Geology of the Yellowstone Controlled Ground-Water Area, South-Central Montana

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Introduction

The Yellowstone Controlled Ground-Water Area (YCGA) was established in January of 1994, when the United States Park Service and the State of Montana signed a compact that established a common area of interest within which ground-water resources are to be investigated and monitored. The focus of the studies and monitoring is the understanding and protection of ground waters that enter the geothermal systems of Yellowstone National Park. The area under the compact includes the watersheds of those Montana lands contiguous with the north and west borders of Yellowstone National Park (fig. 1). While most streams in these watersheds flow out of the Park (fig. 2), ground water could flow into the Park, following flow paths established by geologic units and structures mapped at the surface.

Surficial Geology of the Yellowstone National Park Area

Surficial geology includes the largely unconsolidated sediments deposited during the last 200,000 years, during the Quaternary, including both Pleistocene glacial deposits and Holocene (modern) deposits. It also includes those geologic structures, folds or faults, that deform or offset the Quaternary deposits.

Several Pleistocene glaciations and the associated sedimentation buried much of the bedrock beneath unconsolidated deposits. Surficial deposits presently exposed are mostly of Pinedale (latest glaciation) and younger age. During Pinedale glaciation, which probably reached its maximum extent between 20,000 and 30,000 years ago (Pierce, 1979), all but the highest peaks were buried by a great ice cap that covered most of Yellowstone National Park and whose terminus was far down the Yellowstone Valley near Pray. The icecap was melted by about 14,000 years ago, with small Pinedale alpine glaciers persisting until 4,000 to 7,000 years ago (Pierce, 1979). During the glaciation and melting, unsorted clay-rich till was deposited in moraines, well-sorted fluvial gravel was deposited in kames, ice-marginal channels, and outwash fans and the steep valley sides slumped to form large landslides. Modern stream and fan deposits are still accumulating, particularly in years following forest fires.

Prior to this study, surficial geology outside Yellowstone National Park was poorly known. Pierce (1973a, b; 1974a, b) had mapped surficial geology of the Park with the goal of deciphering the Park's glacial history. The goals of this report are different: to assess the effects of the geology outside the Park on the hydrologic systems, particularly the geothermal systems, within the Park. Whereas Pierce (1973 a, b; 1974a, b) emphasized ages and depositional environments in defining his surficial units, this report distinguishes units based mostly on their lithologic characteristics and their resulting hydrologic properties.

Surficial deposits less than one meter thick were not mapped; these were deemed too thin to be important

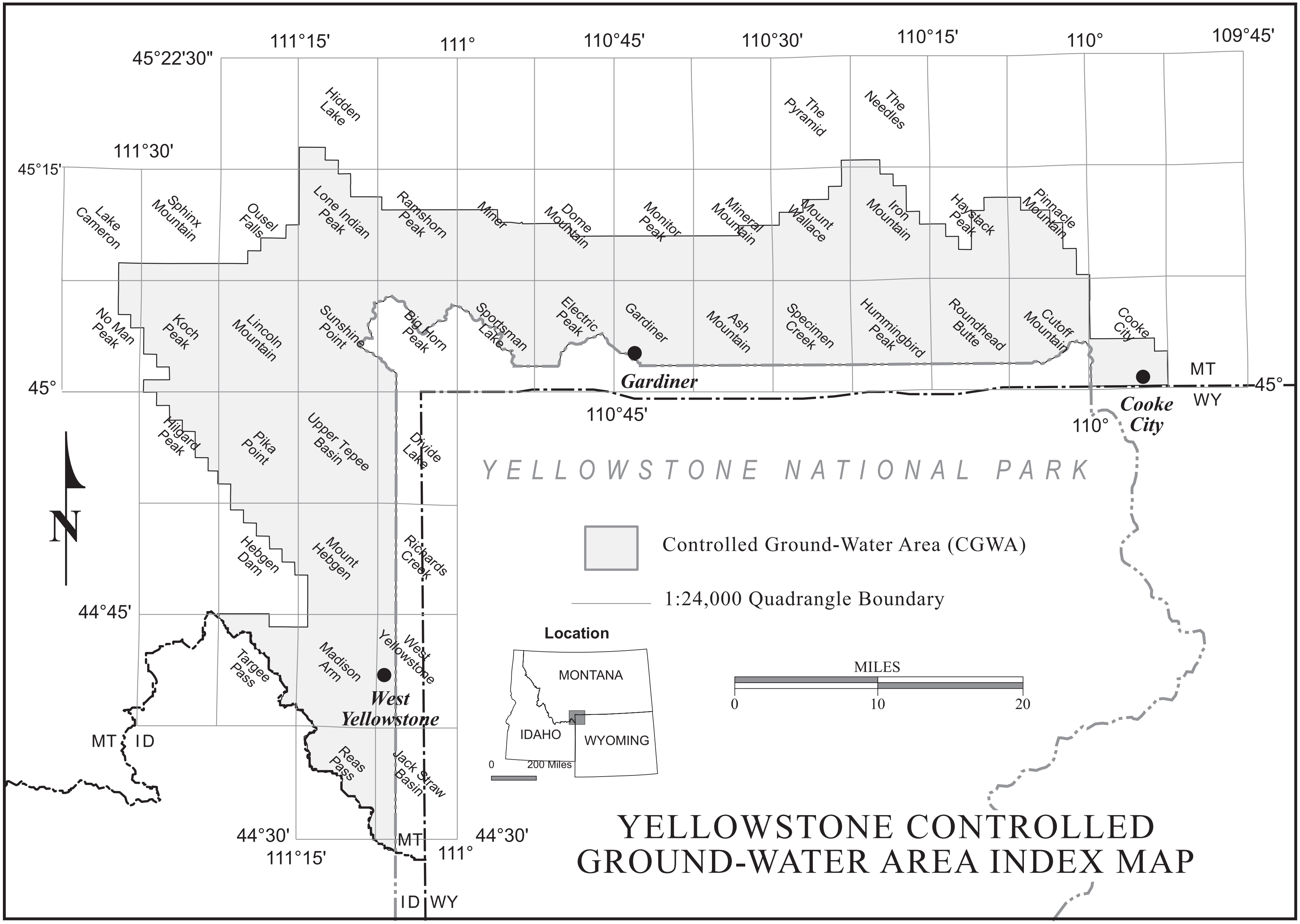

Figure 1. Location of theYellowstone Controlled Ground-Water Area.

