HYDROGEOLOGIC FRAMEWORK OF THE UPPER YELLOWSTONE RIVER VALLEY, PARK COUNTY, MONTANA

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Front photo: Glacial deposits at the base of Emigrant Peak, Absaroka Range, Park County, MT. Photo by Sara Edinberg.

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Montana Bureau of Mines and Geology Ground Water Assessment
Atlas 9, Map 1

Accompanying Pamphlet

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Montana Bureau of Mines and Geology

TABLE OF CONTENTS

FIGURES

INTRODUCTION

This report and the accompanying map (plate 1) are a part of the Montana Bureau of Mines and Geology (MBMG) Ground Water Assessment of Park and Sweet Grass Counties. The report and map describe the hydrogeologic setting of the Upper Yellowstone River Valley between Livingston and Gardiner, with a focus on the Paradise Valley, defined here as the lower elevation slopes and the river valley between Carter's Bridge to the north and Yankee Jim Canyon to the south (fig. 1). The elevation of the river drops from an altitude of 4,995 ft above mean sea level (amsl) at Yankee Jim Canyon to an altitude of 4,546 ft amsl at Carter's Bridge. The map depicts aquifer boundaries and hydrogeologic cross-sections; the report presents aquifer descriptions and statistical summaries of well depths, yields, and use by location and aquifer. This information will help interested citizens and others who may make decisions regarding groundwater development, protection, and management.

Description of Study Area

The upper Yellowstone River Valley, between Livingston and Gardiner, is located in Park County, Montana and encompasses an area of approximately 1,259 mi^2, based on watershed boundaries (figs. 1, 2). The valley is bounded by the Gallatin Range on the west, and the Absaroka Range to the east; peak elevations in these ranges are over 10,000 ft amsl. Yankee Jim Canyon (fig. 1) acts as a transition point in the valley; the Gardiner Basin south of the canyon is a narrow, NW–SE-trending bedrock-bounded basin with limited basin-fill; the Paradise Valley north of the canyon widens with extensive basin-fill deposits, and trends NE–SW. The mountain fronts are bounded by fault systems along which the basin/valley has been downdropped relative to the mountains. The Yellowstone River exits Yellowstone National Park near Gardiner, and flows north to Livingston before turning east toward Billings.

The climate of the upper Yellowstone River Valley is typical of western Montana intermontane basins, with cold winters and mild summers. Based on PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate data between 1990 and 2020, average annual precipitation is 16.2 in/yr in Livingston and 12.5 in/yr in Gardiner. The surrounding mountains receive significantly more precipitation than the valley floor, with some high-elevation areas receiving more than 50 in/yr; the valley floor receives about 15 in/yr based on precipitation data near Pray, MT (Climate Engine, 2022; fig. 2). The majority of groundwater recharge is from mountain-snowpack melt and subsequent leakage from rivers and tributary streams in the late spring.

While census data specific to the Upper Yellowstone River Valley are not available, Park County had a total population of 17,473 in 2021, which includes the city of Livingston, population 8,040 (Montana Department of Commerce, 2022). The area's proximity to Yellowstone National Park and the city of Bozeman has led to increasing development over the past 30 yr. Most people rely on groundwater for water supplies; the town of Gardiner is the only municipal water system in the valley. As a result, the reported well use in the study area is predominantly domestic (86%); other uses include stockwater, irrigation, public water supply, and commercial/industrial (fig. 3). According to MBMG's Ground Water Information Center (GWIC; http://mbmggwic.mtech.edu), there are over 2,300 wells in the valley, the majority (73%) of which are completed in basin-fill sediments on the valley floor (GWIC, May 2022). Along the valley margins and in the mountainous regions of the Gallatin and Absaroka ranges, wells are completed in fractured-bedrock aquifers that have lower storage capacities and higher variability of well depths and yields than the basin-fill aquifers.

MAP CONSTRUCTION AND DATA SOURCES

Aquifer boundaries were derived from the preliminary geologic map of Paradise Valley (Lopez and Reiten, 2003), as well as 1:100,000-scale geologic maps of the Livingston and Gardiner quadrangles (Berg and others, 1999, 2000). Cross-sections were derived from Lopez and Reiten (2003), Berg and others (1999, 2000), Crowley and others (2017), and from well logs on file at MBMG's Ground Water Information Center (GWIC, 2022). The geology of the Paradise Valley is complex and has been extensively studied, beginning with exploration by the Hayden Survey in the late 1800s, which resulted in publication of the first U.S. Geological Survey (USGS) Geological Folio (Iddings and Weed, 1894). Subsequent studies have included more detailed mapping of the Gallatin and Absaroka

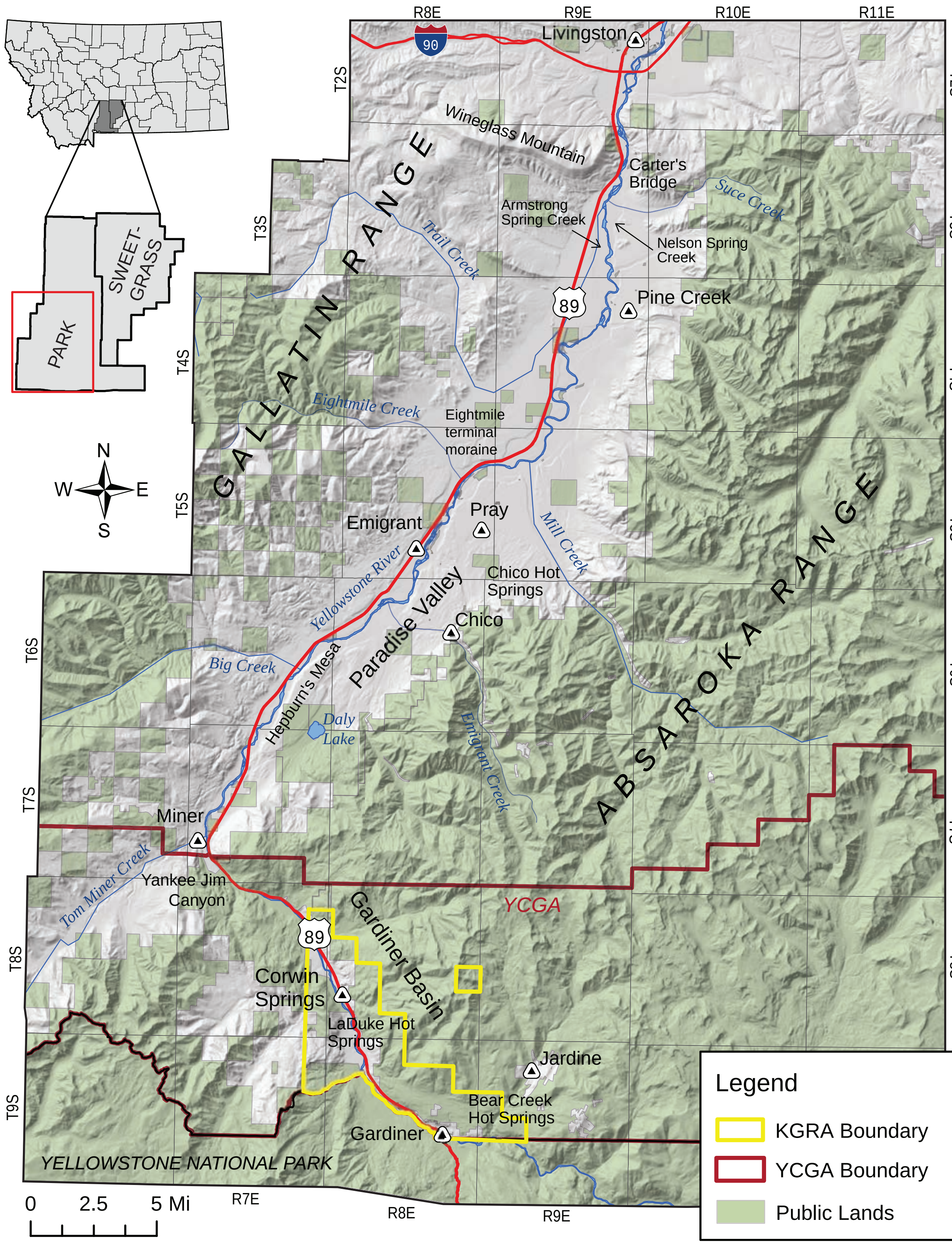

Figure 1. The study area covers the part of the Upper Yellowstone River Valley from Gardiner in the south to Carter's Bridge (upstream of Livingston) to the north. The valley north of Yankee Jim Canyon is commonly referred to as the "Paradise Valley"; south of Yankee Jim to Gardiner is described as the "Gardiner Basin." Notable landmarks referenced in this pamphlet are shown. KGRA, Known Geothermal Resource Area; YCGA, Yellowstone Controlled Groundwater Area.

