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AN EVALUATION OF THE UNCONSOLIDATED HYDROGEOLOGIC UNITS IN THE SOUTH-CENTRAL FLATHEAD VALLEY, MONTANA

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Cover photo: Photo by Andrew Bobst, taken during drilling of BFF#5.

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2022

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ABSTRACT

The population of Flathead County, Montana, is increasing, resulting in increased groundwater development. The Flathead Valley deep alluvial aquifer ("deep aquifer") is generally confined by overlying glacial till and glacial lacustrine deposits; these confining layers are overlain, in turn, by modern sediments which are called the "shallow aquifers." The deep aquifer consists of a thick sequence of sand and gravel deposited in a glaciofluvial environment. It is an important groundwater source, with wells typically producing hundreds of gallons per minute. Prior to this study no wells had penetrated the entire thickness of the deep aquifer. An accurate measurement of aquifer thickness is critical for estimating the volume of water stored and transmitted through the aquifer. The purpose of this project was to drill through the deep aquifer to determine its thickness and to characterize the hydrogeologic properties of the underlying sediments.

The Bigfork Farm (BFF) site is located approximately 1.5 miles north of Flathead Lake, near the center of the Flathead Valley. Four monitoring wells were installed at the site in 2011, completed in different hydrogeologic units; one in the shallow unconfined aquifer, one in the confining unit, and two in the deep aquifer. Monitoring from these wells shows that there is an upward gradient from the deep aquifer to the shallow aquifer, with a gradient ranging from 0.007 to 0.015. These wells also provide information on seasonal groundwater responses and water chemistry. Aquifer tests were conducted at these wells in 2011, supplying hydrogeologic information that has not been previously reported.

To determine the thickness of the deep aquifer, and evaluate the hydraulic properties and water quality of the underlying sediments, we drilled a 1,600-foot well at the BFF site in 2021. This well penetrated the entire thickness of the deep aquifer, and was screened in the underlying fine-grained sediments. Wood fragment ^{14}C dating indicates these fine sediments are more than 43,500 years old, caliper logs show that they are semi-lithified, and they are lithologically similar to the Kishenehn Formation (based on the sand-size fraction). As such, we conclude that these sediments are the Tertiary Kishenehn Formation. This well produced a sustained yield of less than 1 gallon per minute, and had an estimated hydraulic conductivity of about 0.5 feet/day. Groundwater elevations measured in the Tertiary well were lower than in the deep aquifer, resulting in a downward gradient ranging from 0.001 to 0.002.

The deep aquifer is 800 feet thick at the BBF site, where it is overlain by a 320-feet-thick glacial-lacustrine confining layer, and 80 feet of shallow aquifer materials. The Tertiary sediments, encountered at 1,200 feet below ground surface, form a basal aquitard underlying the deep aquifer. The water type in the deep aquifer was Ca-Mg-HCO_3, while the water from the Tertiary sediments was Ca-Na-HCO_3. ^4He concentrations in groundwater in the Tertiary sediments were much higher than in samples from the overlying units, suggesting that groundwater in the Tertiary sediments has been isolated from the atmosphere for longer. The stable isotopes of water (δD and $\delta^{18}O$) from the Tertiary sediments were also relatively light, suggesting that the groundwater recharged during a colder climate.

BACKGROUND AND PURPOSE

The Flathead Valley lies at the southern end of the Rocky Mountain Trench, which extends over 1,000 mi from the Yukon Territory to the Flathead Valley. The trench formed from closely spaced normal faults and extension that caused crustal blocks to drop relative to the surrounding terrane (Harrison and others, 1992). Gravity data suggest that the trench is filled with up to 3,000 ft of basin-fill materials (Smith, 2004a). The Flathead Valley is bounded by the Swan Range on the east, the Salish Range to the west, and the Whitefish Range to the north; Flathead Lake forms the southern boundary of the valley (fig. 1).

The hydrogeologic units in the central Flathead Valley (fig. 2) have been the subject of several studies (Smith, 2004b; LaFave and others, 2004; Konizeski and others, 1968; Rose, 2018; Rose and others, 2022). Shallow aquifers are composed of sand and gravel. Low-permeability glacial till and glacial lacustrine sediments form an aquitard beneath the shallow aquifers. The deep aquifer underlies the confining layer, and consists of sands and gravels deposited in a glacio-fluvial environment. The deep aquifer is an important source of residential, municipal, and irrigation water. Based on observations in other intermontane basins, previous studies suggested that the deep aquifer is underlain by semi-lithified Tertiary sediments (e.g., the Kishenehn Formation; LaFave and others, 2004); however, prior to this study, these sediments had not been encountered in the subsurface in the Flathead Valley. The Tertiary sediments are believed to be underlain by the Precambrian meta-sedimentary rocks of the Belt Supergroup (referred to as Belt Bedrock in this report; fig. 2).

Because wells in the upper part of the deep aquifer typically produce several hundred gallons per minute (gpm), no wells had been drilled to the base of the aquifer; the deepest reported well was about 850 ft deep. Determining the deep aquifer thickness, the productivity of the Tertiary sediments, and the quality of the water in the Tertiary sediments in this area will aid in managing the groundwater resource.

The Bigfork Farm (BFF) site is located approximately 1.5 mi north of Flathead Lake (figs. 1, 3). The results at this site are believed to be representative of the south-central Flathead Valley, where fine-grained lacustrine sediments were deposited; however, conditions likely vary near the basin margins. In 2011 the Montana Bureau of Mines and Geology (MBMG) Ground Water Investigation Program (GWIP) installed four wells at this site, with a maximum depth of 717 ft below ground surface (bgs; fig. 4, table 1; Rose, 2018; Rose and others, 2022). This report focuses on a deeper well (BFF#5; table 1) installed at this site in 2021 to evaluate the total thickness of the deep aquifer, and characterize the hydrogeologic properties and water quality of the underlying sediments (fig. 4). All five wells are located within 200 ft of each other (fig. 3).

The purpose of this report is to compile hydrogeologic information on the unconsolidated basin-fill sediments at the BFF site. This includes unpublished aquifer test information from the previous GWIP investigation, and additional information collected from 2021 to 2022. Information from a related effort to use surficial geophysical methods to identify contacts between hydrogeologic units in the Flathead and Mission Valleys (including at the BFF site) are also included.

METHODS

Well Installation and Geologic Sampling

Stratigraphic information from the wells installed in 2011 was obtained by examining cuttings during drilling (table 1; appendix A). The wells were drilled using a forward air dual-rotary drilling system, which uses steel casing to stabilize the borehole during drilling and provides cuttings samples from the discrete interval between the drill bit and the casing shoe. Dual-rotary drilling provides high-resolution cuttings logs; however, casing the borehole precludes most downhole geophysical methods (i.e., open-hole logging techniques; Asquith and Krygowski, 2004). Dual-rotary drilling requires managing substantial volumes of produced water when drilling through productive zones (e.g., the deep aquifer), and the total drilling depths in unconsolidated sediments is typically limited to about 1,000 ft.