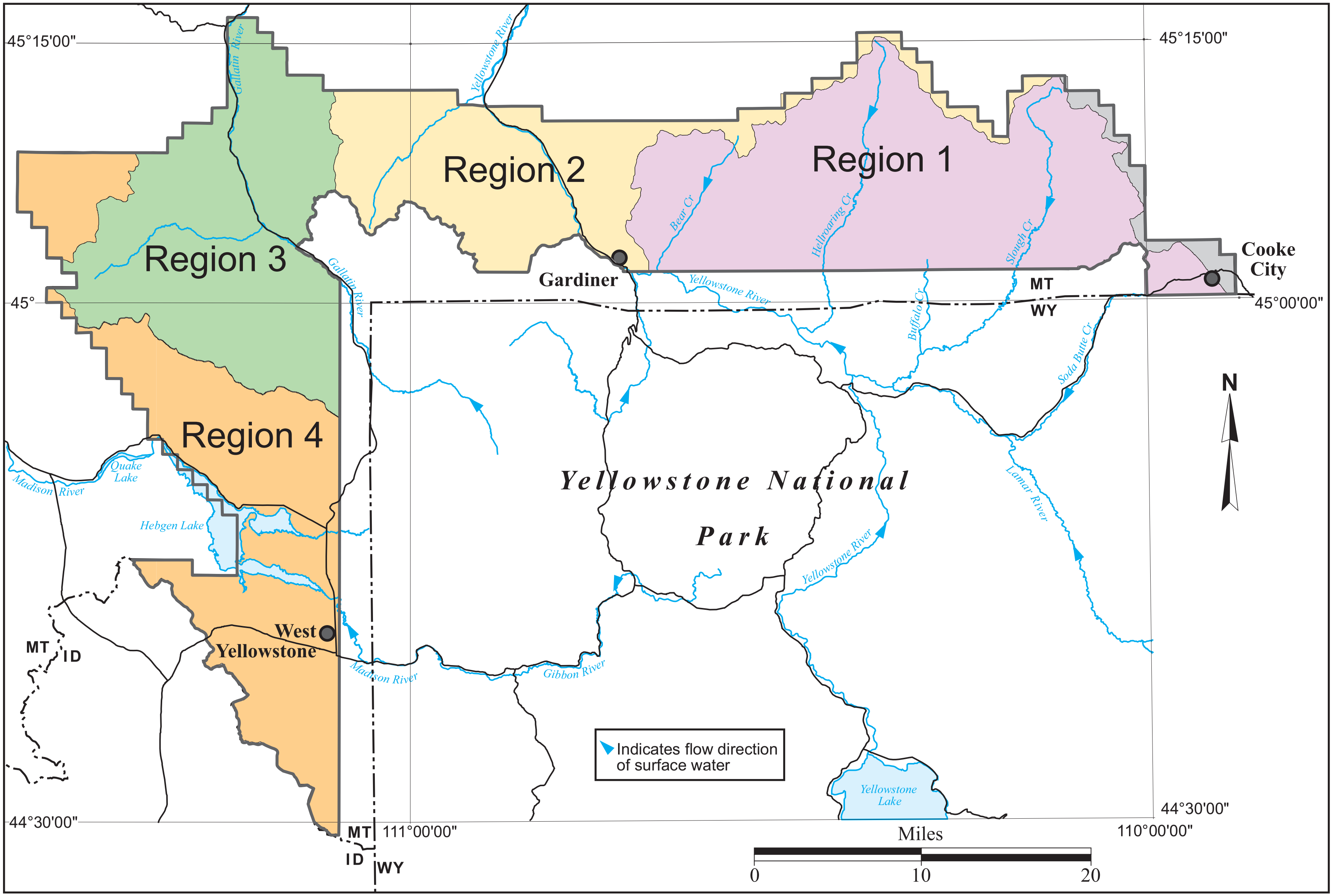

Figure 2. Yellowstone Controlled Ground-water Area, showing the four regions defined in this report.

to the ground-water systems. Additionally, bedrock was examined in a reconnaissance fashion, and portions of existing bedrock maps have been modified. The most surprising finding was the lack of significant surficial deposits in the map area, despite the areal extent of “unconsolidated Quaternary sediments” on earlier maps. In reality, bedrock is at the surface over most of the map area.

Definition of regions within the study area

This report is divided into four sections; each describes a hydrogeologic region defined by common geology and common hydrologic relationships to the geothermal systems of Yellowstone National Park. The regions lie along the north and west boundaries of the Park, with surface drainage into the Park, and within the Yellowstone Controlled Ground-Water Area (fig. 2). For each hydrogeologic region, bedrock geology, surficial geology, and hydrologic speculations are discussed as they relate to Yellowstone’s geothermal systems.

Region 1: Northern Border of Yellowstone National Park
Including Soda Butte, Slough, Bear, and Hellroaring Creek watersheds

The northern border region includes the Soda Butte, Slough, Hellroaring, and Bear Creek drainages (figs. 2, 3). It is characterized by high topography relative to the Park and may represent a recharge area for the Park’s hydrologic systems. However, it lies mostly within the Absaroka-Beartooth Wilderness, and significant development of water resources is unlikely.

Bedrock Geology

Bedrock geology of the area was previously mapped at various scales by the U.S. Geological Survey (1972a), Wedow and others (1975), Elliott (1979), and Casella and others (1982). Bedrock consists of a relatively undeformed sequence of Archean metamorphic rocks, Paleozoic sedimentary rocks, and Eocene volcanic rocks.

Metamorphic rock in the study area is mostly granitic gneiss having north-northeast-striking foliation (Casella and others, 1982; Cartwright, 1984). During the Paleozoic Era, a thick sequence of sedimentary rocks was unconformably deposited on a gently undulating erosional surface that had developed on the metamorphic rocks. Exposed sedimentary rock includes, from oldest to youngest, the Flathead Sandstone (sometimes missing), the Wolsey Shale (sometimes missing), the Meagher Limestone, the Park Shale, the Pilgrim Limestone, the Snowy Range Formation, the Bighorn Dolomite, and the Madison Group. Younger units stratigraphically above the Madison Group were apparently eroded off prior to deposition of Tertiary volcanic rocks.