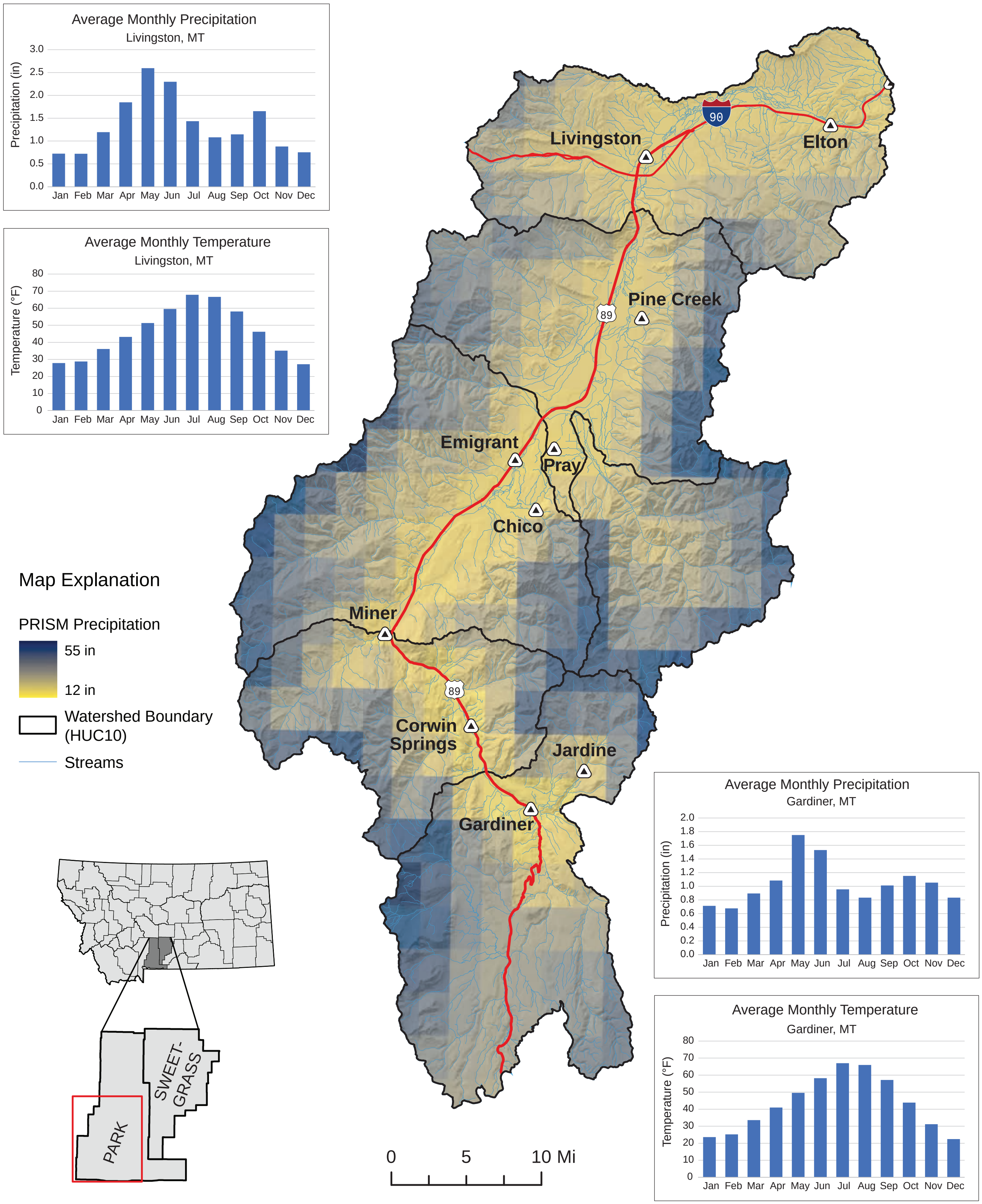

Figure 2. Average annual PRISM precipitation data from 1990 to 2020 for the Upper Yellowstone River Valley watershed area (Climate Engine, 2022). Values range from 12 in near Gardiner to more than 50 in in high-elevation areas of the Gallatin and Absaroka Ranges. Monthly average precipitation and temperature are shown for the towns of Livingston and Gardiner.

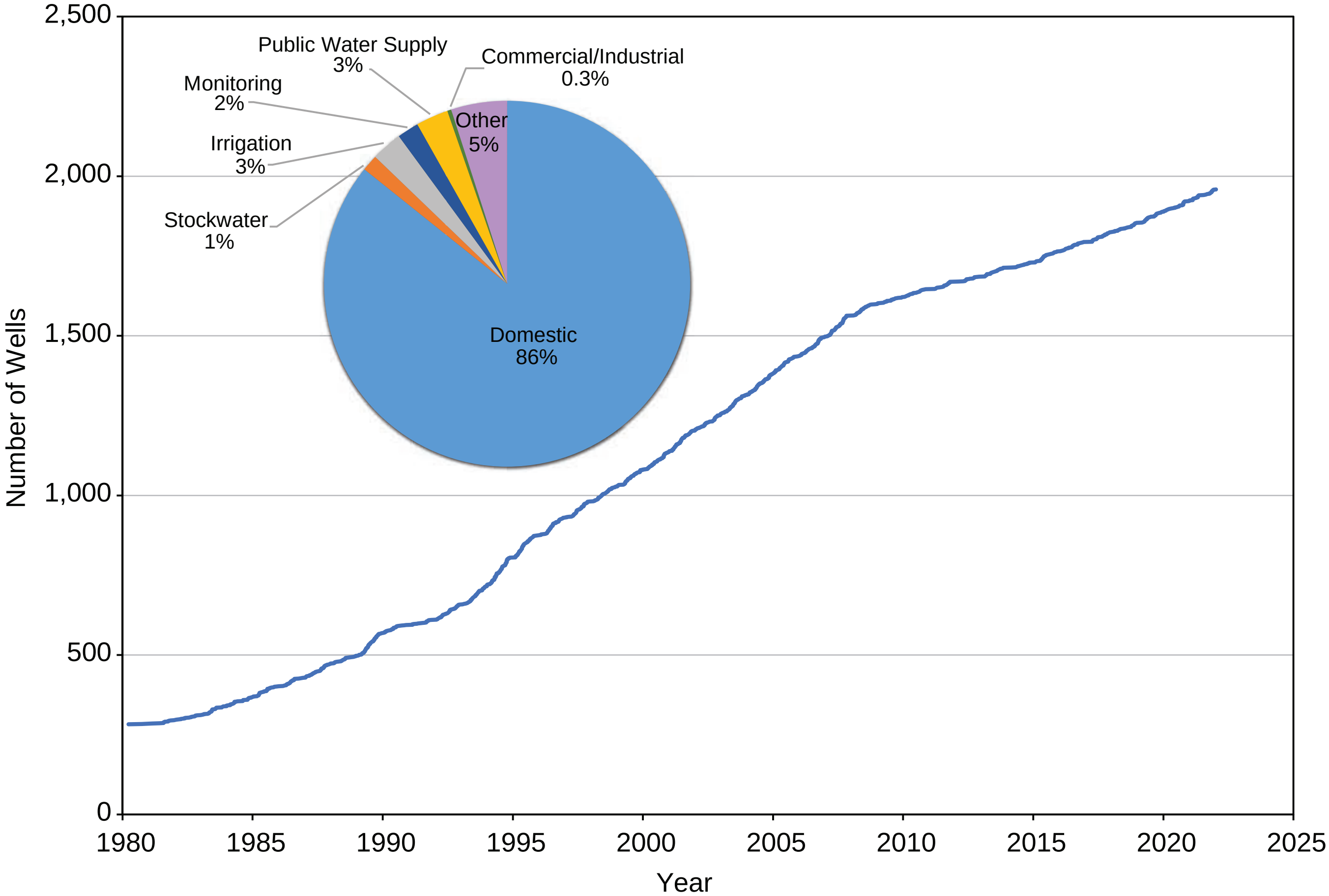

Figure 3. Pie diagram showing percentage of wells by use as designated in GWIC (http://mbmggwic.mtech.edu), and a graph showing the cumulative number of domestic wells drilled in the study area from 1980 to 2021. Similar to other areas in Montana, the number of wells increased sharply beginning in the mid-1990s, with the total number of domestic wells reaching 1,979 in 2022. The majority of wells in the valley (86%) are for domestic use; other uses include public water supplies, irrigation, and stockwater.

ranges (Wilson and Elliott, 1997; Van Gosen and others, 2000; Simons and others, 1985; Chadwick, 1982; Reid and others, 1975; Mogk and others, 1988; Van Voast, 1964); mapping of the Livingston and Gardiner 1:100,000 quadrangles (Berg and others, 1999, 2000; Lopez and Reiten, 2003); examination of the stratigraphy and depositional history of Tertiary volcanics in the Yellowstone area (Smedes and Prostka, 1972); and interpretation of the unconsolidated Quaternary glacial and alluvial deposits that fill the valley floor (Pierce, 1979; Licciardi and Pierce, 2018).

Source aquifer determinations (GWIC aquifer codes) were made for 2,303 wells on file in GWIC; these records were used to summarize well depths and yields for the different aquifers in the valley. Well logs with partial or incomplete records were used where appropriate; the total number of wells evaluated for each statistic in this report may vary based on available information on the well logs.

GEOLOGY

The geologic setting of the upper Yellowstone Valley, and the Paradise Valley in particular, are typical of western Montana intermontane basins, where the valley has been structurally downdropped relative to the surrounding mountains and filled with unconsolidated to poorly consolidated sediments (Kendy and Tresh, 1996). The following discussion focuses primarily on the Paradise Valley.

Structurally, the Paradise Valley has been affected by Sevier–Laramide style compression (folding; thrust faulting/reverse faulting), Basin-and-Range extension (normal faulting), and migration of the Yellowstone Hotspot into the area. It is a NE-striking valley primarily controlled by the Deep Creek fault system along the east margin of the valley, which forms a half-graben structure that produces the topographic relief between the Absaroka–Beartooth mountains and the upper Yellowstone River Valley (Wu, 1995; Van Voast, 1964). Exposed bedrock on the east and west sides includes Archean and Proterozoic metamorphic rocks, and Tertiary volcanics of the Absaroka Supergroup. Cambrian through Cretaceous sedimentary rocks occur in the northwest end of the valley and in the Gardiner Basin.

Late Pleistocene glaciation, also known in the Rocky Mountains as the Pinedale glaciation, has influenced the composition and distribution of basin-fill deposits in the Paradise Valley. Northward-flowing glaciers advanced down the valley from present-day Yellowstone National Park during the Middle Pinedale glaciation [18 to 16 thousand years ago (ka)] as part of the northward expansion of the Greater Yellowstone Glacial System (Licciardi and Pierce, 2018). The northernmost extent of the last glacial advance reached the confluence of Eightmile Creek and the Yellowstone River, approximately 3 mi north of Emigrant (fig. 1). This was the largest extent of glaciation in the Paradise Valley; this advance eroded or covered most deposits from previous glacial advances during the early Pinedale and Bull Lake glaciations. Some remnants of Bull Lake glacial deposits remain within mountain valley drainages that contained localized glaciers, especially along the eastern margin of the valley near Pine Creek, where glaciofluvial alluvial fans are present at the mouth of the drainages. The last advance of glacial ice receded from the valley relatively rapidly, and was completely gone by 14 ka (Licciardi and Pierce, 2018). The glaciation filled much of the valley floor with till, and left well-developed terminal and medial moraines near Emigrant and Chico that are composed of poorly sorted cobble–boulder till. North of the moraine, on the west side of the Yellowstone River, is an outwash plain that is about 200 ft above the modern Yellowstone River.

The till and outwash deposits, alluvium from the Yellowstone River and its tributaries, and some limited Tertiary sediments constitute the unconsolidated "basin-fill" materials that have filled the valley. The Quaternary glacial deposits and alluvium are underlain by either Tertiary sediments or bedrock. The total thickness of the basin-fill is unknown and is likely variable throughout the valley, but the deepest water wells penetrate depths up to 400 ft.