The 1,600 ft well drilled in 2021 (BFF#5) was installed primarily using mud drilling. The mud circulates cuttings, stabilizes the borehole, prevents the production of large volumes of water during drilling, allows for a wide suite of borehole geophysical logs, and allows drilling to greater depths (maximum 2,000 ft for the truck-mounted drill rig used for this project). Cuttings were described by MBMG hydrogeologists based on continuous observation of the sediments

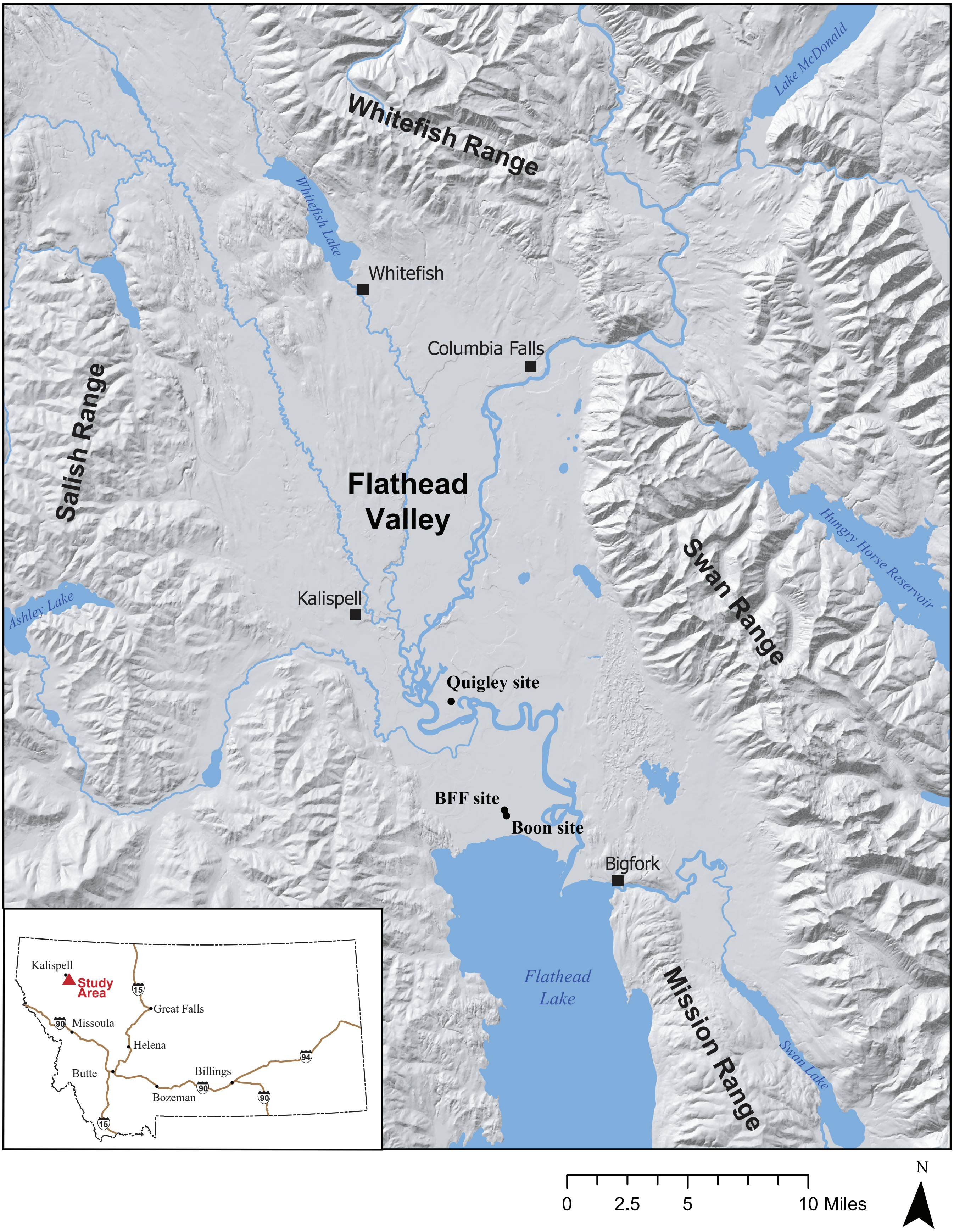

Figure 1. The Flathead Valley is located in northwest Montana, with mountain ranges on three sides and Flathead Lake to the south.

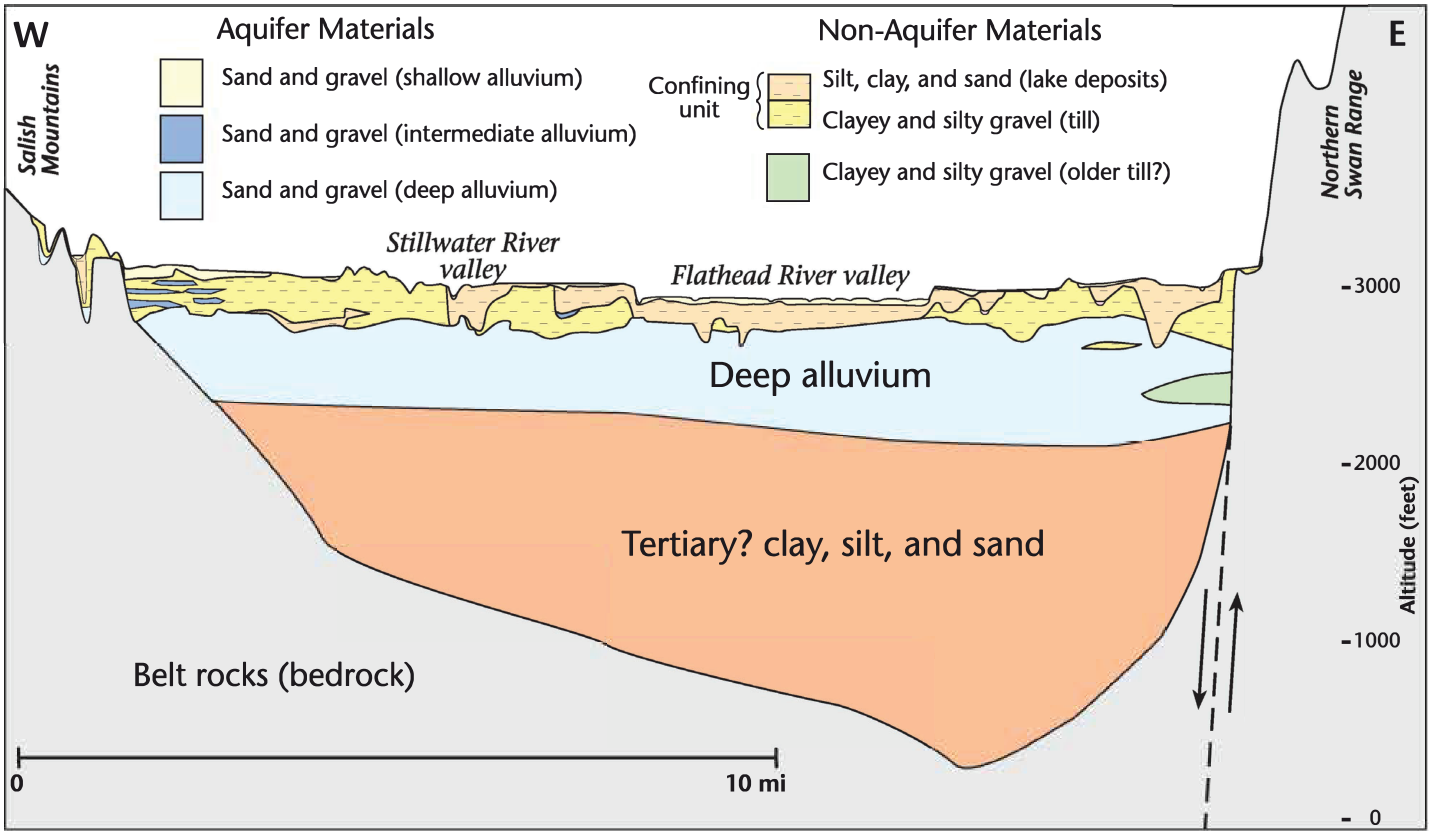

Figure 2. Schematic cross section of the geologic deposits in the Flathead Valley, from LaFave and others, 2004.