The Absaroka volcanic field (Chadwick, 1969, 1970; Smedes and Prostka, 1972) became active in the Eocene Epoch and began with deposition of Washburn Group andesitic rocks on an erosional surface developed on the Madison limestone and having at least 152 m (500 ft) of relief (Wedow and others, 1975). In the southeastern part of Region 1, around Cooke City, the Heart Mountain Detachment Fault (Pierce, 1957) moved Ordovician and younger rocks eastward on a nearly flat fault plane during this early period of volcanism. Continued deposition of the Washburn Group and the younger flows, and volcaniclastic rocks of the Mount Wallace, Wapiti, and Langford Formations blanketed the detachment fault as well as the undeformed areas. Intermediate to felsic igneous rocks intruded these layered volcanic

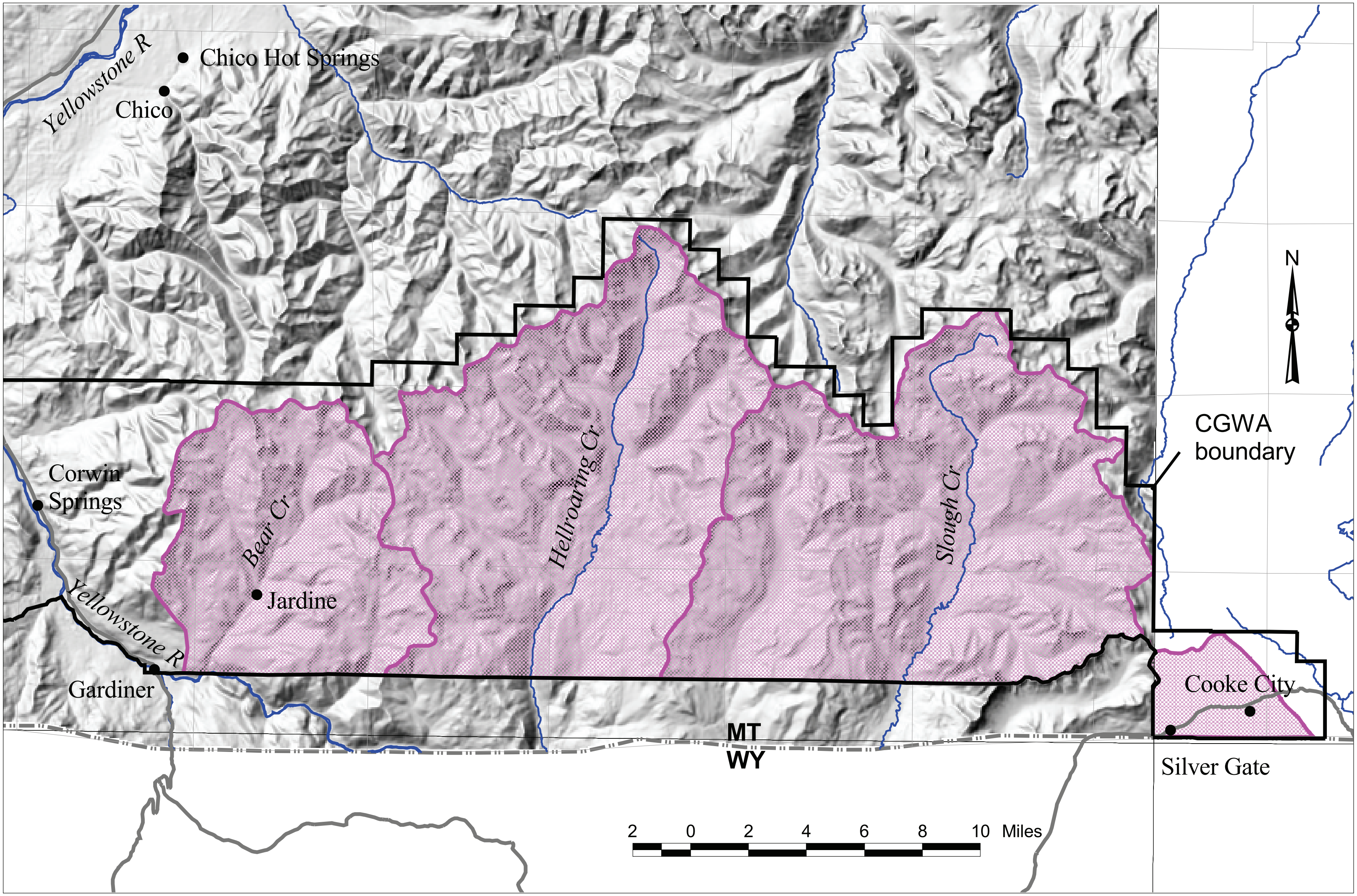

Figure 3. Region 1 as defined for this report, showing watershed boundaries of Slough, Hellroaring and Bear Creeks.

rocks to form stocks, dikes, and sills.

Despite this complex history, most sedimentary bedrock remained nearly horizontal and forms the striking layers evident today. Faults with minor displacement and of several ages and orientations cut the bedrock. Some, mostly west-northwest-striking faults, only cut Madison and older rocks. Other younger faults that mostly strike north-northeast, displace the Eocene volcanic rocks as well. These younger faults appear to control the location of the Buffalo Fork and Hellroaring Creek Valleys north of the Yellowstone National Park boundary.

Surficial Geology

Mapping suggests that the bedrock valleys are shallow, with unconsolidated deposits having a probable maximum thickness of about 61 m (200 ft). The thickest of these sediments appear to have accumulated behind dams of resistant Precambrian metamorphic rock structurally elevated by Tertiary(?) faults. Pinedale glaciers may have scoured lake basins behind these resistant blocks that then filled with fluvial and lacustrine sediments. Frenchy's Meadow, the meadows within Yellowstone National Park on Slough Creek, and the lower meadow on Buffalo Fork are examples. The upper meadow on Buffalo Fork appears to have formed on sediments trapped behind a landslide dam. Tertiary tuffaceous bedrock, misidentified on previous maps as Quaternary sediments, underlies the lower end of the Hellroaring Creek meadow.

Hydrogeology Interpretations

The relatively thick but isolated unconsolidated sedimentary units in these valleys do not extend across the borders of Yellowstone National Park. Thus, they cannot transport significant ground water into the Park.

It appears that the valleys of Slough Creek, Buffalo Fork, and Hellroaring Creek are essentially underlain by Precambrian crystalline rock. Fracture and joint systems that could be important water conduits are not obvious at the outcrop scale. However, in some areas they are evident on air photos. The Lake Abundance area has a west-northwest trending joint system, and lower Buffalo Fork has a north-striking joint system, as well as a north-northeast-striking fault system. The Hellroaring Creek valley contains both north- and northeast-striking faults. The faults and joints in the lower Buffalo Fork and lower Hellroaring Creek areas have the potential for transmitting ground water south into the Park. Metamorphic rocks that floor the Slough Creek valley contain no such features that could contribute significant flow of ground water into the Park. The hydrogeology of Soda Butte Creek was described in an earlier study (Metesh and others, 1999). That report made a more thorough examination of surface-water ground-water interaction as well as a hydrologic budget for the basin. Unlike the aforementioned basins, Soda Butte Creek is a narrow, steep drainage with a thin deposit of alluvial material to serve as the principal near-stream aquifer. The alluvial aquifer is underlain by fractured granite in the area of Cooke City and by Paleozoic rocks in the area of Silver Gate.