HYDROGEOLOGY

Groundwater in the Paradise Valley occurs in bedrock and basin-fill sediments. The bedrock aquifers are utilized in the mountainous regions and along the valley margins, while basin-fill aquifers dominate the valley bottom. Well records on file in the GWIC database show the majority of wells (73%) are completed in the unconsolidated Quaternary basin-fill sediments; the rest are in fractured or sedimentary rock aquifers (fig. 4). The smaller proportion of fractured/sedimentary rock wells is in part due to the distribution of public lands with respect to the presence of bedrock (fig. 5). Exposed bedrock is most prominent in mountainous areas, which are predominantly public land; as a result, most of the area's population is concentrated on the valley floor, where basin-fill sediments are the primary aquifer. The Absaroka Volcanics are stratigraphically the first bedrock unit beneath the basin-fill, which likely explains the higher proportion of bedrock wells completed in this unit (about 50%).

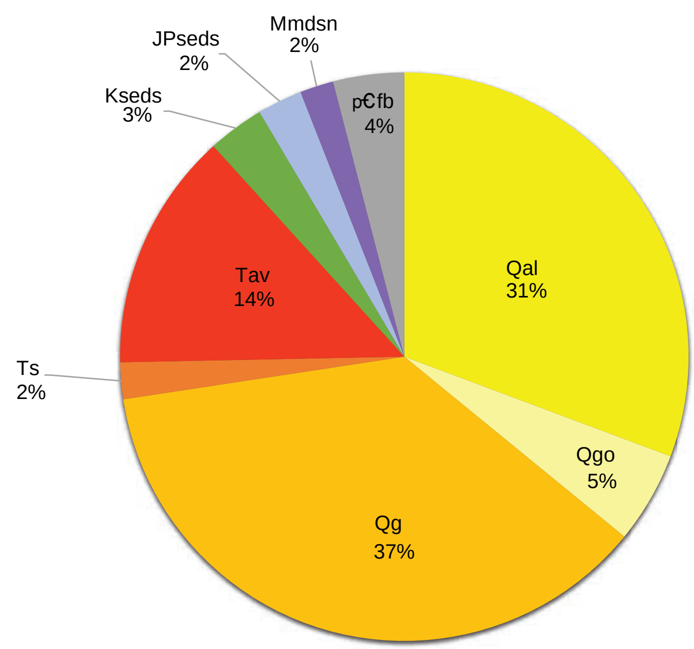

Figure 4. Distribution of wells by aquifer. The majority (73%) of wells are completed in unconsolidated basin-fill deposits, which includes Yellowstone River alluvium and Pleistocene-age glacial drift and outwash.

Basin-Fill Aquifers

Basin-fill aquifers consist of unconsolidated or semi-consolidated sediments deposited by rivers (alluvium) or glaciation (glacial till and outwash). Basin-fill aquifers are located in valley bottoms, sometimes directly overlying bedrock; groundwater occurs under unconfined conditions in the surficial deposits, and

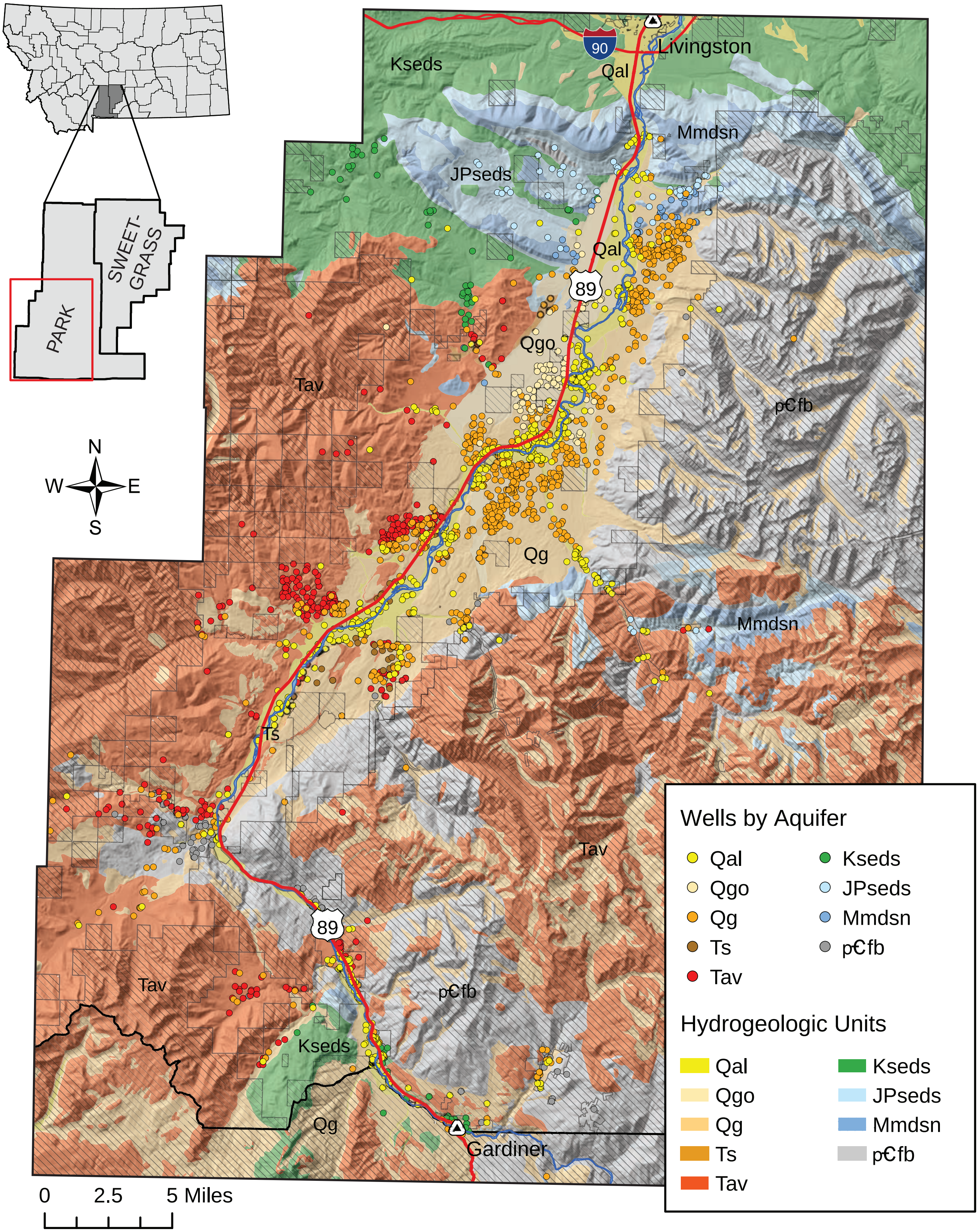

Figure 5. Distribution of wells by aquifer plotted with respect to hydrogeologic units and public lands (hatched). Qal, Alluvium; Qgo, Glacial outwash; Qg, Glacial drift; Ts, Tertiary sediments; Tav, Absaroka Volcanics; Kseds, Cretaceous sedimentary rocks; JPseds, Jurassic through Paleozoic sedimentary rocks; Mmdsn, Madison Limestone; pЄfb, Precambrian metamorphic rocks.

confined to semi-confined conditions at depth where low-permeability layers of silt and clay cap deeper sand/permeable layers. Surficial deposits are often connected to local surface-water features, and their unconfined nature makes them more susceptible to contamination and impacts from drought.

Alluvium (Map Unit, Qal; Aquifer Codes, 110ALVM and 111ALVM)

Yellowstone River flooding and channel migration have produced alluvial deposits of sand and gravel, with some clay and boulders, up to 150 ft thick, generally within the confines of the floodplain, which contains a surficial, unconfined aquifer. The length of time the river has flowed through the Paradise Valley is not well constrained, but the river existed prior to, during, and after Pleistocene glaciation and therefore alluvial deposits can be difficult to differentiate from glacial deposits in some areas.

The thickness of the alluvium decreases northward as the valley narrows and the bedrock ramps up to the surface, creating a “pinch point” at the bedrock canyon south of Livingston, near Carter’s Bridge (fig. 1). The constriction and thinning of alluvium causes groundwater to be forced up to the surface, as evidenced by the presence of several springs (Armstrong Spring Creek and Nelson Spring Creek, fig. 1) at the north end of the valley (Clarke, 1991; Locke and others, 1995).

The Quaternary alluvium includes modern (Holocene) Yellowstone River deposits, as well as older river alluvium and terrace deposits that consist of sand and gravel with some clay and boulders; drillers report that heaving sands are common. Groundwater in the Quaternary alluvial aquifer is unconfined and shallow, with a median well depth of 65 ft below ground surface (bgs; fig. 6) and a median yield of 35 gpm (fig. 7); it is the most productive aquifer in the Paradise Valley. Thirty-one percent of wells in the study are completed in the Quaternary alluvium (figs. 4, 8). Alluvial terrace deposits are present along the Yellowstone River channel; these deposits are up to 40 ft thick and are grouped as Quaternary alluvium because wells present in the terrace deposits are typically screened at depths greater than 40 ft.