Table 1. Wells installed at the BFF site.

GWIC ID	Well Name	Total Depth (ft)	Hydrogeologic Unit
260891	BFF#4	80	Shallow Aquifer
260889	BFF#3	365	Confining Layer
260888	BFF#2	672	Deep Aquifer
260892	BFF#1	717	Deep Aquifer
317644	BFF#5	1,600	Tertiary Sediments

Note. Also see fig. 4 and appendix A.

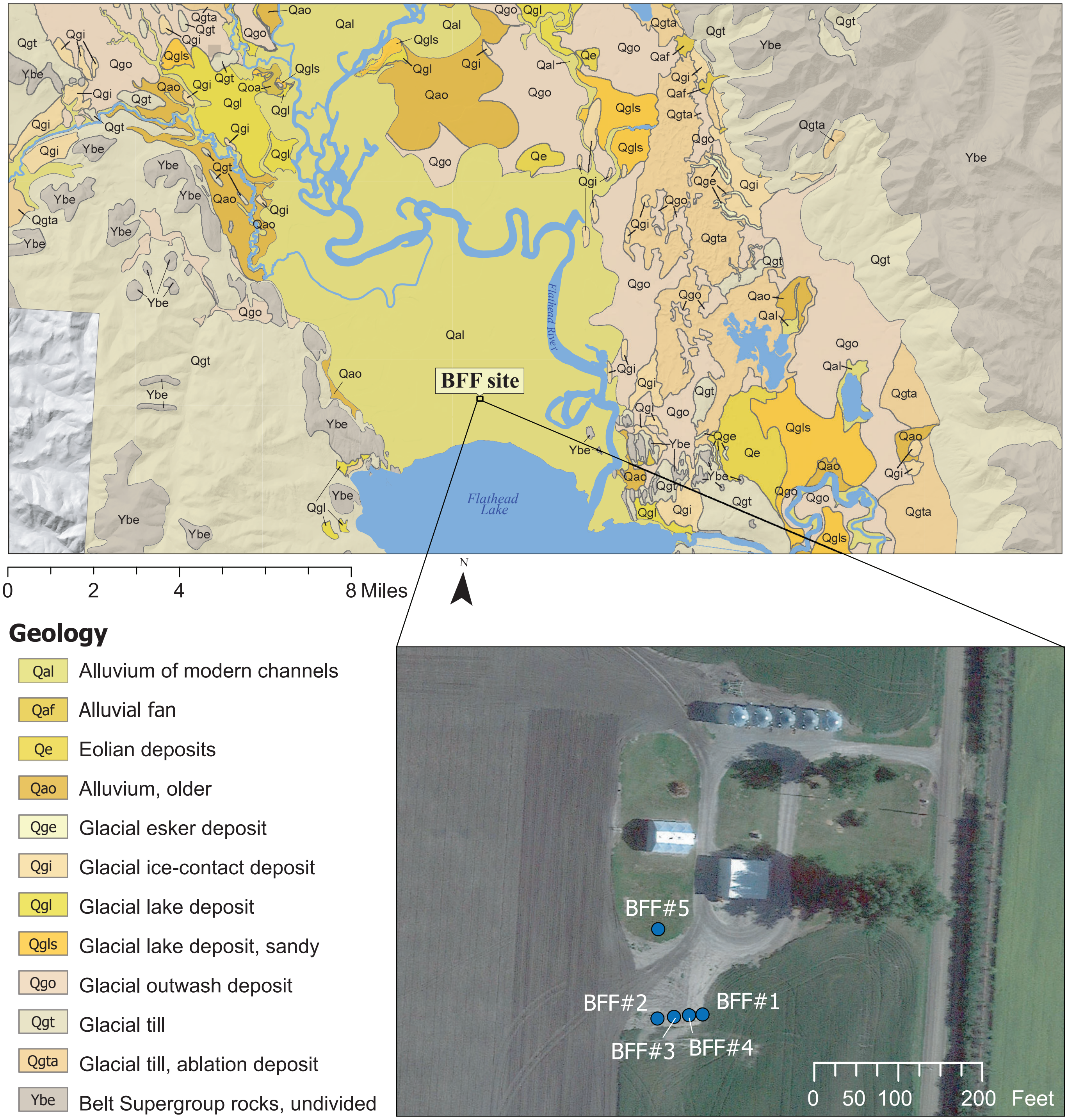

Figure 3. Location of the Big Fork Farm (BFF) site, and geologic map from Smith, 2004b. Inset shows site layout, with well names used in this report.

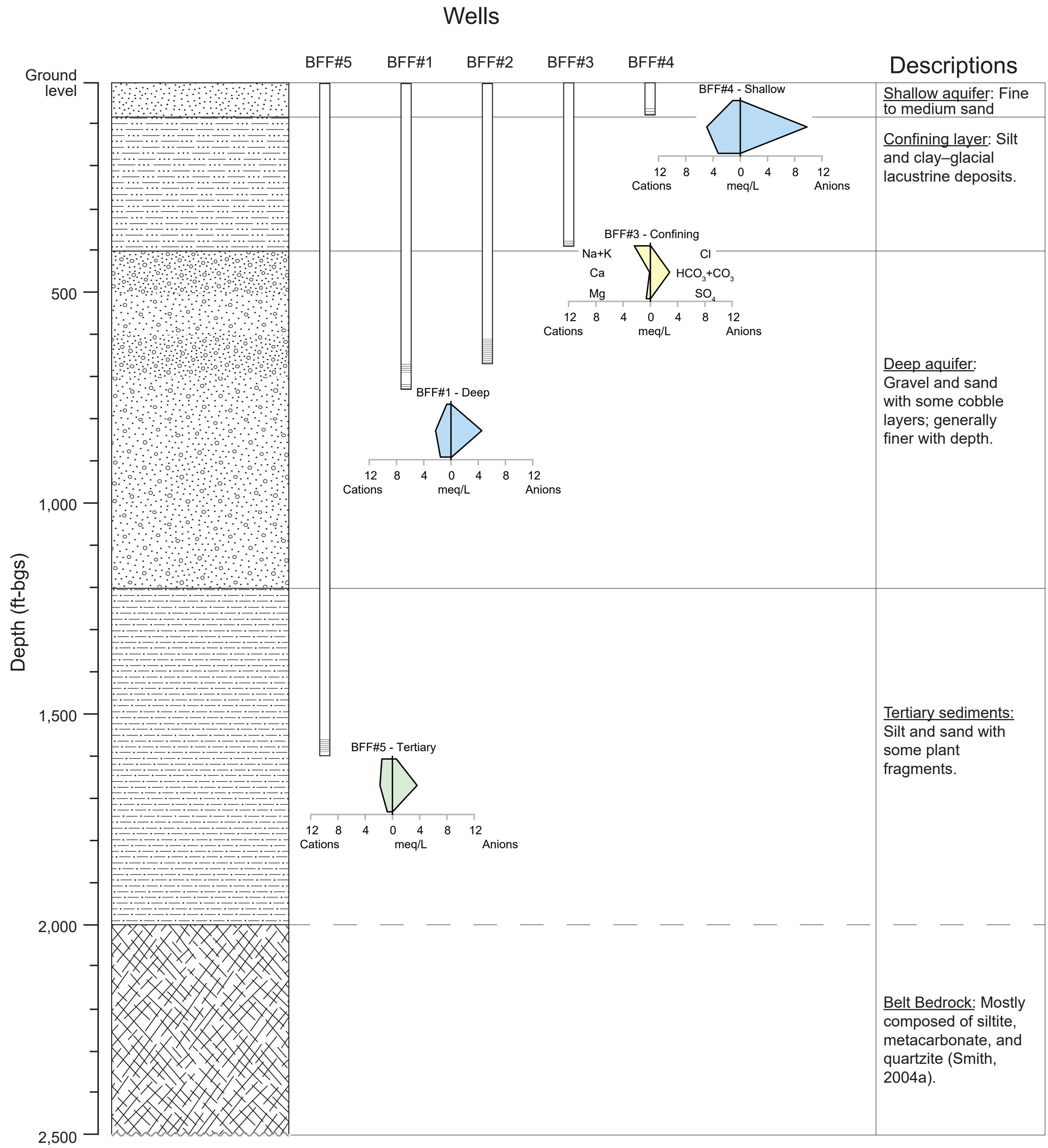

Figure 4. Well depths, hydrogeologic units, and Stiff plots of water quality at the BFF site.