In this Region, rocks younger than Precambrian are probably not important to the deep geothermal systems of the Park. Although some, such as the Pilgrim Formation and Madison Group limestones, have ground-water transmitting capabilities, erosion has dissected them into isolated islands in a sea of Precambrian metamorphic rocks. Further, they are capped by flat-lying volcanic tuff and conglomerate with a fine-grained matrix. The volcanic rocks are probably relatively impermeable and unfractured, and prevent recharge to any potential Paleozoic aquifers.

Region 2: Gardiner and the Yellowstone River Valley

Region 2 includes only the Yellowstone River Valley and its flanks from the community of Gardiner north to the YCGA boundary (figs. 2, 4). Region 2 is bounded on the east by the Bear Creek-Yellowstone River drainage divide and on the west by the Yellowstone River-Gallatin River divide. Region 2 also includes the Tom Miner Creek drainage. It is characterized by complex geology and hosts geothermal systems that are not included in the Park. Elevations are lower than those of the Park, and surface water drainage is out of and away from the Park.

Bedrock Geology

Numerous geologic studies (Wilson, 1934; Fraser and others, 1969; U.S. Geological Survey, 1972; Struhsaker, 1976; Berg and others, 1999) examined bedrock geology of the region. However, Pierce and others (1991) provided a compilation that is especially useful because it was prompted by an attempt to determine the relationships between Mammoth Hot Springs and geothermal waters north of the Park boundary (LaDuke Hot Springs and the geothermal well on the Church Universal & Triumphant (CUT) property) (Sorey, 1991).

Rock types present in the Gardiner area include Archean gneiss and a thick section of Paleozoic and Mesozoic sediments. These rocks were complexly deformed by contraction of the crust in Late Cretaceous time to form the northwest-trending, up-to-the-east, Gardiner reverse fault and the associated syncline. The Gardiner fault places Archean gneiss in its hanging wall on top of Paleozoic and Mesozoic rocks caught within an overturned, southwest-verging syncline in its footwall. The syncline itself is complicated by small-scale thrusts and normal faults. The Gardiner fault delineates the northeast side of the Yellowstone River Valley in the Gardiner area.

The Eocene Absaroka volcanic field (Chadwick, 1969, 1970; Smedes and Prostka, 1972) deposited mostly andesitic flows and epiclastic rocks over the older, deformed rocks, with intrusive activity accompanying the volcanism. The Gardiner fault and associated syncline are covered by these volcanic rocks in the northwestern part of Region 2, but these structures may emerge farther to the northwest in Region 3 as the Spanish Peaks reverse fault that also hosts an overturned, southwest-verging syncline in its footwall.

The north-south, down-to-the-east, Reese Creek-East Gallatin normal fault system formed later and cuts both the Eocene volcanic rocks and the Late Cretaceous structures. This system defines the west side of the Yellowstone Valley near Gardiner.

Finally, in the last 2 million years, volcanic rocks associated with the Yellowstone hotspot were deposited. In this part of the Controlled Ground-Water Area, Quaternary volcanic rocks are sparsely distributed and occur mostly as basalt flows in the area of the Travertine Bench (pl. 1).

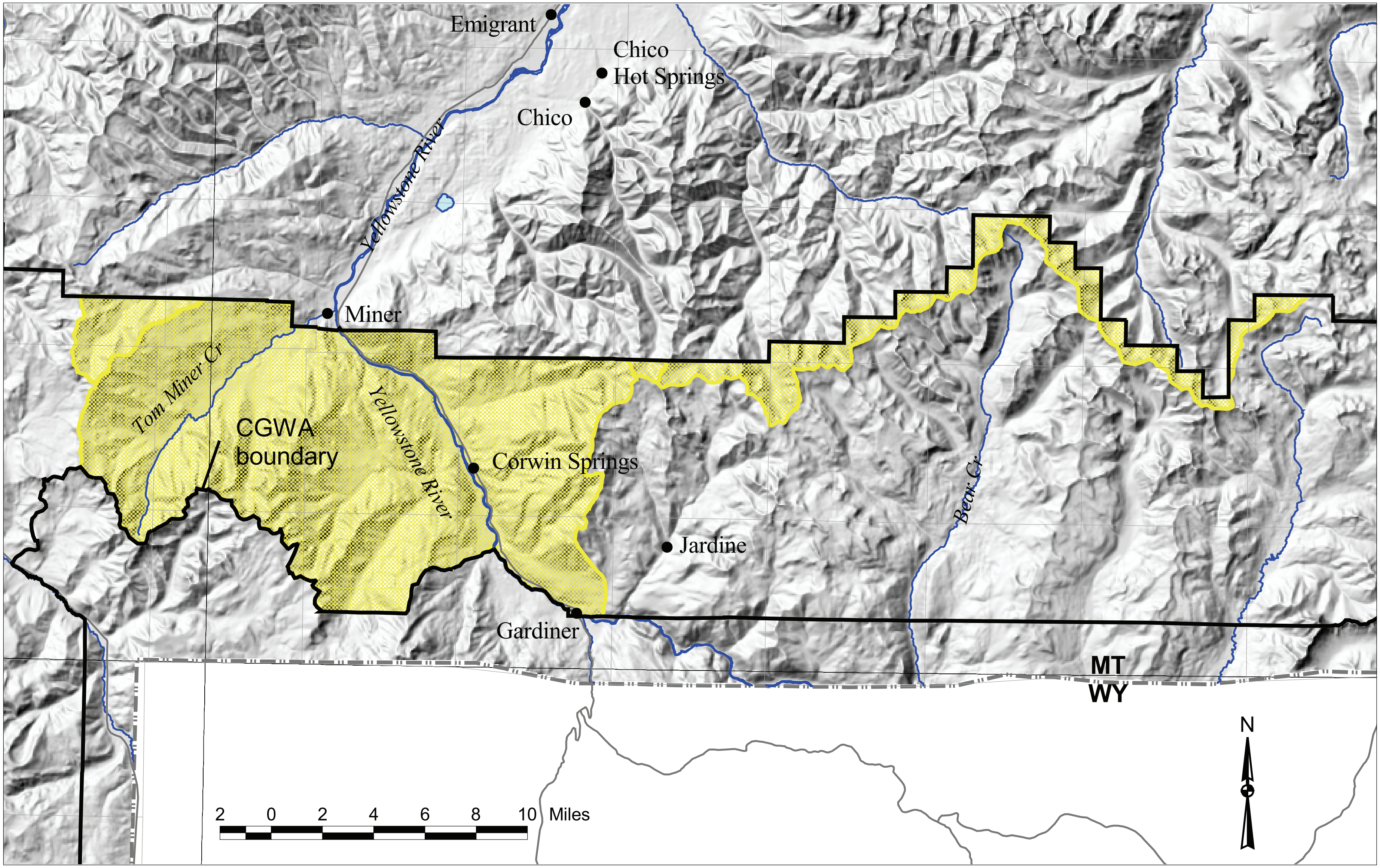

Figure 4. Region 2 as defined by this report.