Pleistocene Glacial Deposits (Map Units, Qg and

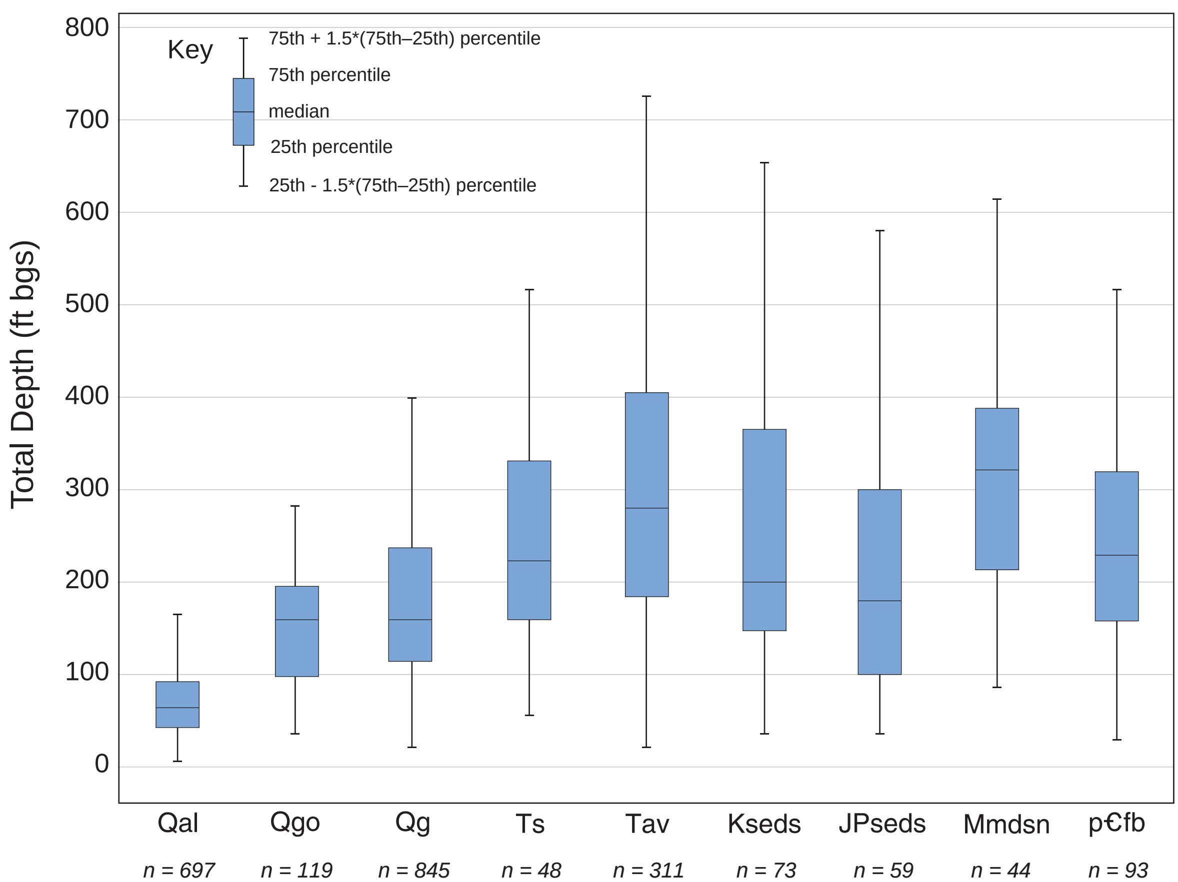

Figure 6. Total well depth by aquifer. Fractured bedrock wells are typically deeper than basin-fill wells, and show more variability due to the variable distribution and connectivity of fractures (secondary permeability).

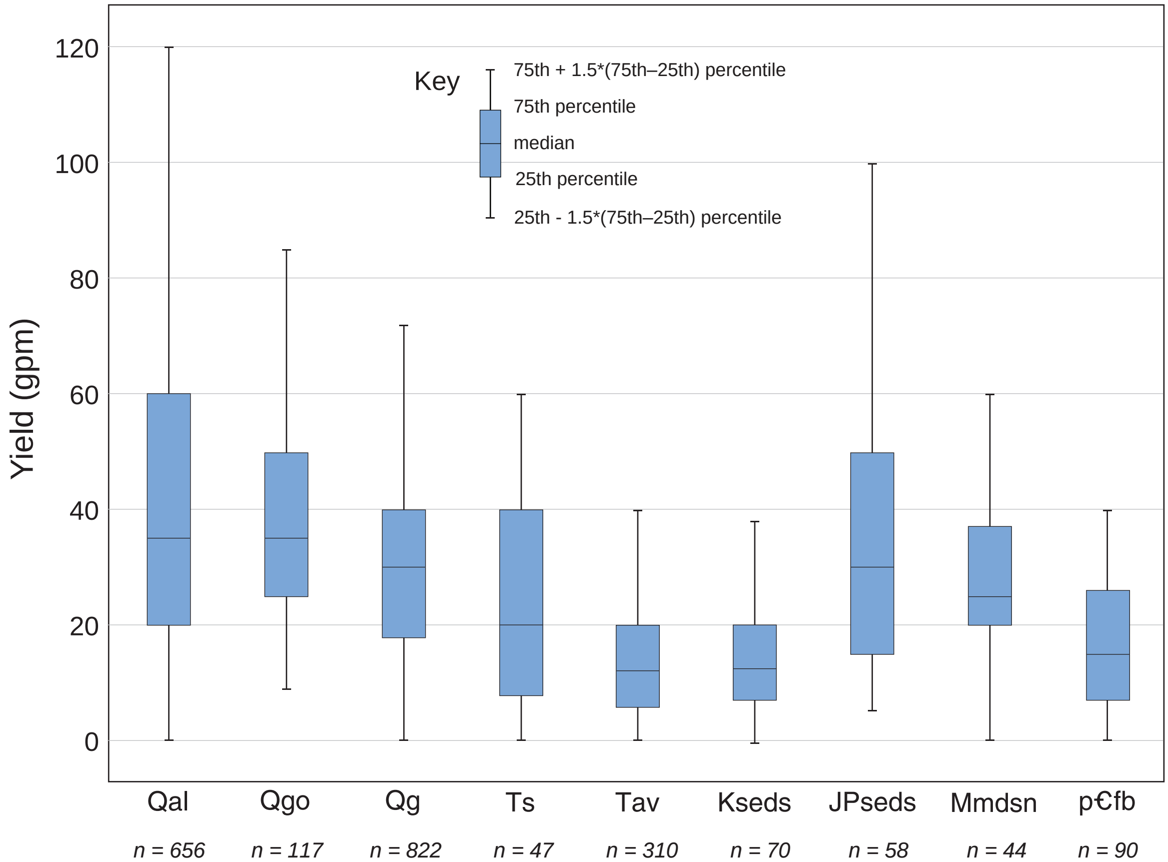

Figure 7. Yields by aquifer. Basin-fill aquifers have overall higher yields because of the unconsolidated nature of the aquifer, and generally higher proportions of coarse-grained materials (such as sand and gravel), produce higher yields.

Qgo; Aquifer Codes, 112DRFT and 112OTSH)

Glacial deposits are widespread throughout the valley and are more than 400 ft thick in some areas based on well logs. The glacial deposits (Qg) are termed “glacial drift,” which includes till, glaciofluvial alluvial fans, and some Pleistocene-age terrace deposits (Locke and others, 1995). The glacial drift consists of non-stratified, claybound gravel and boulders with localized layers of clay, sand, and gravel. Wells are typically completed in the sand and gravel lenses; the lateral connectivity and extent of these lenses is variable and difficult to map out in the subsurface. Drift deposits host the largest percentage of wells in the Paradise Valley (37%; figs. 4, 9), and are generally productive, with yields ranging up to 72 gpm, with a median of 30 gpm (fig. 7). Well depths range from 22 to 400 ft bgs with a median of 159 ft bgs (fig. 6).

The outwash plain (Qgo) deposited north of the Eightmile Creek terminal moraine along the west side of the Yellowstone River (fig. 1) forms a distinct sand and gravel deposit that, although limited to the northwest part of the valley, hosts a productive aquifer for residences in that area; 5% of wells in the study area are completed in the outwash (figs. 4, 9). The Eightmile Creek outwash plain is distinct from other drift deposits because of the larger proportion of sand and gravel and resulting higher yields (median of 35 gpm, but ranging up to 85 gpm; fig. 7). The outwash is thickest (approximately 300 ft) near the Eightmile terminal moraine and thins northward until it pinches out at the entrance to the canyon south of Livingston. Well depths range from 36 to 283 ft bgs, with a median of 158 ft (fig. 6). While the Eightmile outwash primarily consists of sand and gravel, clay content increases with increasing distance (northward) from the terminal moraine.

Tertiary Sediments (Map Unit, Ts; Aquifer Code, 120SDMS)

Tertiary sediments are exposed in the Hepburn’s Mesa area (figs. 1, 4, 10), where they are overlain by gravel, basalt, and glacial till. They consist of white or light tan, poorly bedded siliceous siltstone and claystone (Van Voast, 1964); fossil records indicate these sediments were deposited during the late Miocene or early Pliocene. Wells completed in these sediments are

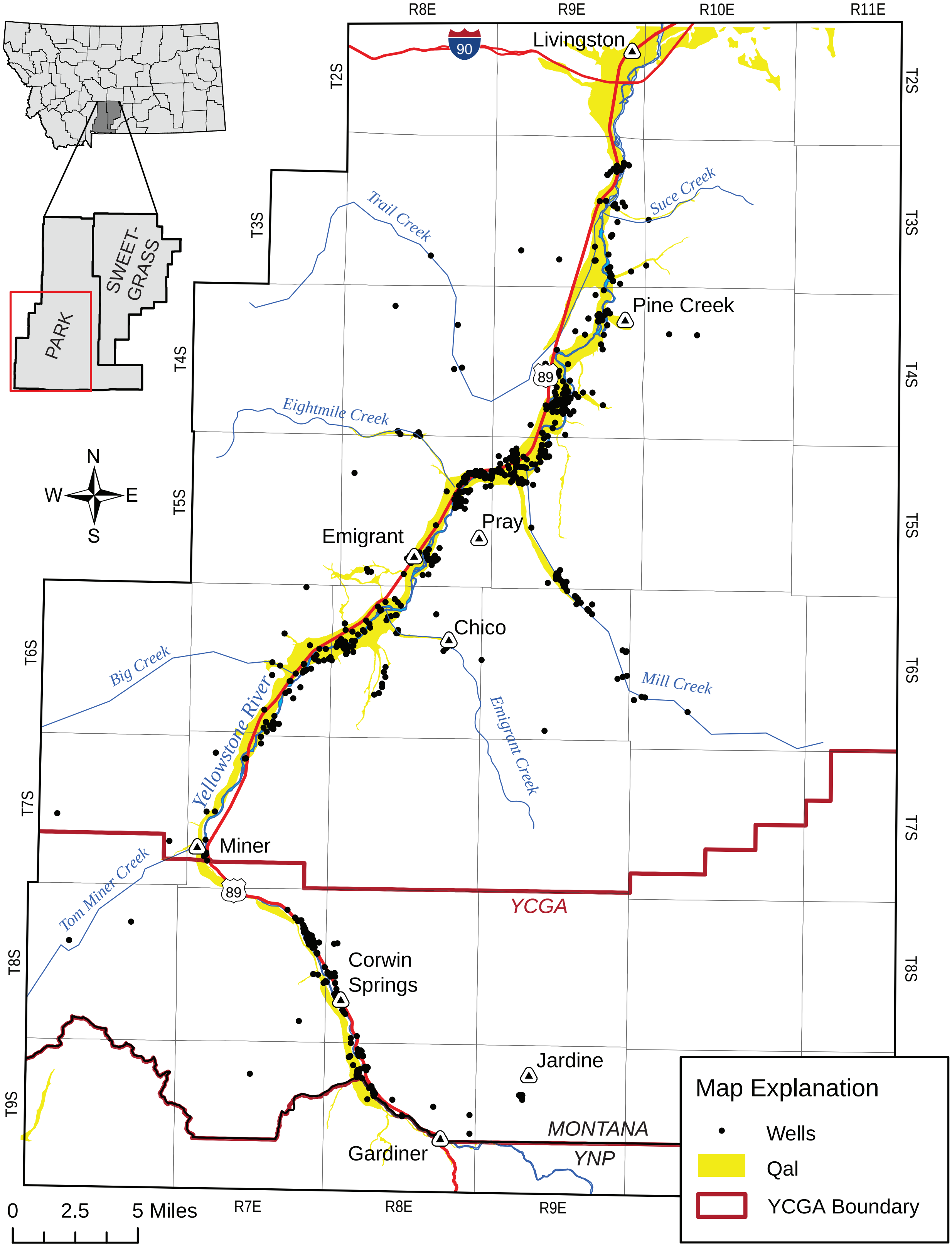

Figure 8. Distribution of wells screened in Quaternary alluvium (Qal), mapped in yellow. Most wells are completed near the Yellowstone River or its tributaries; wells located outside the mapped alluvium are completed in unmapped alluvial deposits.