expelled by the mud conditioner (aka, Mud Puppy). Sediments finer than sand were not identified because these materials could not be separated from the mud. A sample of woody material collected from the cuttings at approximately 1,280 ft-bgs was analyzed for ^{14}C by Beta Analytic (2021, Miami, FL; appendix B).

BFF#5 was installed by setting and cementing a 12-in steel surface casing from ground surface to 380 ft bgs so that the well could be shut in if flowing artesian conditions were encountered. Unstable cobble-rich zones in the upper portion of the deep aquifer necessitated running 10-in steel casing to 540 ft-bgs to stabilize the borehole. This 10-in casing was not cemented and was left in place. The remainder of the borehole was drilled without casing, to allow borehole geophysical logging. A 6-in steel casing with 20 ft of 20-slot, 5-in-diameter stainless steel screen was run in the mud-filled borehole following geophysical logging. The screened interval is from 1,540 to 1,560 ft bgs. Once the 6-in casing and screen were suspended, mud was removed from the borehole by purging with fresh potable water introduced through the 6-in casing and screen. Silica sand was used as filter pack around the screen, and to fill the lower portion of the borehole. Sand volume was based on the caliper log, with sand calculated to extend 20 ft above the top of screen. The well was developed for 6.5 h by air surging after allowing the well to sit for 21 h.

Measuring Groundwater Levels

The measuring point elevation for BFF#5 was determined by reference to the existing wells, which were surveyed by a licensed surveyor using a survey level. Groundwater levels were recorded using e-tapes and pressure transducers following MBMG SOPs (Gotkowitz, 2022).

Geophysics

Geophysical logs were run by COLOG, Inc. (Lakewood, CO) in the mud-filled borehole of BFF#5 (appendix C). These logs included natural gamma, normal resistivity (16-in and 64-in), single point resistivity, spontaneous potential, caliper (three-arm and one-arm), fluid temperature, fluid resistivity, full waveform sonic, compensated density, thermal neutron, and nuclear magnetic resonance (NMR). These methods are described in detail in appendix C.

Surficial geophysical surveys were conducted at the BFF site and several other locations in the Flathead and Mission Valleys (appendix D). The objective of this work was to determine if time-domain electromagnetics (TEM; e.g., Payne and Teeple, 2011) or magnetotellurics (MT; e.g., Tournerie and Chouteau, 2005; Pierce and Thomas, 2009) could identify the top and bottom of the deep aquifer where drilling information was lacking. The results of this work were published as a Montana Technological University Master's Thesis (Breitmeyer, 2022).

Aquifer Tests

Three aquifer tests were conducted at the BFF site (appendix E) to characterize the hydrogeologic properties of the unconsolidated hydrogeologic units. These tests generally followed MBMG SOPs (Gotkowitz, 2022). This includes analysis of two tests conducted in 2011 that had not been previously published, and one test conducted in 2022.

- A 7-d test of the deep aquifer (pumping from BFF#1), with an average discharge rate of 485 gpm (appendix E1).
- A recovery test of the confining layer well (BFF#3) following purging (appendix E2).
- An analysis of drawdown and recovery data collected during groundwater sampling from the well in the Tertiary sediments (BFF#5), with an average discharge of 0.6 gpm (appendix E3).

The 7-day and recovery tests were performed in 2011 after wells BFF#1 to BFF#4 were installed (Rose and others, 2022). The test of BFF#5 occurred in April 2022. Detailed aquifer test data (633 forms) are available by clicking on the "View scanned aquifer test" link on each well's GWIC page (https://mbmggwic.mtech.edu/).

Water Quality

Groundwater-quality samples were obtained from wells BFF#1, BFF#3, BFF#4, and BFF#5 (table 2, appendix F). Due to the large volume of casing water and the low well yield, only 1.6 well volumes were removed from BFF#5 prior to sampling rather than the MBMG's typical purging volume of three casing volumes (Gotkowitz, 2022); however, this was consistent with the USGS protocol for "at least one borehole volume" (Wilde, 2006), and field parameters were

Table 2. Selected water-quality parameters for wells at the BFF site.

GWIC ID	Well Name	Hydrogeologic Unit	Sample Date/Time	TDS	Ca	Mg	Na	K	HCO_3	SO_4	Cl	SiO_2	Fe	Mn
				(mg/L)										
260891	BFF#4	Shallow Aquifer	4/28/11 16:05	520	98.7	39.4	22.1	5.8	598	<2.5	0.9	46.9	10.742	0.110
			4/26/12 11:52	521	98.7	38.4	18.9	5.1	592	1.2 J	0.8	50.6	16.402	0.148
260889	BFF#3	Confining Layer	4/26/12 9:56	152	2.1	7.3	53.8	0.9	114	1.1 J	1.9	0.08 J	0.01 J	0.005 J
260892	BFF#1	Deep Aquifer	6/13/11 15:10	231	45.2	18.9	13.3	1.6	276	4.6	1.1	10.1	0.003	0.001
317644	BFF#5	Tertiary Sediments	4/7/22 10:00	230	36.6	9.2	34.9	1.3	221	1.0 J	20.6	11.2	7.185	0.265

GWIC ID	Well Name	Hydrogeologic Unit	Sample Date/Time	As	Ba	Li	Sr	Zn	Ga	Nb	W
				(µg/L)							
260891	BFF#4	Shallow Aquifer	4/28/11 16:05	7.6	1705	<10	323	19.1	<2.5	<2.5	<2.5
			4/26/12 11:52	15.4	1447	<1	332	4.1	<0.25	<0.25	<0.25
260889	BFF#3	Confining Layer	4/26/12 9:56	0.12 J	5	1.9	4	0.3 J	<0.1	<0.1	0.17 J
260892	BFF#1	Deep Aquifer	6/13/11 15:10	0.20 J	407	2.1	116	11.6	<0.1	<0.1	<0.5
317644	BFF#5	Tertiary Sediments	4/7/22 10:00	<0.10	199	8.4	93	8.7	7.4	0.8	0.7

Note. See appendix F and GWIC for additional parameters. Yellow highlight indicates exceedance of Drinking Water Maximum Contaminant Level (MCL). Blue highlight indicates exceedance of Secondary Drinking Water Maximum Contaminant Level (SMCL).

<##, less than the reported detection limit.

J, Above detection limit but below reporting limit.