Pierce and others (1991) defined a Quaternary structure that they called the Mammoth Corridor. It is a swath of active and inactive geothermal features and young volcanic vents less than 0.6 Ma in age that extends from the margin of the Yellowstone caldera near Norris Geyser Basin to LaDuke Hot Springs north of Gardiner. They postulated that the Mammoth Corridor is related to north-south-trending extensional faults. Its eastern boundary in the Gardiner area is defined by the Gardiner reverse fault.

Surficial Geology

Surficial geology of the Gardiner area was mapped in detail by Pierce (1973a, b) within the Park and by this study adjacent to the Park. Surficial geology is dominated by deposits related to the Pinedale glaciation. During Pinedale glaciation, the thickness of the ice at Gardiner was estimated to have been 1,100 m (Pierce, 1979). From drill logs, Pierce and others (1991) postulated that the glacier created a scour basin that was as much as 100 m below present river level. During deglaciation 12,000 to 15,000 years ago (Pierce, 1979), this basin was a lake that filled up with alternating layers of impermeable clay and porous, permeable sand. Catastrophic floods also swept through the valley and left coarse bouldery deposits on terraces along the Yellowstone River. Large landslides on the valley's flanks developed mainly on the Cretaceous Landslide Creek Formation. Thin Holocene alluvial fan deposits emanate from the mouths of side drainages. Travertine was deposited by geothermal activity on the Travertine Bench from 19,000 to 23,000 and from 50,000 to 60,000 years ago, at the mouth of Bear Creek about 10,000 years ago, and presently is being deposited at LaDuke Hot Springs (Pierce and others, 1991).

Hydrologic Interpretations

Recent and ongoing geothermal activity is occurring in this region of the Yellowstone Controlled Ground-Water Area. This activity appears to be mostly localized along the Gardiner reverse fault where the cavernous Madison limestone crops out with a near vertical attitude. This apparent structural control combined with a postulated minimum depth of circulation of 2 to 3 km (Sorey, 1991) make it clear that the bedrock geology is controlling the geothermal system. Surficial geology probably has an insignificant effect on these deep systems, especially because the Gardiner area lies topographically below and down gradient from geothermal features within the park.

Sorey (1991), and Pierce and others (1991) determined that the recharge area for Mammoth Hot Springs is to the south, and that hydrologic and geologic relations suggest a south-to-north direction for ground-water flow between Mammoth and the Gardiner-LaDuke area. These systems may be hydrogeologically connected by the Madison aquifer within the Gardiner syncline. However, geochemical evidence suggests that no Mammoth water reaches LaDuke (Sorey, 1991). Either geologic barriers are present (faults?) and no hydrogeologic connection exists, or present hydraulic head conditions prevent the movement of water from Mammoth to LaDuke. If hydraulic head conditions are responsible, then significant drawdown in the Gardiner area could change the hydraulic head constraints and thereby affect Mammoth Hot Springs.

Quaternary surficial deposits in the Gardiner area probably contribute little water to the deep geothermal system. Instead, they may be recharged by the deep system, in which case significant drawdown of these waters could affect Mammoth Hot Springs.

Region 3: The Gallatin River Watershed

Region 3 (figs. 2, 5) comprises the Gallatin River drainage, with the eastern border being the Gallatin River-Yellowstone River drainage divide, and the southern boundary being the Gallatin River-Madison River drainage divide. Surface water drainage in Region 3 is out of and away from the Park.

Bedrock Geology

Bedrock geology of Region 3 has been compiled at the 1:100,000 scale by Kellogg and Williams (2000) and O'Neill and Christiansen (2002); our data are largely from these sources. However, part of the YCGA map was compiled from more detailed maps by Hall (1961) and Simons and others (1985).

The geology of Region 3 is similar to that of the Yellowstone Valley area (Region 2 of this report): Archean metamorphic rocks are unconformably overlain by a thick Paleozoic and Mesozoic sedimentary section with the entire section deformed by Late Cretaceous contraction. Nearly flat-lying extrusive rocks of the Eocene Absaroka Volcanics (Chadwick, 1969, 1970; Smedes and Prostka, 1972) cover these complex structures in the northeastern part of the region. In the northern part of Region 3, the northwest-striking, up-to-the-northeast Spanish Peaks reverse fault bears a strong resemblance to the Gardiner reverse fault of Region 2. The two structures are separated by an area of Absaroka Volcanics cover, and may be exposures of the same system, although one that has probably been cut by a major northeast-trending, down-to-the-northwest, Tertiary normal fault postulated to lie beneath Tom Miner Basin. The 2.0 Ma Huckleberry Ridge Tuff covers areas of deformed sedimentary rocks in the southern part of Region 3.

Surficial Geology

Surficial geology of the Gallatin River region has been well mapped by Kellogg and Williams (2000), Sollid (1973), Pierce (1973b), and this study. Surficial deposits consist mostly of landslide deposits developed on exposures of Cretaceous sedimentary rocks and of glacial deposits that include till and kame deposits of Pinedale and Bull Lake age. Thin fluvial and alluvial deposits are present along the Gallatin River and other major streams. The thickest and most extensive glacial deposits exist at high elevations and have a maximum thickness of about 49 m (160 ft) (Kellogg and Williams, 2000).

Hydrologic Interpretations

Although surface drainage of the region is away from the Park, large areas of cavernous Madison limestone crop out in the syncline in the footwall of the Spanish Peaks reverse fault (see map). If the Gardiner and Spanish Peaks faults are indeed one and the same, then the Madison limestone of the Gallatin River region may be in hydraulic continuity with the Madison limestone of the Gardiner area, and also connected to the Madison aquifer that supplies Mammoth Hot Springs (see the Region 2 section of this report). Currently available data are not sufficient to resolve the question, but it is an important one because the Madison limestone aquifer is the water source for the rapidly growing Big Sky development that lies west of Gallatin Canyon. Surficial deposits in Region 3 are thin, discontinuous, and scattered, and are unlikely to play a major role in supplying water to the deep geothermal systems of Yellowstone Park.