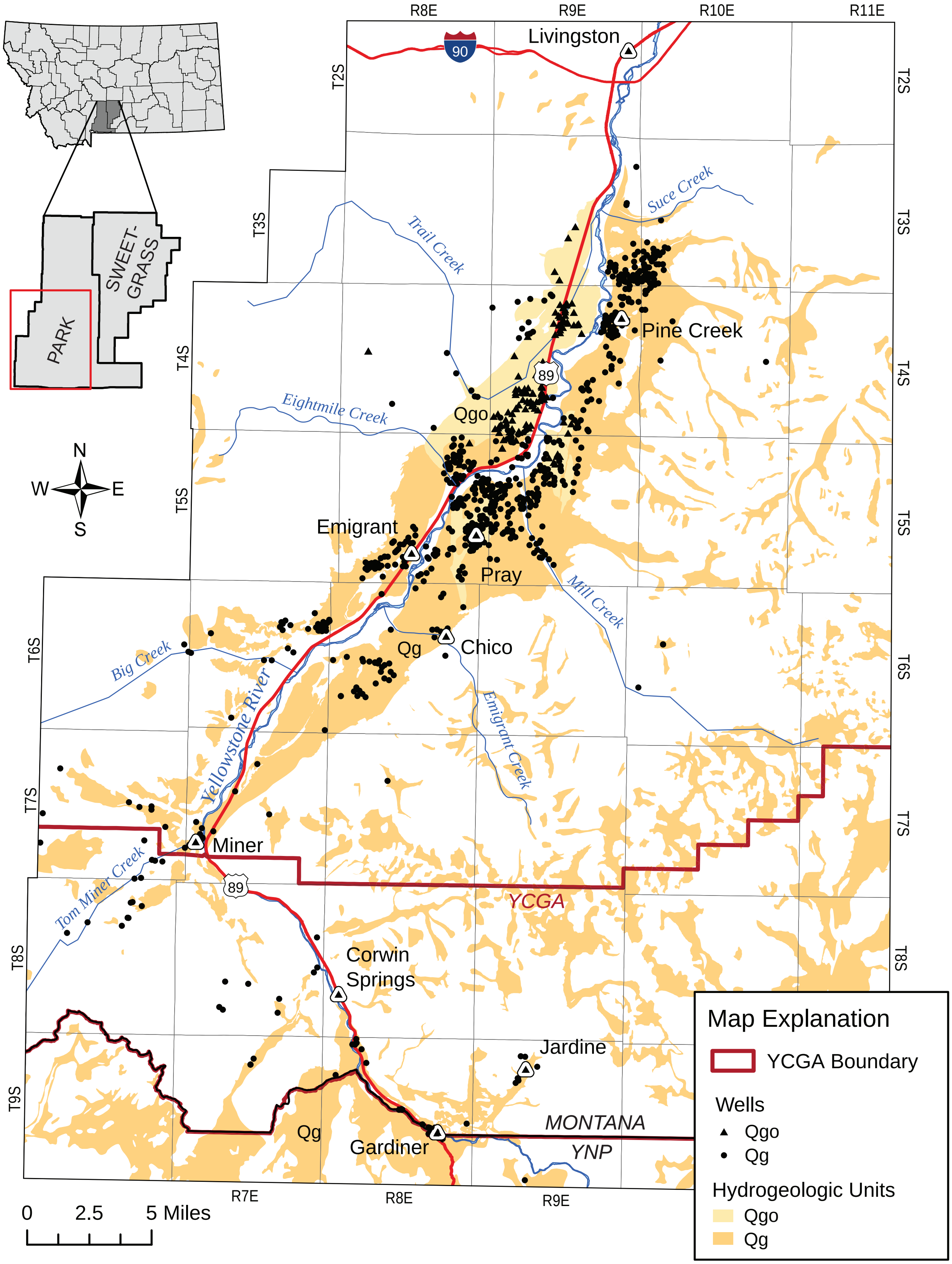

Figure 9. Distribution of wells screened in Pleistocene glacial deposits, mapped in dark yellow (glacial drift; Qg) and light yellow (glacial outwash; Qgo). Wells located outside the mapped glacial deposits are completed in areas where the glacial deposits are located in the subsurface (overlain by a different unit).

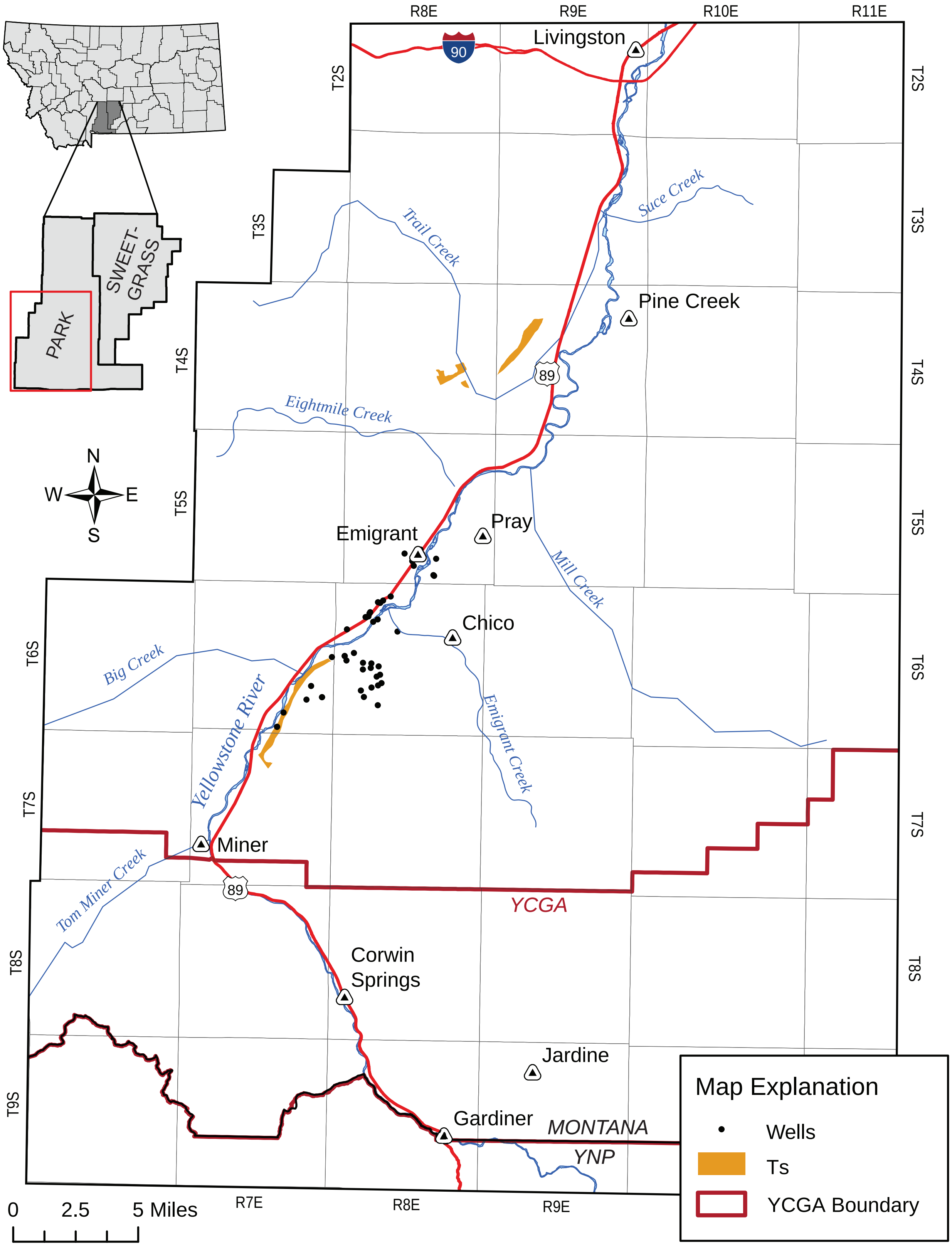

Figure 10. Distribution of wells screened in Tertiary sediments (Ts), mapped in orange. Wells located outside the mapped sediments are completed in areas where the sediments are present at depth (overlain by glacial deposits, alluvium, or in the Hepburn's Mesa area, volcanics).

limited to the area near Hepburn's Mesa. The subsurface extent of these deposits is unknown, but Pleistocene glaciation likely eroded much of the Tertiary basin-fill. The deposits near Hepburn's Mesa may have been protected from this erosion by the overlying basalt. Because most wells are able to produce sufficient water from the overlying Quaternary basin-fill aquifer, few wells are completed in the deeper Tertiary sediments, and therefore the extent is not well documented. A petroleum exploration well drilled northwest of Pray (GWIC ID 325740) reports "volcanics" at 800 ft bgs; personal communication with onsite personnel described 243 m (800 ft) of alluvium followed by 457 m (1,500 ft) of "white tuff" (Locke and others, 1995). It is unknown whether this tuff is the same deposit described at Hepburn's Mesa.