GWIC, http://mbmggwic.mtech.edu/.

stable. Samples for pH, specific conductivity, alkalinity, major ions, trace elements, nitrate, and water isotopes (δD and $\delta^{18}O$) were analyzed by the MBMG analytical laboratory, and were collected and stored following MBMG SOPs (Timmer, 2020; Gotkowitz, 2022). BFF#5 samples (also collected on 4/7/22) were also analyzed for ^{14}C and water isotopes (δD and $\delta^{18}O$) by Beta Analytics (2021, Miami, FL), and for tritium at the University of Waterloo Environmental Isotope Laboratory (Waterloo, Ontario Canada). MBMG and Beta Analytics analyzed a split sample for stable water isotopes, providing a blind laboratory duplicate. Noble gases were collected using diffusion samplers and analyzed by the University of Utah Noble Gas Lab (Salt Lake City, UT; table 3). Samples were collected and stored following SOPs from those labs (Beta, 2021; Waterloo, 2022; Noble Gas Lab, 2022). All stable water isotope results are reported using del notation (δ) relative to Vienna standard mean ocean water (VSMOW), and results are on a per mil basis ($^{o}/_{oo}$) (Kendall and Caldwell, 1998). ^{14}C results are reported as percent modern carbon (pMC), where 100 percent refers to estimated atmospheric concentrations in 1950 (prior to substantial atmospheric testing of thermonuclear weapons, and adjusted for fossil fuel effects of the industrial revolution; Stenström and others, 2011).

Data Management

Many of the data collected for this project are stored in MBMG's GWIC database (http:// mbmg-gwic.mtech.edu/). GWIC contains well completions, drillers' logs, groundwater levels, water chemistry, aquifer tests, and other information. GWIC identification numbers for each well are provided in table 1.

RESULTS AND INTERPRETATIONS

Stratigraphic Information

The cuttings descriptions developed by MBMG hydrogeologists (appendix A), downhole geophysical logs (appendix C), and previous interpretation of surficial gravity data (Smith, 2004a) support interpretation of the unconsolidated hydrostratigraphic units at the BFF site (fig. 4). The shallow aquifer is dominated by sand and extends to a depth of 80 ft-bgs. It is underlain by a lacustrine silt and clay confining layer from 80 to 400 ft-bgs. The deep aquifer, composed of sand, gravel, and some cobble layers, extends from 400 to 1,200 ft-bgs. Fine-grained sediments, which we interpret to be the Tertiary Kishenehn Formation, underlie the deep aquifer from 1,200 ft-bgs to at least 1,600 ft-bgs (the total depth drilled). The gravity data (Smith, 2004a) indicate the depth to bedrock at this site is about 2,000 ft, and we assume that the Kishenehn Formation is continuous to bedrock. A sample of woody material from approximately 1,280 ft-bgs did not have detectable ^{14}C activity, indicating that it was more than 43,500 yr old (appendix B), consistent with the sediments being Tertiary aged (the boundary between Quaternary and Tertiary is at 2.6 million years ago, well beyond the range of ^{14}C dating).

The geophysical logs show a distinct transition at 1,200 ft-bgs (appendix C); for instance, the caliper log becomes less variable (less rugosity), and the resistivity curves decline and are closer together, consistent with a transition to finer grained and less permeable sediments. Notably, the gamma log showed little response to the fine-grained confining layer and Tertiary sediments, even though fine-grained sediments typically have substantially greater gamma readings than

Table 3. Noble gas and tritium results.

Site	Well	GWIC ID	Tritium (TU)*	1s Tritium error (TU)	Total Ne	Total Ar	Total Kr	Total Xe	^{4}He	$^{4}He/Ne$
					(mole fraction)					
Quigley	Shallow	318265	2.39	0.13	1.68E-07	2.73E-04	8.17E-08	1.12E-08	2.6E-07	1.6
	Intermediate	318266	<0.09	-0.03	1.70E-07	4.76E-04	1.50E-07	2.27E-08	1.4E-07	0.8
	Deep	318263	<0.06	-0.02	1.56E-07	3.07E-04	9.19E-08	1.19E-08	3.4E-06	21
BFF	Tertiary	317644	<0.8	0.15	8.56E-06	7.84E-03	9.02E-07	6.13E-08	9.7E-03	1,138

Note. Yellow highlight indicates non-detect. Orange highlight: ^{4}He concentrations were much higher than the standards; results should be interpreted qualitatively.

*For tritium the BFF Tertiary Sample was analyzed by Waterloo while the other samples were analyzed by the University of Utah.

sand and gravel due to potassium, uranium, or thorium associated with clay minerals. We attribute the lack of a gamma response at this site to the composition of the fine-grained sediments, which are primarily composed of silt and clay-sized lithic fragments of Belt Bedrock (e.g., glacial flour) rather than clay minerals, which results in a relatively low cation exchange capacity. The NMR results, processed with the default assumptions, show the permeability of the Tertiary sediments as greater than the deep aquifer; however, both aquifer tests (appendix E) and resistivity logs show that it is less permeable. We interpret the high permeability calculated from NMR as resulting from water in the fine-grained materials not being bound to the lithic fragments the same way that it would bind to clay minerals. The assumptions for NRM result in the higher porosity of the well-sorted fine-grained sediments, and the unbound water, being interpreted as high permeability, similar to a well-sorted sand.

The surficial TEM surveys identified the shallow aquifer and confining layer thicknesses at sites with drilling records. TEM was useful to determine the thicknesses of these relatively shallow units in the Flathead Valley. However, the top of the Tertiary sediments was below the depth of investigation for TEM (Breitmeyer, 2022). The MT surveys did not provide sufficient resolution to delineate any of the hydrogeologic units.

Aquifer Properties

The deep aquifer test data (appendix E1) matched the Theis solution for confined aquifers (Theis, 1935) with a calculated hydraulic conductivity (K) of 700 ft/d. Analysis of recovery data from the well completed in the overlying confining layer (appendix E2) indicated a K of about 0.0007 ft/d. Analysis of water levels in well BFF#5 (appendix E3) showed a hydraulic conductivity of about 0.5 ft/d in the Tertiary sediments, much lower than that of the deep aquifer.