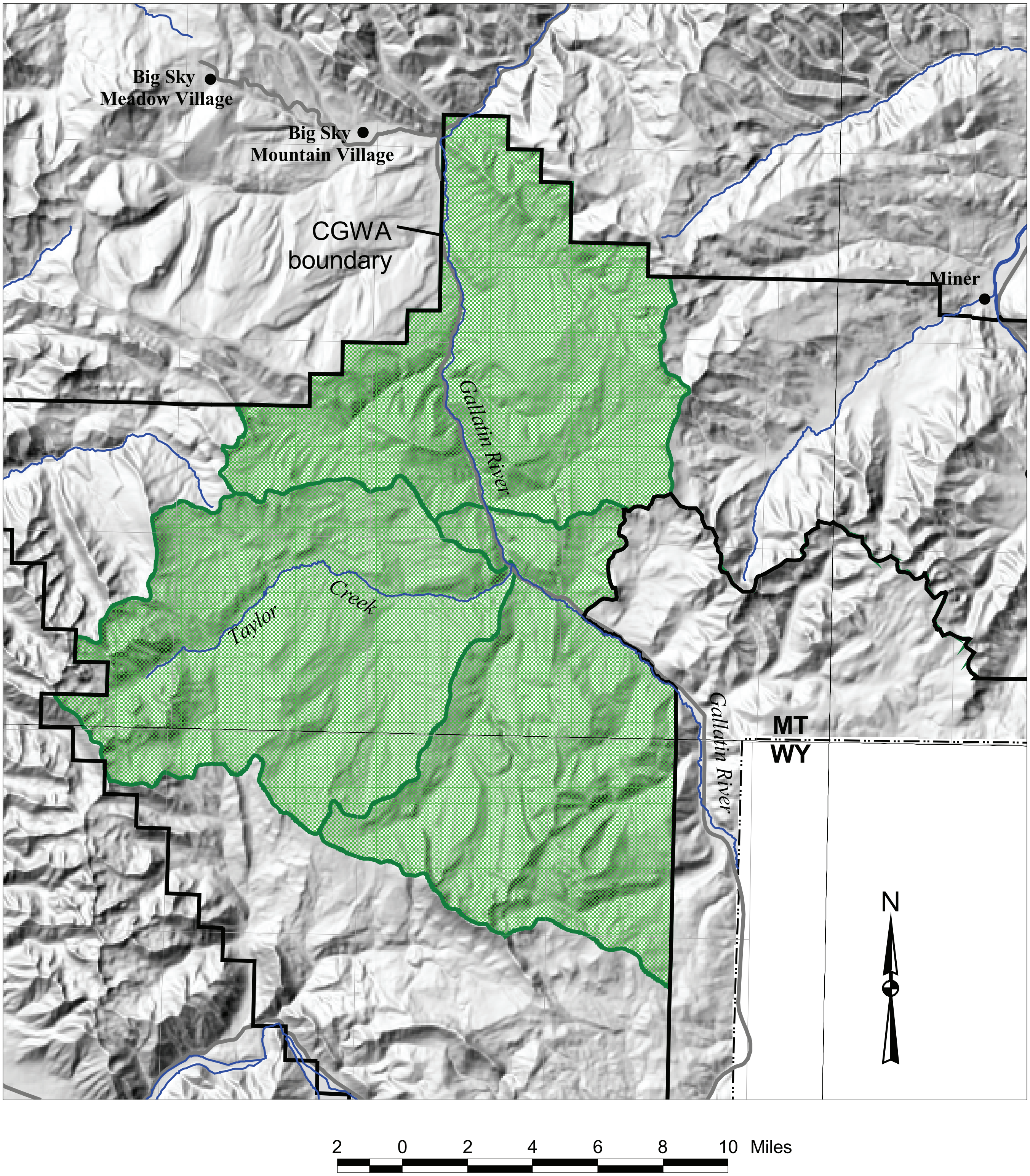

Figure 5. Region 3 as defined for this report.

Region 4: The West Yellowstone Basin

Region 4 (figs. 2, 6) includes the West Yellowstone Basin and the mountainous areas surrounding it. The northern boundary of Region 4 is the Madison River-Gallatin River drainage divide, and the southern boundary is the Madison River-Henry's Fork divide that also forms the Montana-Idaho border. Surface water drainage in Region 4 is out of and away from the Park.

Bedrock Geology

The geology of most of Region 4 is shown on a detailed map by the U.S. Geological Survey (1964) that was done as part of a study of the 1959 Hebgen Lake earthquake. Geology of the remainder of Region 4 was compiled by O'Neill and Christiansen (2002). This latter map is used, with modifications, in the present report.

As in the rest of the YCGA, the rocks of Region 4 consist of Archean metamorphic rocks and Paleozoic and Mesozoic sedimentary rocks that were complexly deformed during Late Cretaceous contraction. A major thrust system extends north-northwest from the west end of Hebgen Lake and places older rocks to the west over younger rocks to the east. Rocks of all ages have been cut by Tertiary through Holocene, high-angle, normal(?) faults, some of which were localized by pre-existing reverse faults (Witkind and others, 1964). This structurally complex bedrock is overlain and covered near the Park border and in the southern part of Region 4 by both glacial deposits and lava flows related to volcanism in the Yellowstone Park region; in the southern part of the region (Hamilton, 1964; Richmond, 1964), Pleistocene rhyolite overlies Bull Lake-age moraine deposits.

Surficial Geology

Detailed summaries of the region's surficial geology have been provided by Richmond (1964), Pierce (1973b), and Waldrop (1975). The U.S. Geological Survey (1964) and Waldrop (1975) provided surficial geologic mapping that has been incorporated into the present report.

At least three glaciations, pre-Bull Lake, Bull Lake, and Pinedale, affected the West Yellowstone Basin, with the Pinedale event being the least significant in this area. On the geologic map for this report (pl. 1), glacial deposits are not divided by age. Thickness of the glacial deposits is unknown and variable. A deposit of obsidian sand (unit Qos) overlies Bull Lake glacial deposits in much of the West Yellowstone Basin. Because the obsidian sand is an extensive and thick deposit (up to 30 m; Waldrop, 1975) of porous and permeable material, it is probably of major importance to the hydrologic systems of the area.

Hydrologic Interpretations

The complexity of the pre-Tertiary geology and the extent to which it has been covered by both unconsolidated surficial deposits and Pleistocene lava flows make hydrologic interpretations difficult. Although surface drainage is away from the Park in Region 4, the extent and continuity of the deep