Only 2% of wells in the Paradise Valley are completed in Tertiary sediments (figs. 4, 10). Well depth ranges from 57 to 518 ft bgs, with a median of 223 ft (fig. 6). Yields are slightly lower than other aquifers in the study area, with a median of 20 gpm (fig. 7).

Bedrock Aquifers

Fractured-rock aquifers occur in crystalline (volcanic, igneous, metamorphic) bedrock that is characterized by fracture (secondary) permeability resulting in lower inherent storage capacity as compared to aquifers with intergranular (primary) permeability; wells completed in fractured-rock aquifers typically have variable well depths and lower yields. Sedimentary bedrock aquifers often have a combination of intergranular (primary) and fracture (secondary) permeability.

In the study area, the crystalline metamorphic rock aquifer is characterized by fracture permeability. The volcanic rock aquifer is mainly characterized by fracture permeability, but brecciated textures observed in this unit may contribute some intergranular permeability. However, no distinct differences in yield were observed between the metamorphic and volcanic rocks.

Igneous and Metamorphic Bedrock Aquifers

Volcanics (Map Unit, Tav; Aquifer Code, 124ABSK)

Tertiary volcanism in northwestern Wyoming and southwestern Montana deposited the Absaroka Volcanic Supergroup, which is present in the Gallatin and Absaroka ranges surrounding the Paradise Valley and likely occurs below Quaternary and Tertiary sediments on the valley floor. The volcanic units of hydrogeologic interest consist of Eocene dacites, the Hyalite Peak Volcanics, and the Golmeyer Creek Volcanics; these units are all part of the Washburn Group of the Absaroka Volcanics, which extends into the northern part of Yellowstone National Park (Smedes and Prostka, 1972). Lithology of the volcanics varies by unit, but generally consists of dacitic or andesitic flows, dikes, sills, porphyries, and breccias.

Fourteen percent of wells in the Paradise Valley are completed in the Absaroka Volcanics (figs. 4, 11), with a median depth of 280 ft bgs (fig. 6); however, well depth ranges up to 700+ ft, reflecting the variable permeability and topographic relief associated with the volcanics. In some areas, wells are completed through surficial deposits of glacial drift into the underlying volcanics. Yields from wells completed in the volcanics are generally lower than those in other aquifers in the valley, ranging up to 40 gpm with a median of 12 gpm (fig. 7).

Proterozoic/Archean Metamorphic (Crystalline) Bedrock (Map Unit, p₵fb; Aquifer Code, 500GNSC)

Much of the bedrock on the east side of the Paradise Valley consists of Archean granitic and metasedimentary rocks as old as 3.6 billion yr, known as the North Snowy Block. These highly deformed rocks occupy a structural boundary that separates the Archean granitic rocks in the Beartooth and Bighorn Mountains to the east from the metasedimentary rocks and gneisses to the west (Locke and others, 1995). This fractured-rock aquifer consists of mylonite, granite gneiss, biotite–schist, amphibolite, quartzite, and marble. Drill logs sometimes describe these units as "black granite."

Approximately 4% of wells in the Paradise Valley are completed in this unit (figs. 4, 11). Total depth ranges from 28 to 520 ft bgs, with a median depth of 230 ft (fig. 6). The fracture permeability results in relatively low well yields; the median is 15 gpm (fig. 7).

Sedimentary Rock Aquifers

Cretaceous Sedimentary Rocks (Map Unit, Kseds; Aquifer Code, 210UDFD)

Sedimentary rocks of upper and middle Cretaceous age are limited to the mountainous areas of the northwest and south parts of the study area. These units include the Landslide Creek Formation, Everts Forma-

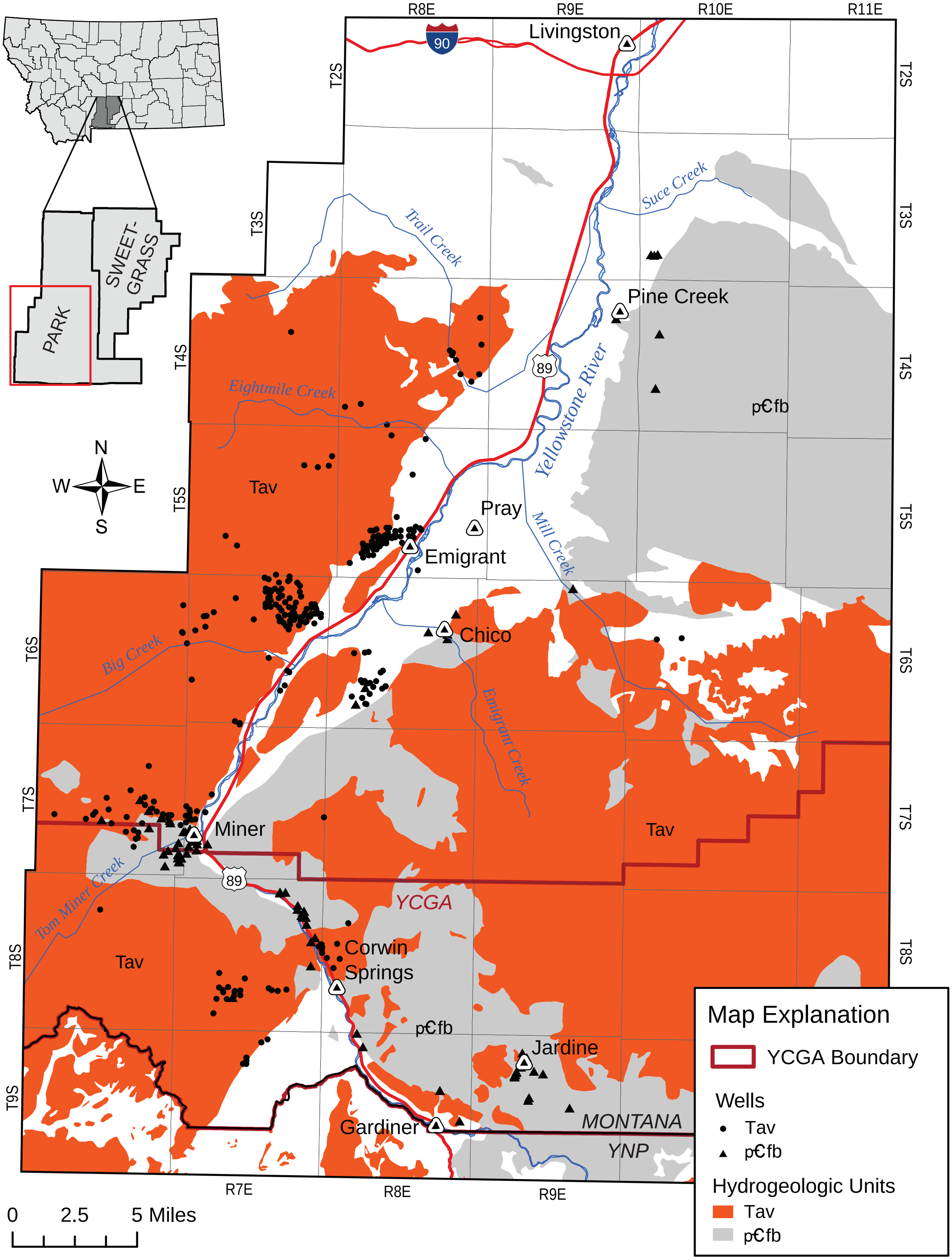

Figure 11. Distribution of wells screened in the Absaroka Volcanics (Tav), mapped in red, and Precambrian metamorphic rocks (p€fb), mapped in gray. Wells located outside the mapped volcanics are completed in areas where the volcanics are present at depth, typically overlain by younger glacial deposits or alluvium.

tion, Eagle Sandstone, Telegraph Creek Formation, Cody Shale/Frontier Formation, Mowry Shale through Fall River Sandstone (undivided), and the Kootenai Formation. The Landslide Creek and Everts Formations are only present in the Gardiner area in the south part of the study area. Lithologies of the Cretaceous sedimentary rocks include alternating layers of sandstone, siltstone, mudstone, claystone, shale, and (within the Eagle Sandstone) coalbeds. The total thickness of these combined units is over 6,000 ft (Lopez and Reiten, 2003). Because these units are highly faulted and folded, and because the lithology of the units are generally similar, it is difficult to differentiate between the individual units based on well logs. Therefore, this sequence of Cretaceous sedimentary rocks is grouped as one aquifer; most groundwater production is likely sourced from sandstone units within this series.

Approximately 3% of wells are completed in the Cretaceous sedimentary aquifer (figs. 4, 12). Well depths range up to 650+ ft, with a median depth of 200 ft bgs; the combination of intergranular and fracture porosity contributes to the wide range of well depths (fig. 6). Well yields are generally low, with a median of 12.5 gpm (fig. 7). The well depth and yield statistics are comparable to the Absaroka volcanics wells, which are close to and sometimes overlie the Cretaceous sediments.

Jurassic–Paleozoic Sedimentary Rocks (Map Unit, JPseds; Aquifer Codes, 220UDFD and 300UDFD)

Jurassic through Paleozoic sedimentary rocks in the study area are indistinguishable as individual aquifers and are therefore grouped together; the exception is the Madison Limestone, which is discussed separately below. The Morrison Formation and underlying Ellis Group constitute the sequence of Jurassic sedimentary rocks that are present along the north end of the valley near Pine Creek, and up Mill Creek (fig. 13). The Ellis Group includes interbedded shales, limestones, and calcareous sandstones; the Morrison consists of mudstone, interbedded shales, limestones, and calcareous sandstone. Groundwater is present in the sandstone intervals within these sequences. Thickness of the Ellis Group is approximately 500 ft; the Morrison is about 200 ft.

Paleozoic sedimentary rocks cover a large timespan, from 250 to 543 Ma. Geologically, the rocks can be grouped into Upper Paleozoic/Permian–Pennsylvanian (Phosphoria, Quadrant, and Amsden Formations); Middle Paleozoic/Mississippian (Madison Limestone); Middle Paleozoic/Devonian–Ordovician (Three Forks and Jefferson Formations, Bighorn Dolomite); and Lower Paleozoic/Cambrian (Pilgrim, Park, Meagher, Wolsey, and Flathead Formations). Total thickness is up to 3,000 ft.