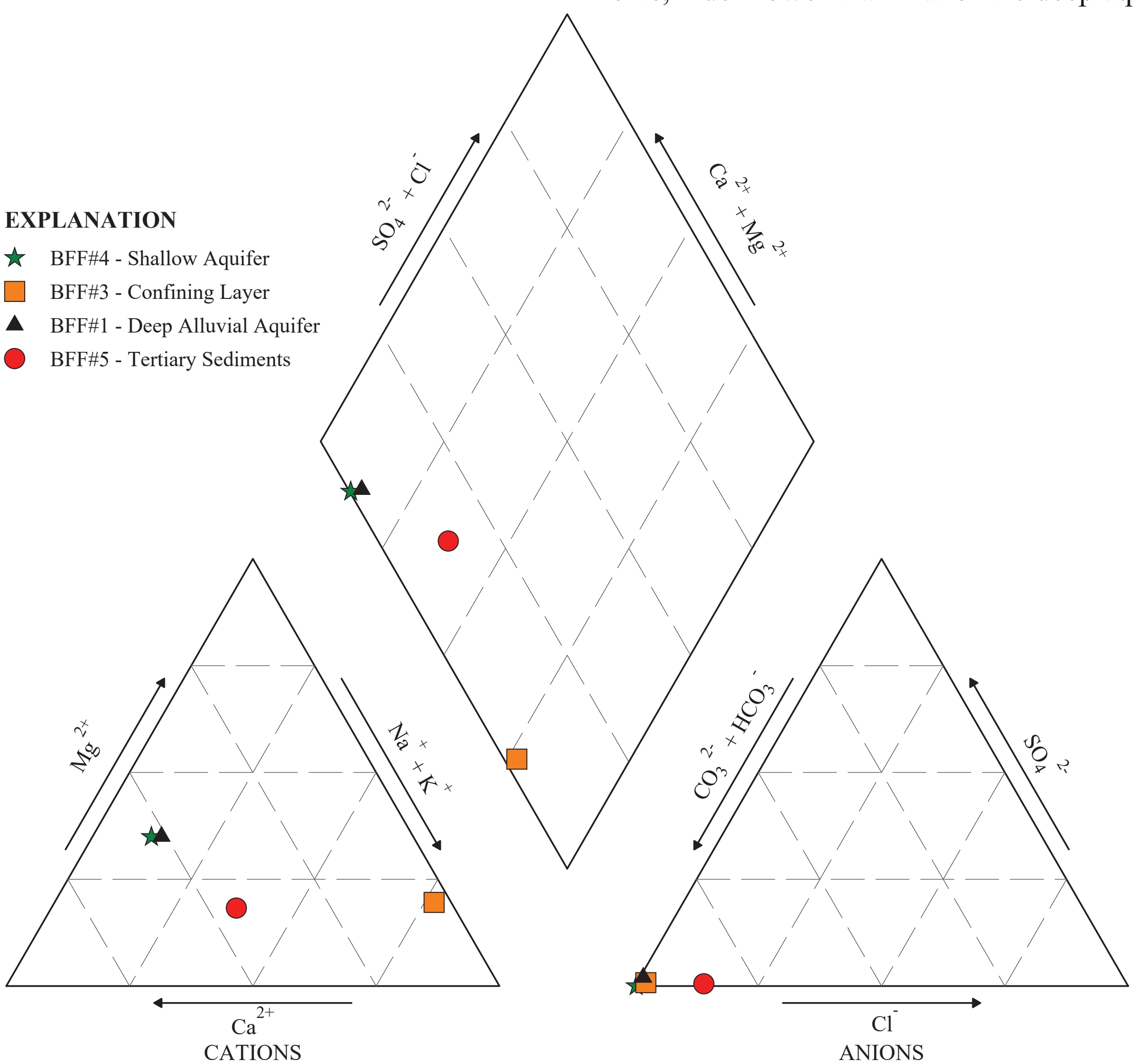

Figure 5. This Stiff diagram illustrates the relative concentrations of major ions in groundwater. Groundwater in the shallow aquifer and the deep alluvial aquifer is similar and differs from that in the confining unit and the basal aquitard.

Groundwater Sampling and Analysis

Results from each of the wells show that total dissolved solids (TDS), major ion composition, and trace element composition differ among the hydrogeologic units. This suggests variations in either the sources of recharge or the age of the groundwater, or differences in the minerology of sediments that affect rock/water interactions (table 2, figs. 4, 5; appendix F).

The shallow aquifer (well BFF#4) was sampled twice and has a calcium–magnesium–bicarbonate (Ca-Mg-HCO_3) type water. Compared to the deep aquifer, it has relatively high TDS (520 mg/L). Shallow aquifer groundwater also had relatively high iron (Fe), manganese (Mn), arsenic (As), and barium (Ba) concentrations (table 2). The As and Ba concentrations (average of 11 and 1,576 µg /L, respectively) exceed the Montana Department of Environmental Quality drinking water maximum contaminant levels (MCLs; 10 µg/L and 1,000 µg/L, respectively; MDEQ, 2019), and the Fe and Mn concentrations exceeded the secondary MCLs (SMCLs, for aesthetics; MDEQ, 2019).

Groundwater from the confining layer (well BFF#3) was a sodium–bicarbonate (Na-HCO_3) type, with a TDS of 152 mg/L. Compared to the overlying and underlying aquifers, the water from this well had relatively low silica (SiO_2), strontium (Sr), zinc (Zn), and Ba (table 2).

Groundwater from the deep aquifer (well BFF#1) was a calcium–magnesium–bicarbonate (Ca-Mg-HCO_3) type, with the relative abundance of major ions similar to the shallow aquifer. The TDS (231 mg/L) was about half that of the shallow aquifer, and Fe, Mn, As, and Ba were lower (table 2).

Groundwater from the Tertiary sediments (well BFF#5) showed a mixed calcium–sodium–bicarbonate (Ca-Na-HCO_3) type water. The TDS (230 mg/L) was similar to the deep aquifer, but Fe and Mn concentrations exceeded their SMCLs, and the lithium (Li) concentration was higher than in the other wells (table 2). Groundwater from Well BFF#5 had higher concentrations of trace elements gallium (Ga), niobium (Nb), and tungsten (W) than that in other wells (table 2).

Stable water isotopes (δD and $\delta^{18}O$) from BFF#5 were compared to nine other sampled wells in the area (fig. 6; appendix F). Water isotopes from all wells generally follow the Global Meteoric Water Line (GMWL; Rozanski and others, 1993), suggesting that the water is meteoric in origin and has not been substantially altered by evaporation or geothermal exchange. Samples from all wells other than BFF#5 had δD values between -148 and -127‰ and $\delta^{18}O$ values between -19.3 and -16.4‰. The water from BFF#5 was distinctly lighter than the other samples in the area with δD values of -165 and -163‰, and $\delta^{18}O$ values of -21.7 and -21.1‰ (fig. 6). Results from the nearest sampled well in the deep aquifer (Boon, well 141562; fig. 6) showed δD and $\delta^{18}O$ values of -139 and -18.5, respectively (LaFave and others, 2004). The relatively light isotopic signature of the water from the Tertiary sediments suggest that it may have been recharged during colder climatic conditions.

Groundwater analyzed for ^{14}C from the Tertiary well contained a percent modern carbon activity (pMC) of 2.89 (±0.05), and a $\delta^{13}C$ value of -7.4‰ (the calculated apparent age is 28,480 years—however, without additional geochemical information this is not considered a reliable “age”). The pMC value is similar to the lower end of the range from previous samples from the bedrock aquifer, but lower than values from the deep aquifer (fig. 7; LaFave and others, 2004). The bedrock water samples had pMC values as low as 0.48, while samples from the deep aquifer ranged from 19.66 to 87.82 pMC. As such, it appears that the water in the Tertiary sediments is older than the water in the deep aquifer.

The tritium and noble gas results from BFF#5 were compared to results (using the same sampling methods) from the Quigley site (fig. 1), approximately 5 mi north of BFF. Wells at the Quigley site are completed in the shallow aquifer (well 318265), the confining layer (well 318266), and the deep aquifer (well 318263; table 3). At these sites tritium was less than detection [< 0.8 tritium units (TU)] in the Tertiary sediments, the deep aquifer, and the confining layer. This indicates that groundwater in these hydrogeologic units is premodern (>70 yr old; Lindsey and others, 2019). The shallow aquifer at the Quigley site (well 318265) had a tritium concentration of 2.39 TU, indicating that the water in the shallow aquifer contains modern water (< 70 yr old).