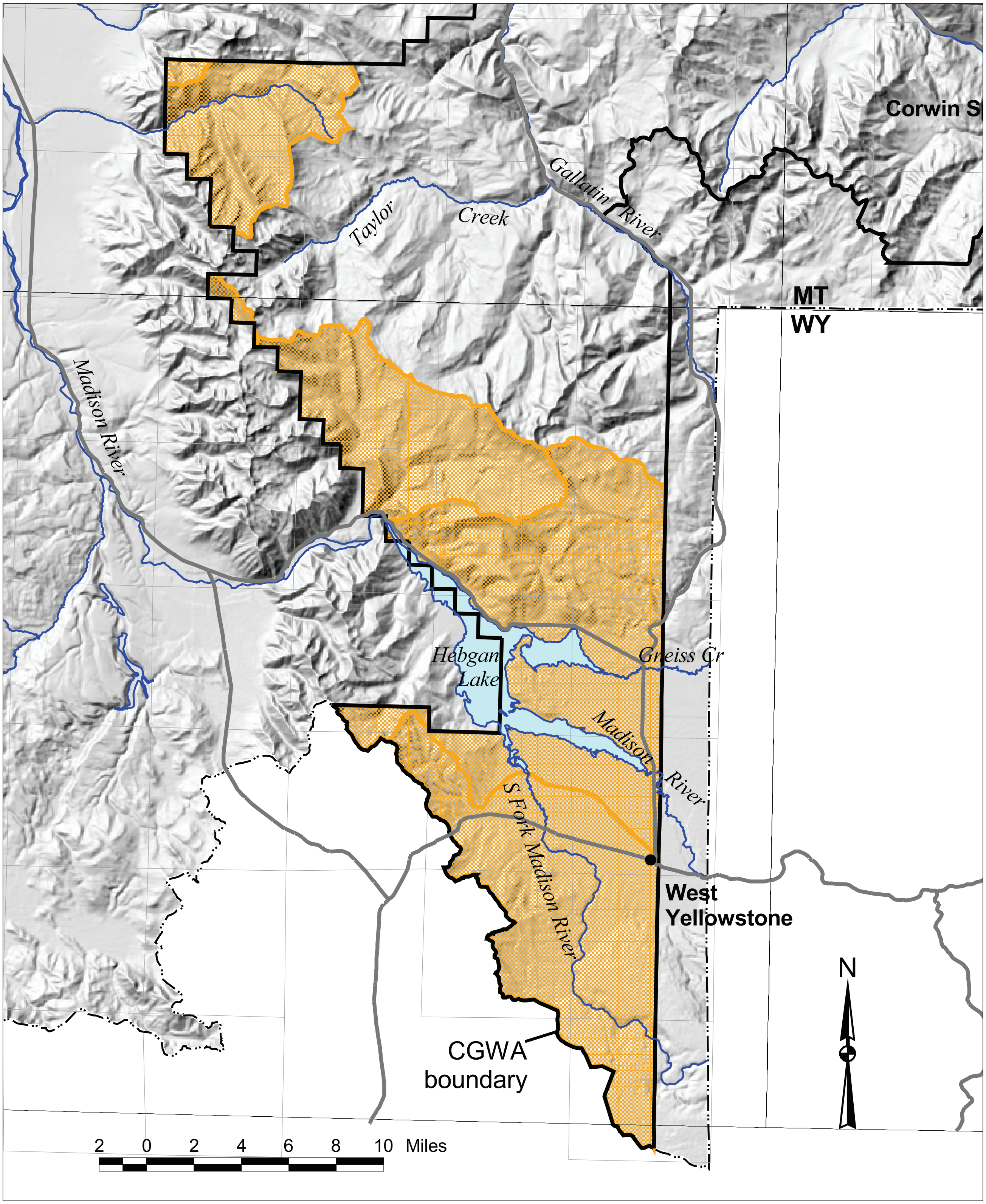

Figure 6. Region 4 as defined in this report.

aquifers such as the Madison limestone are completely unknown. Also, the extensive, thick, and complexly interlayered surficial deposits are likely to be of importance in storing and transmitting water. Of particular importance are the porous and permeable deposits of the obsidian sand plain; their interaction with the Madison River is completely unknown. Further study of surface water flow may unveil some of these relationships. Holocene fault zones may also provide pathways for water transmission.

Correlation Chart

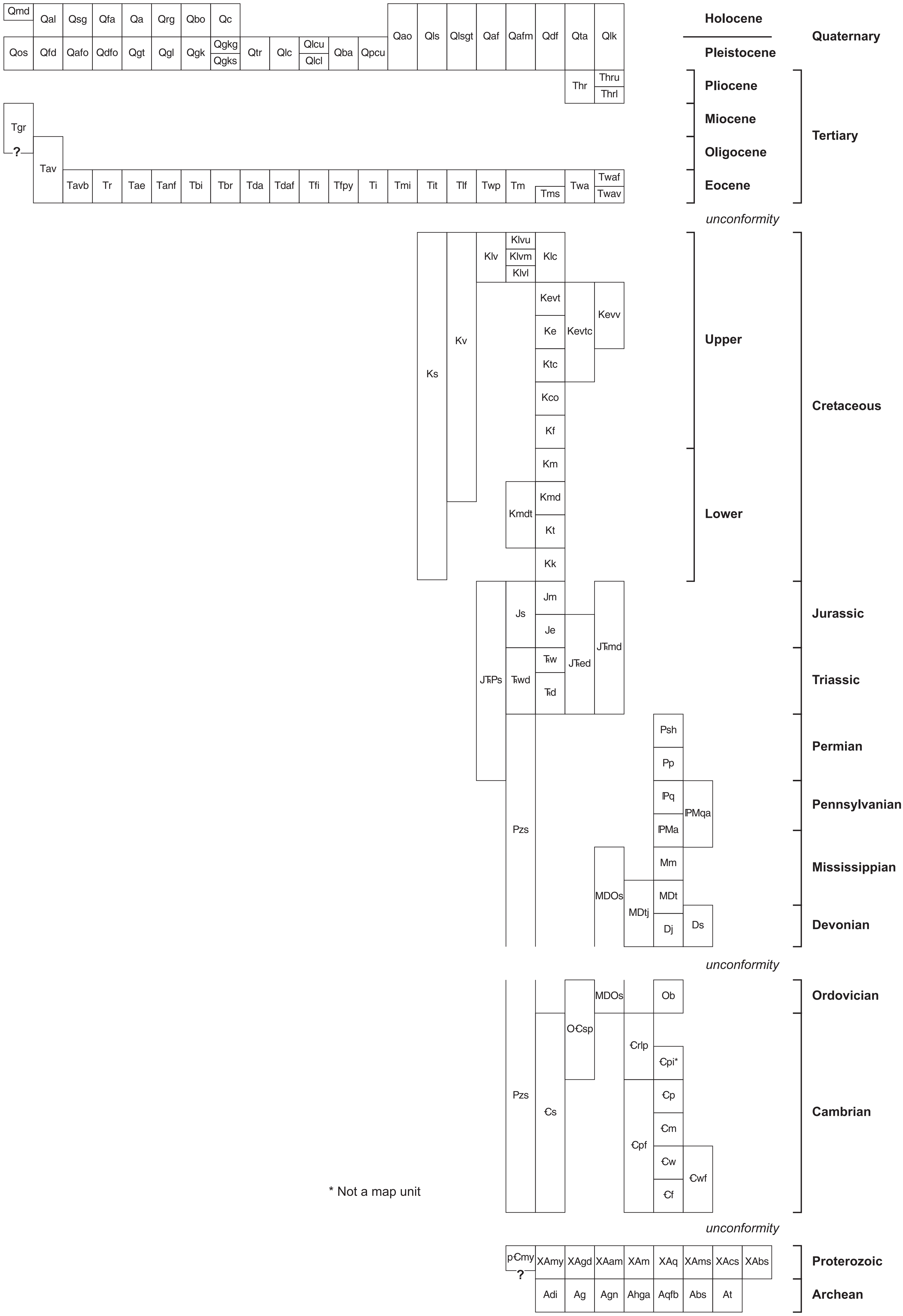

Figure 7. Correlation chart for map units shown on geologic map of Yellowstone Controlled Ground-Water Area, Montana.