Only 2% of wells are completed in Jurassic–Paleozoic sedimentary rocks (figs. 4, 13); this number does not include the Mississippian Madison Limestone, which is discussed separately below. These wells are concentrated in the northernmost part of the study area, along Suce Creek and the south flank of Wineglass Mountain (fig. 1). Total depths range from 40 to 580 ft bgs, with a median of 180 ft (fig. 6). Median yield is 30 gpm, ranging up to 100 gpm (fig. 7).

Madison Limestone (Map Unit, Mmdsn; Aquifer Code, 330MDSN)

The Madison Limestone is 800–1,000 ft thick and crops out in the north part of the Paradise Valley where the geologic structure is dominated by thrust faulting and folding, resulting in bedrock units that are tipped up on end and dipping into the subsurface. Lithology consists of limestone and dolomitic limestone; caves and collapse features are common when exposed at or near the surface (Lopez and Reiten, 2003).

The aquifer typically has good productivity and water quality. Because of its limited exposure, only 2% of wells are completed in this unit (figs. 4, 14); most are in or near outcrop areas. Total well depth ranges from 90 to 620 ft bgs, with a median depth of 322 ft (fig. 6). Yields are good when compared to other bedrock aquifers, with a median of 25 gpm (fig. 7).

Known Geothermal Areas

The Upper Yellowstone River Valley encompasses the Corwin Springs Known Geothermal Resource Area (KGRA; Goodwin and others, 1971; Taylor and Hinds, 1976) and part of the Yellowstone Controlled Groundwater Area (YCGA; English and others, 2021; Metesh, 2000, 2004 fig 1). The YCGA was established in 1994 as a result of a USGS study commissioned by the U.S. Congress that concluded that development of geothermal resources north of the park, within the KGRA, could potentially reduce the discharge of geothermal springs in some areas of the park (English and others, 2021). In cooperation with a Technical

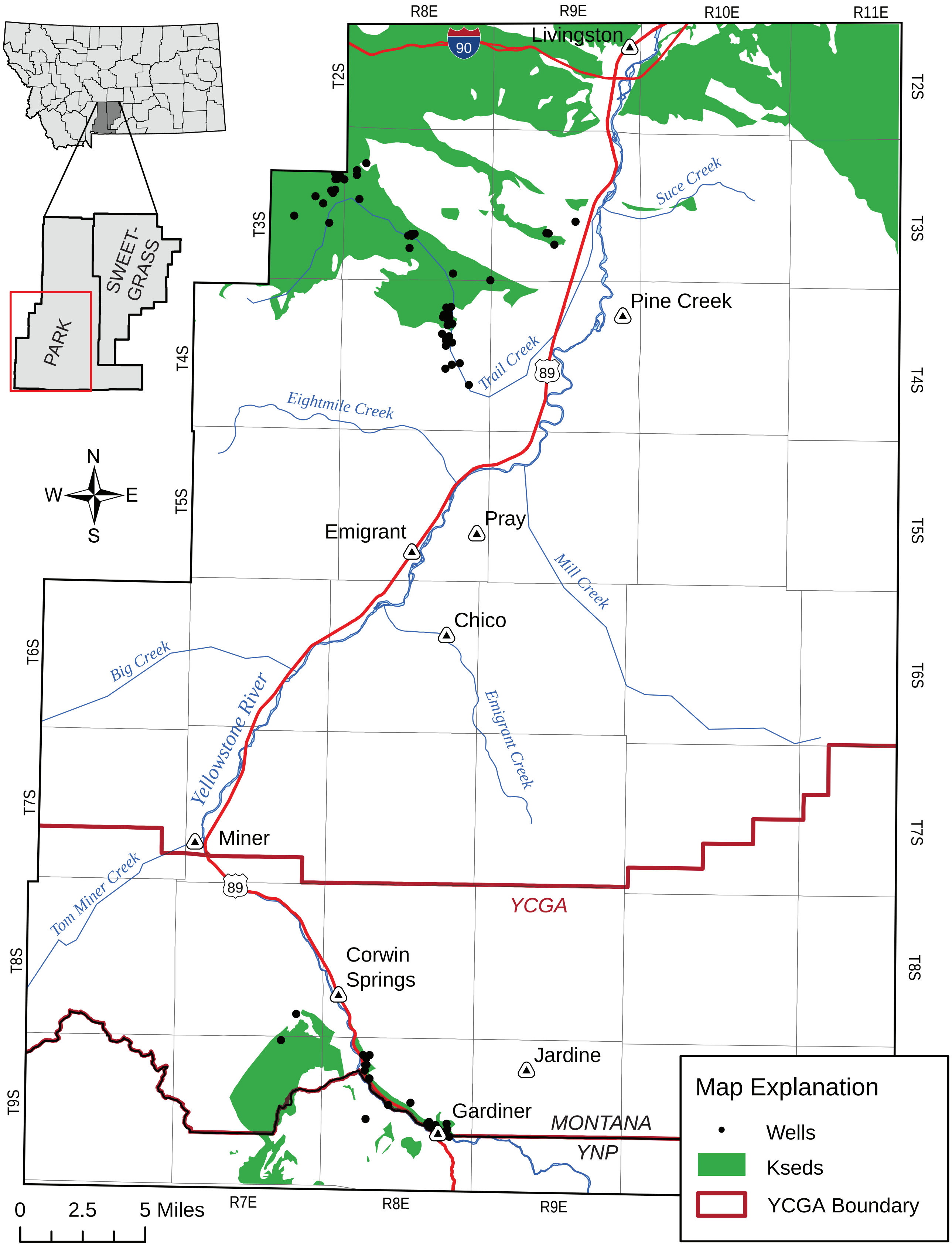

Figure 12. Distribution of wells screened in Cretaceous sedimentary rocks (Kseds), mapped in green. Wells located outside the mapped sedimentary rocks are completed in areas where the rocks are present at depth, overlain by younger units.

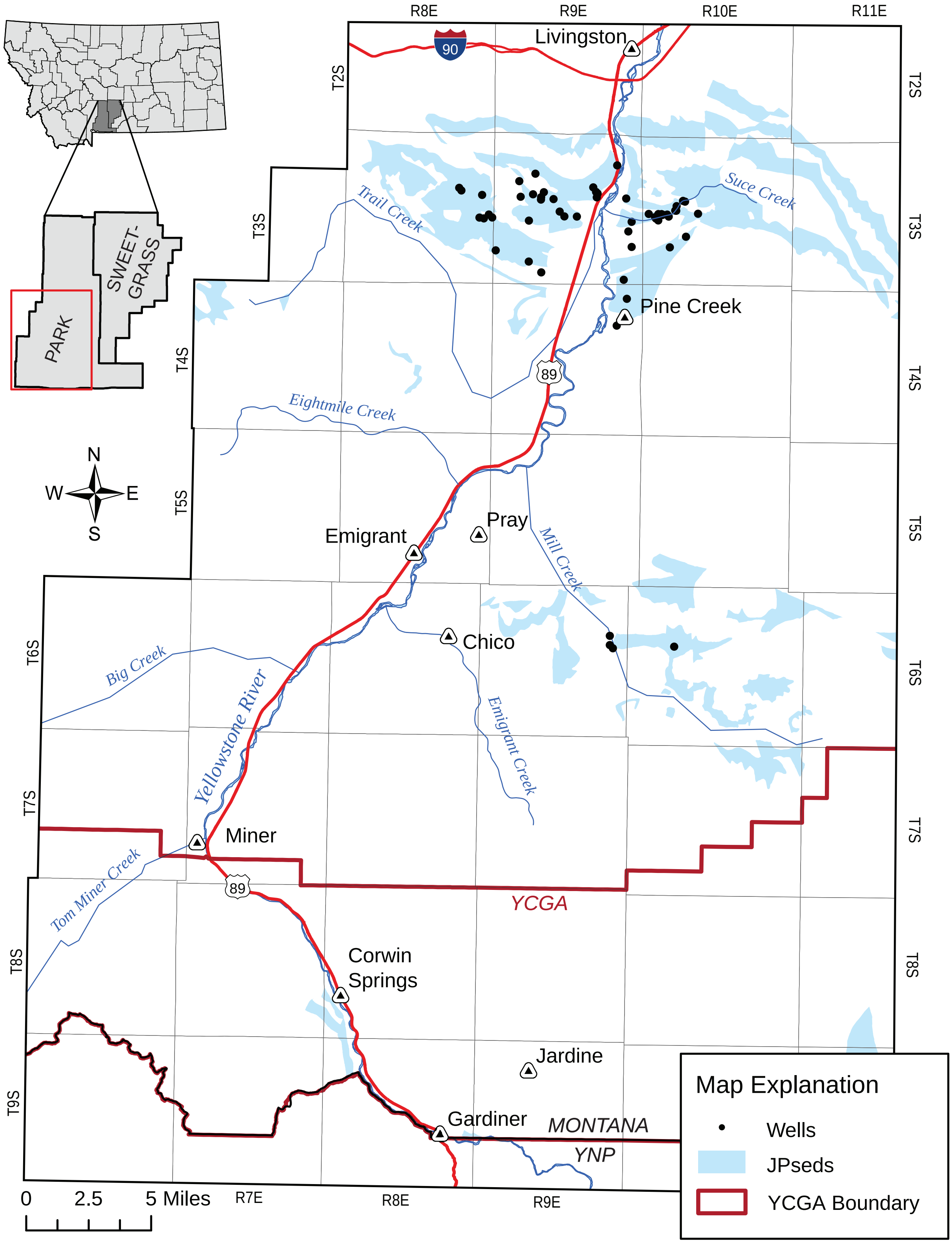

Figure 13. Distribution of wells screened in Jurassic through Paleozoic sedimentary rocks (JPseds), mapped in light blue. Wells located outside the mapped sedimentary rocks are completed in areas where the rocks are present at depth, overlain by younger units.