The ratio of $^4He/Ne$ provides an indication of excess ^4He accumulation in a groundwater sample (i.e., terrigenic ^4He; Gardner and others, 2012). The ratio of $^4He/Ne$ in shallow unconfined groundwater

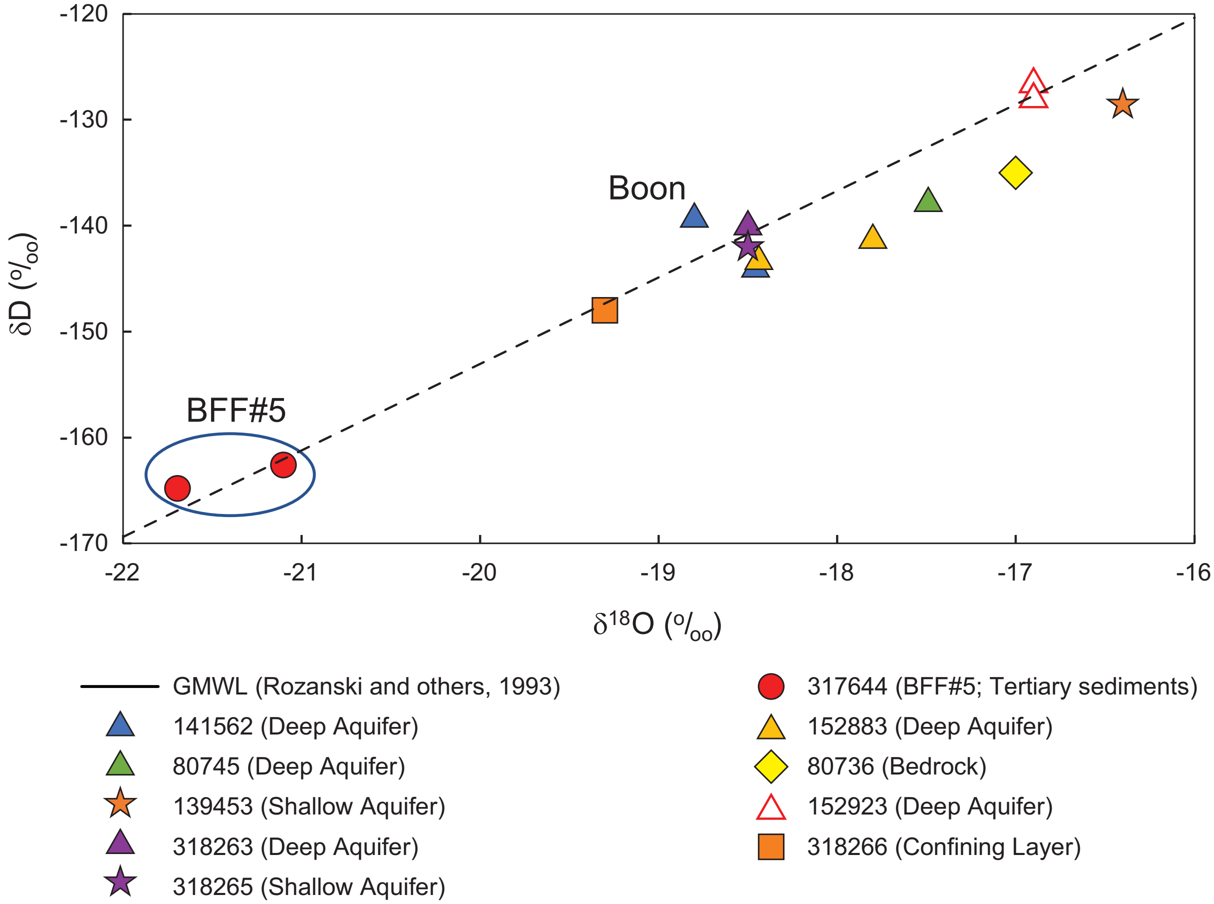

Figure 6. The isotopic composition of groundwater samples from BFF#5 (well 317644) relative to other wells in the area. Samples generally follow the global meteoric water line (GMWL), but groundwater from the Tertiary sediments (BFF#5) was more depleted, suggesting recharge during a colder climate. See appendix F for sample locations. The Boon site (well 141562; fig. 1) is 0.25 mi from the BFF site, and is completed in the deep aquifer.

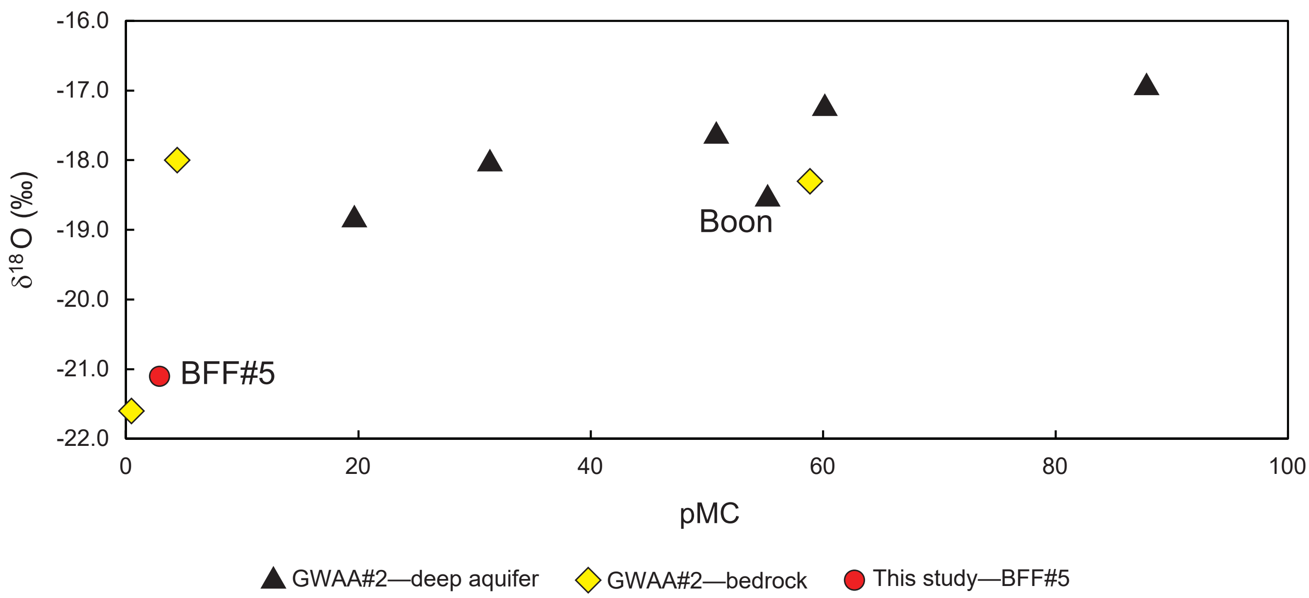

Figure 7. Percent modern ^{14}C (pMC) vs. $\delta^{18}O$ in groundwaters from BFF#5 and other wells in the area [from Ground-Water Assessment Atlas (GWAA) #2 (LaFave and others, 2004)], with waters with lower pMC (interpreted as older) also indicating recharge during a colder climate. The Boon site (well 141562; fig. 1) is 0.25 mi from the BFF site, and is completed in the deep aquifer.

is generally similar to the atmosphere (~0.3). Terrigenic ^{4}He is produced by the release of alpha particles during natural radioactive decay (e.g., decay of ^{235}U to ^{231}Th) of aquifer sediments along with crustal and mantle degassing (Castro and others, 1998; Torgersen and Clarke, 1985; Zhao and others, 1998). It is assumed that the only source of Ne is the atmosphere and it is incorporated into the water during recharge. The accumulation of ^{4}He in groundwater increases with residence time, the degree to which the aquifer is confined (cannot outgas), and the geochemistry of the aquifer matrix. The shallow and intermediate wells at the Quigley site had relatively low $^{4}He/Ne$ molar ratios of 1.6 and 0.8, respectively, compared to the deep aquifer at 21.4. These results suggest that groundwater from the deep aquifer is older (consistent with the tritium results) and confined (consistent with aquifer testing). Groundwater from BFF#5 in Tertiary sediments was enriched in ^{4}He, and the results were above the analytical calibration range, precluding precise quantification. However, by extending the calibration curves beyond the calibrated range, the estimated $^{4}He/Ne$ ratio is close to 1,100 (table 3). Despite the high level of uncertainty in this estimate, this clearly indicates that groundwater from the Tertiary sediments has much higher ^{4}He concentrations than the deep aquifer, suggesting a longer residence time.

