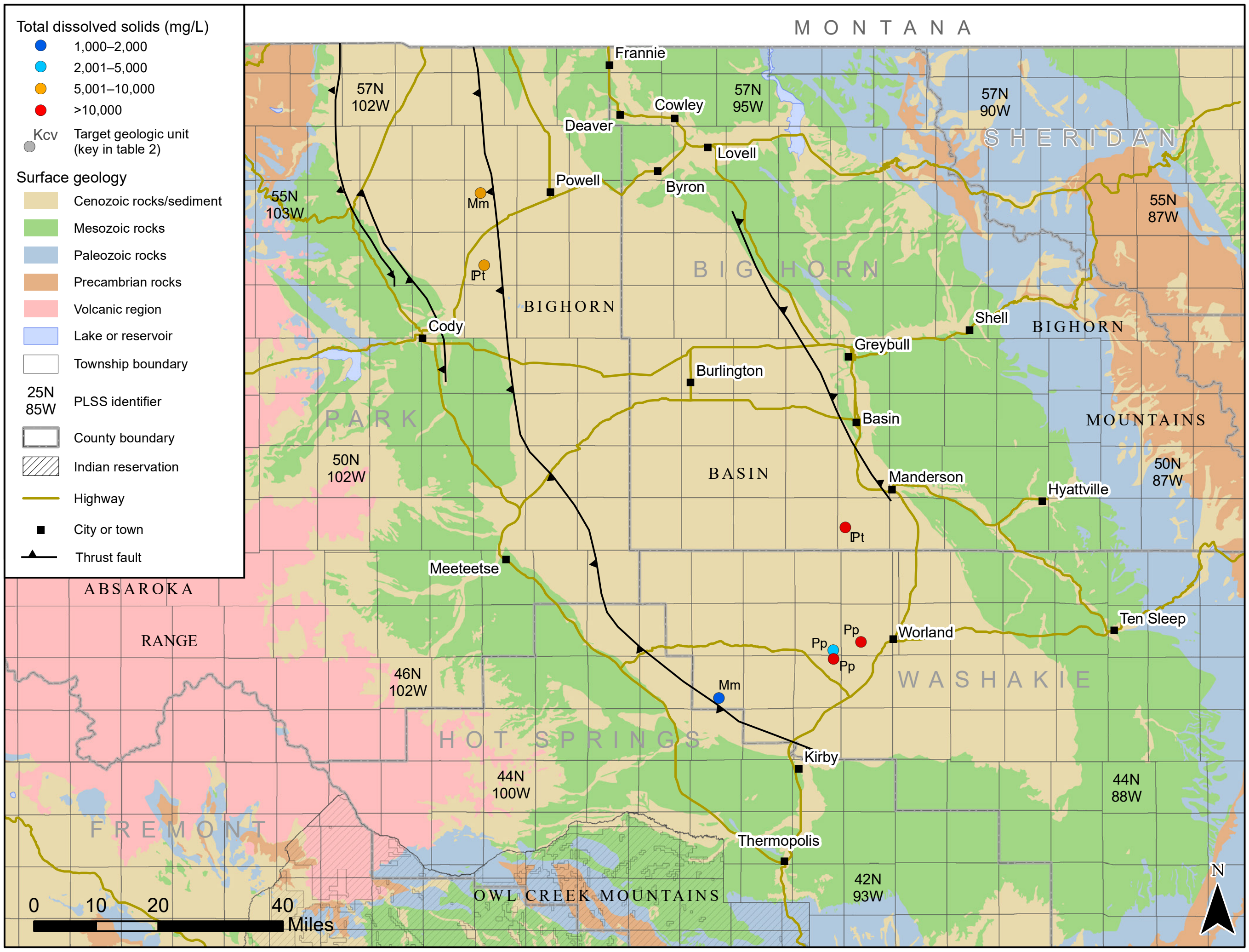
Subsurface geologic unit	Geologic age	Count	TDS (mg/L)			Count TDS>5,000 mg/L
			Minimum	Mean	Maximum	
Frontier Fm	Cretaceous	4	4,382	13,255	32,425	3
Muddy Ss	Cretaceous	1	6,697	6,697	6,697	1
Cloverly Fm	Cretaceous	1	14,825	14,825	14,825	1
Dinwoody Fm	Triassic	2	11,233	13,185	15,137	2
Phosphoria Fm	Permian	14	3,587	20,699	52,680	11
Tensleep Ss	Pennsylvanian	1	14,843	14,843	14,843	1
Unspecified unit	Unspecified	1	1,842	1,842	1,842	0

Figure/Table A2–11. Figure and table show saline waters in the 11,000–12,000-ft depth interval in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



Subsurface geologic unit	Geologic age	Count	TDS (mg/L) Minimum	TDS (mg/L) Mean	TDS (mg/L) Maximum	Count TDS>5,000 mg/L
Dinwoody Fm	Triassic	2	26,716	34,200	41,683	2
Phosphoria Fm	Permian	2	5,768	6,979	8,189	2
Tensleep Ss	Pennsylvanian	4	4,794	11,975	17,642	3
Madison Ls	Mississippian	3	1,486	6,352	15,557	1

Figure/Table A2–12. Figure and table show saline waters at depths greater than 12,000 ft in the Bighorn Basin. [Abbreviations: Fm, formation; Ls, limestone; Ss, sandstone]



Subsurface geologic unit	Geologic age	Count	TDS (mg/L) Minimum	TDS (mg/L) Mean	TDS (mg/L) Maximum	Count TDS>5,000 mg/L
Phosphoria Fm	Permian	3	3,457	20,947	42,397	2
Tensleep Ss	Pennsylvanian	2	8,450	10,044	11,637	2
Madison Ls	Mississippian	2	1,272	5,124	8,975	1