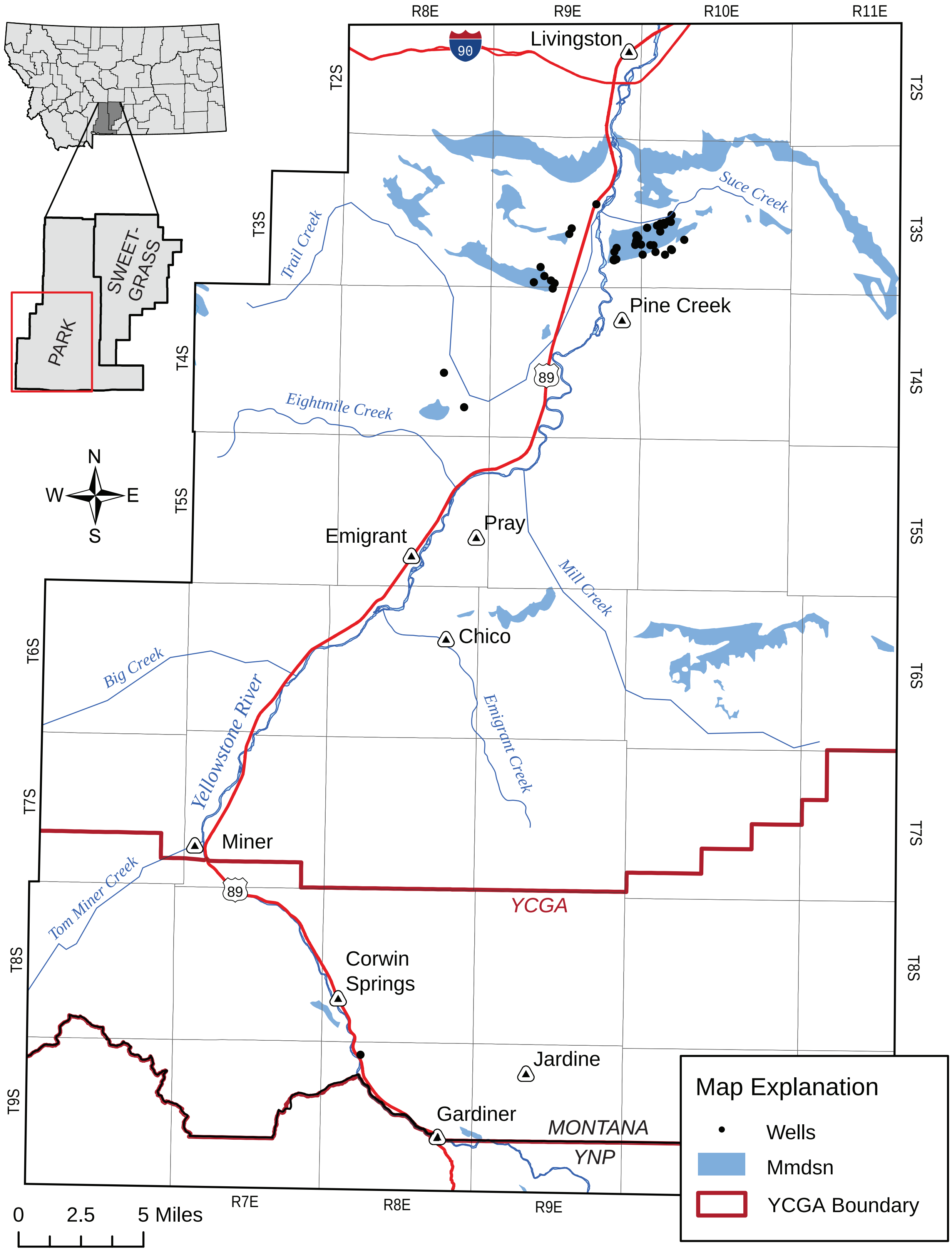

Figure 14. Distribution of wells screened in Madison Limestone (Mmdsn), mapped in blue. Wells located outside the mapped limestone are completed in areas where the rock is present at depth, overlain by younger units.

Oversight Committee, the MBMG operates a long-term monitoring program of select wells and springs in the YCGA.

Two prominent geothermal springs, LaDuke Hot Springs and Bear Creek Hot Springs, are located within the YCGA; another, Chico Hot Springs, is located near the town of Pray (fig. 1). LaDuke Hot Springs is located at the intersection of the NW-trending Gardiner reverse fault and the NE-trending Reese Creek fault. The intersection of these faults provides a flow path for deeply sourced geothermal water, possibly from the Madison Limestone, to discharge at the land surface. Bear Creek Hot Springs is likely sourced from deep fractures in the Madison Limestone and rises to the surface along the Gardiner fault. The Yellowstone magmatic system serves as the likely heat source for these springs (Chadwick and Leonard, 1979; Struhsacker, 1976). Chico Hot Springs may also be sourced from Madison Limestone along the fracture system controlled by the intersection of the E–W-trending Mill Creek fault and a NE-trending range-front fault (Chadwick and Leonard, 1979).

STUDY LIMITATIONS

Descriptions of aquifers and confining units are based on the mapped geology and information reported on drillers' logs. Some errors may exist due to variations in the quality and precision of driller-reported data. However, the large number of well records in this study area support the reliability of information on well and aquifer characteristics presented here. Water well and borehole records are continuously updated in GWIC. Current water well information can be accessed to supplement the data shown here at: http//mbmggwic.mtech.edu.

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REFERENCES

Berg, R.B., Lonn, J.D., and Locke, W.W., 1999, Geologic map of the Gardiner 30′ x 60′ quadrangle, south-central Montana: Montana Bureau of Mines and Geology Open-File Report 387, 11 p., 1 sheet, scale 1:100,000.

Berg, R.B., Lopez, D.A., and Lonn, J.D., 2000, Geologic map of the Livingston 30′ x 60′ quadrangle, south-central Montana: Montana Bureau of Mines and Geology Open-File Report 406, 21 p., 1 sheet, scale 1:100,000.

Chadwick, R.A., 1982, Igneous geology of the Fridley Peak quadrangle, Montana: Montana Bureau of Mines and Geology Geologic Map 31, scale 1:62,500.

Chadwick, R.A., and Leonard, R.B., 1979, Structural controls of hot-spring systems on southwestern Montana: U.S. Geological Survey Open-File Report 79-1333, 25 p.

Clarke, W.D., 1991, Hydrogeology of Armstrong and Nelson Springs, Park County, Montana: Bozeman, Mont., Montana State University, unpublished M.S. thesis, 143 p.

Climate Engine, 2022, available at https://climateengine.com/ [Accessed October 2022].

Crowley, J.J., LaFave, J.I., Bergantino, R.N., Carstarphen, C.A., and Patton, T.W., 2017, Principal aquifers of Montana: Montana Bureau of Mines and Geology Hydrogeologic Map 11, 1 sheet, scale 1:1,000,000.

English, A., LaFave, J.I., and Richter, M., 2021, Yellowstone Controlled Groundwater Area, Montana long-term monitoring program: Data summary report: Montana Bureau of Mines and Geology Open-File Report 743, 126 p.

Goodwin, L.H., Haigler, R.L., Rious, R.L., White, D.E., Muffler, L.J.P., and Wayland, R.G., 1971, Classification of public lands valuable for geothermal steam and associated geothermal resources: U.S. Geological Survey Circular 647, 9 p.

Groundwater Information Center (GWIC), 2022, available at https://mbmggwic.mtech.edu/ [Accessed January 2024].

Iddings, J.P., and Weed, W.H., 1894, Livingston Folio: U.S. Geological Survey Folio 1, Geological Atlas of the United States, 5 p.

Kendy, E., and Tresh, R.E., 1996, Geographic, geologic, and hydrologic summaries of intermontane basins of the northern Rocky Mountains, Montana: U.S. Geological Survey Water Resources Investigations Report 96-4025, 233 p.

Licciardi, J.M., and Pierce, K.L., 2018, History and dynamics of the Greater Yellowstone Glacial System during the last two glaciations: Quaternary Science Reviews, v. 200, p. 1–33.

Locke, W.W., Clarke, W.D., Elliott, J.E., Lageson, D.R., Mogk, D.W., Montagne, J., Schmidt, J.G., and Smith, M., 1995, The middle Yellowstone valley from Livingston to Gardiner, Montana: A microcosm of northern Rocky Mountain geology: Northwest Geology, v. 24, p. 1–65.

Lopez, D.A., and Reiten, J.C., 2003, Preliminary geologic map of Paradise valley, south-central Montana: Montana Bureau of Mines and Geology Open-File Report 480, 22 p., 1 sheet, scale 1:50,000.

Metesh, J.J., 2000, Geothermal springs and wells in Montana: Montana Bureau of Mines and Geology Open-File Report 415, 58 p., 1 sheet.

Metesh, J.J., 2004, Spring inventory, Yellowstone controlled ground-water area: Montana Bureau of Mines and Geology Open-File Report 510, 54 p.

Mogk, D.W., Mueller, P.A., and Wooden, J.L., 1988, Archean tectonics of the North Snowy Block, Beartooth Mountains, Montana: Journal of Geology, v. 96, p. 125–141.

Pierce, K.L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park area: U.S. Geological Survey Professional Paper 729 F, 91 p., 4 plates.

Reid, R.R., McMannis, W.J., and Palmquist, J.C., 1975, Precambrian geology of North Snowy block, Beartooth Mountains, Montana: Geological Society of America Special Paper 157, 1:24,000.

Simons, F.S., Van Loenen, R.E., and Moore, S.L., 1985, Geologic map of the Gallatin Divide Roadless Area, Gallatin and Park Counties, Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF-1569-B, scale 1:62,500.

Smedes, H.W., and Prostka, H.J., 1972, Stratigraphic framework of the Absaroka Volcanic Supergroup in the Yellowstone National Park region: U.S. Geological Survey Professional Paper 729-C, 32 p.

Struhsacker, E.M., 1976, Geothermal systems of the Corwin Springs–Gardiner area, Montana—Possible structural and lithologic controls: Bozeman, Mont., Montana State University, M.S. thesis, 93 p.

Taylor, H.C.J., and Hinds, J.S., 1976, Corwin Springs Known Geothermal Resources Area, Park County, Montana: U.S. Geological Survey Open-File Report 76-293, 28 p.

Van Gosen, B.S., Elliott, J.E., LaRock, E.J., du Bray, E.A., Carlson, R.R., and Zientek, M.L., 2000, Generalized geologic map of the Absaroka–Beartooth study area, south-central Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF-2338, scale 1:126,720.

Van Voast, W.A., 1964, General geology and geomorphology of the Emigrant Gulch–Mill Creek area, Park County, Montana: Bozeman, Mont., Montana State University, M.S. thesis, 65 p., scale 1:24,000.

Wilson, A.B., and Elliott, J.E., 1997, Geologic maps of western and northern parts of Gallatin National Forest, south-central Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-2584, scale 1:1,126,720.

Wu, Z., 1995, Structural geometry of the Paradise Valley, Park County, southwest Montana: Bozeman, Mont., Montana State University, M.S. thesis, 80 p.