Groundwater Levels

Groundwater levels at the BFF site were monitored at the wells drilled in 2011 following their completion for about 3 yr (2011–2014); monitoring resumed in 2019 (fig. 8A). Groundwater levels in the shallow aquifer (fig. 8B) rise in the spring in response to snowmelt, peaking in early July, and then decline until the next spring. Water levels in the confining layer do not show seasonal variations and are slightly lower than the deep aquifer (figs. 8A, 8C). Water levels in the deep aquifer (figs. 4, 8A, 8B) rise in the spring, peak in late June, sharply decline in July and August, recover in the fall, and decline through the winter until the following spring. We attribute the deep aquifer seasonality to recharge during spring snowmelt, followed by water-level decline due to summertime irrigation pumping, followed by recovery after irrigation ceases, and then decline until the next spring. Limited groundwater-level monitoring of the Tertiary well shows groundwater levels are lower than the deep aquifer; however, a long-term record is necessary to evaluate seasonality.

There is an upward vertical hydraulic gradient at this site. In 2012 and 2013 water levels in the deep aquifer were on average 6.8 ft higher than the shallow aquifer (fig. 8B), resulting in an upward gradient that varied between 0.007 and 0.015. Limited monitoring data from BFF#5 suggests a downward gradient between the deep aquifer and the Tertiary sediments of between 0.001 and 0.002 (fig. 8C); however, a long-term monitoring record would aid in defining this relationship.

SUMMARY AND RECOMMENDATIONS

At the BFF site in the south-central Flathead Valley, the deep aquifer is 800 ft thick, extending from 400 to 1,200 ft-bgs (1,708 to 2,508 ft above mean sea level). The deep aquifer is a confined, and aquifer testing in a cobble layer indicated a hydraulic conductivity (K) of about 700 ft/d. It is likely that K values in the more sand-rich zones would be lower, with a likely overall range from about 100 to 1,000 ft/d (Rose and others, 2022).

The underlying Tertiary sediments extend from 1,200 ft-bgs to an estimated approximate depth of 2,000 ft-bgs, and are orders of magnitude less permeable (K ~0.5 ft/d) than the deep aquifer. The Tertiary sediments are likely underlain by Belt Bedrock. The distinct water chemistries, and the accumulation of ^{4}He in the Tertiary sediments, suggest that the deep aquifer and the Tertiary sediments exchange little water. The Tertiary sediments form a basal aquitard that is distinct from the overlying deep aquifer in the Flathead Valley.

The installation of well BFF#5 has resulted in a complete hydraulic profile of the groundwater system in the Flathead Valley at the BFF site. Ongoing monitoring by MBMG's Groundwater Assessment Program (GWAP; https://www.mbmg.mtech.edu/WaterEnvironment/GWAP/main.asp) will aid in developing a long-term groundwater-level record from each hydrogeologic unit at the BFF site. This ongoing monitoring will provide a more complete picture of how these hydrogeologic units respond to stresses, such as changes in pumping rates, total groundwater withdrawals, or periods of drought.

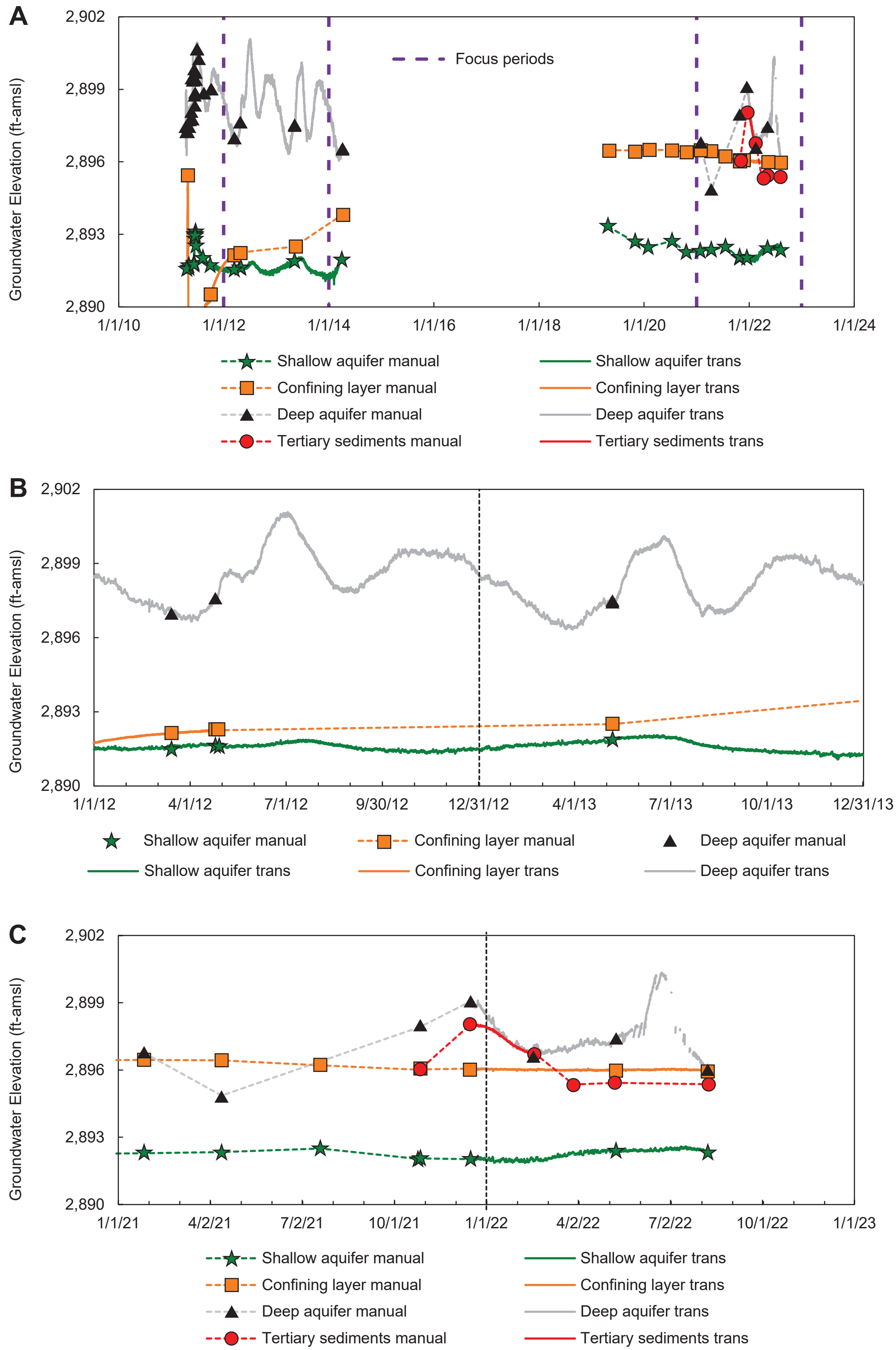

Figure 8. Groundwater levels at the BFF site from 2011 to 2022 (A) show the long-term data from these wells. The record from 2012 to 2014 (B) shows the annual groundwater-level cycles in the shallow and deep aquifers, and an upward gradient between 0.007 and 0.015. Monitoring from 2021 to 2022 (C) shows that groundwater levels in the confining unit (BFF#3) recovered over several years. Limited groundwater-level measurements in the Tertiary sediments (BFF#5) from after well testing show a downward gradient between 0.001 and 0.002.

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