Description of Map Units

QUATERNARY

HOLOCENE

Qmd	MILL TAILINGS (HOLOCENE) – Fine-grained sand; may have a high metal content; usually devoid of vegetation.
Qal	ALLUVIUM OF MODERN CHANNELS AND FLOOD PLAINS (HOLOCENE) Includes both fine-grained overbank deposits (Qfa) and coarse-grained channel deposits (Qsg). The thickest deposits accumulated behind bedrock dams, possibly in glacially scoured basins, or behind landslide dams. Probably capable of transmitting and storing significant ground water, but discontinuous, and not extending across Yellowstone National Park boundaries. Thickness 1.5-61 m.
Qsg	SAND AND GRAVEL DEPOSITS IN MODERN STREAM CHANNELS (HOLOCENE) – Well-sorted, sub-rounded to well-rounded, well-stratified sand, pebbles, and boulders deposited in fluvial environments. Clast lithologies represent the entire watershed. Interfingers with Qfa. High permeability and porosity make this unit an important aquifer.
Qfa	FINE-GRAINED HUMIC ALLUVIUM (HOLOCENE) – Organic-rich clay and silt deposited in flood plains of modern streams and in depressions in glacial deposits. This unit is especially common immediately upstream of encroaching fan and bedrock "dams" along Soda Butte, Slough, and Buffalo Fork Creeks. Permeability is generally poor, and in the upper Soda Butte Creek valley this unit forms a confining layer above underlying Qsg (Metesh and others, 1999). Mostly less than 1.5 m thick.
Qa	AVALANCHE DEBRIS, COLLUVIUM, SCREE, TALUS, AND SMALL DEBRIS FLOW DEPOSITS (HOLOCENE) – Unsorted, sub-angular to angular pebble- to boulder-sized rocks often in a fine-grained matrix, often forming lobate deposits at the bases of avalanche chutes. Includes scree, colluvium, and talus-flow deposits (tf) of Pierce (1973, 1974a, 1974b), and small debris flow deposits. Larger debris flow deposits (Qdf) are mapped separately. Often gradational downslope into debris flow fan deposits (Qdf). Emplaced by debris avalanches, piecemeal accumulation, and mudflow. Thickness 1.5-9 m.
Qrg	ROCK GLACIERS (HOLOCENE) – Lobate accumulations of angular boulders. Like talus, but contains convex-downslope ridges and furrows. Emplaced by flow of an ice core. Active and inactive rock glaciers are not divided; both probably contain at least some ice at depth. Mostly unvegetated.
Qbo	BOULDERS OF BOULDER FIELD (HOLOCENE) – Unsorted accumulation of angular boulders on steep slopes.
Qc	COLLUVIUM (HOLOCENE) – Unconsolidated deposits of silt, sand, angular pebbles,

and cobbles formed by mass movement downslope. Thickness generally less than 2 m.

HOLOCENE AND PLEISTOCENE

Qao — OLDER ALLUVIUM (HOLOCENE AND PLEISTOCENE) – Mostly well-sorted, sub-rounded to well-rounded, well-stratified sand, pebbles, and boulders deposited by streamflow processes. Clast lithologies are from the entire watershed. Deposited by older streams in terraces 1.5-12 m above modern streams, or in ice marginal channels. Several different topographic levels and ages are represented by this unit. Flat topographic surfaces distinguish this unit from kame deposits (Qgk, Qgkg, Qgks) that are lithologically similar. Probably an important aquifer, especially in the Cooke City area, where the public water supply issues from the base of Qao unit (Metesh and others, 1999). Thickness 6 m.

Qls — LANDSLIDE DEPOSITS (HOLOCENE AND PLEISTOCENE) – Unsorted and unstratified mixtures of mud and boulders transported by mass movement down steep slopes. Characterized by irregular topography and the presence of huge angular boulders up to 6 m in diameter. Most landslides formed during the Pinedale deglaciation as the valley walls slumped against the melting ice. A few landslides are still active, but these are not differentiated on this map.

Qlsgt — LANDSLIDE DEPOSITS AND GLACIAL TILL, UNDIVIDED (HOLOCENE)

Qaf — ALLUVIAL FAN DEPOSITS DEPOSITED DOMINANTLY BY STREAM FLOW PROCESSES (HOLOCENE AND PLEISTOCENE) – Mostly moderately to well-sorted, well-rounded, stratified deposits of locally derived sand, pebbles, and boulders, and deposited in fans dominated by stream flow processes rather than debris flow processes. Grain size decreases and degree of sorting increases toward the toes of the fans. Interfingers with Qal in the subsurface, and the rapid encroachment of fans on main streams appears to have partially dammed the mainstreams at times (Metesh and others, 1999); 3-30 m thick. The fan at the mouth of Silver Creek in Silver Gate is a good example of this type of deposit.

Qafm — ALLUVIAL FAN DEPOSITS, MUDDY (HOLOCENE AND PLEISTOCENE) – Poorly sorted deposits consisting mainly of clay and silt particles. Commonly develop as mudflows below areas of fine-grained Cretaceous sedimentary rocks or tuffaceous volcanic rocks. Probably relatively impermeable. Thickness 3-30 m.

Qdf — DEBRIS FLOW ALLUVIAL FAN DEPOSITS (HOLOCENE AND PLEISTOCENE) – Poorly to moderately sorted, sub-angular to sub-rounded deposits of locally derived silt, sand, pebbles, and boulders, and deposited in fans dominated by debris flow and hyperconcentrated flow processes. These muddy, bouldery deposits generally form poor aquifers. This unit includes both modern and Pleistocene fan deposits. Like Qaf, debris flow fans interfinger with Qal and appear to have partially dammed main streams (Metesh and others, 1999). Thickness 3-39 m. The fan at the mouth of Miller Creek near Cooke City is an example of this type of deposit.

Qta — TALUS DEPOSIT (HOLOCENE AND PLEISTOCENE) – Accumulations of angular boulders below cliffs. Older talus usually has more fine-grained matrix material than active talus, and is often partially vegetated. However, the two are not distinguished on this map. Thickness 1.5-9 m.

Qlk LACUSTRINE DEPOSIT (HOLOCENE AND PLEISTOCENE) – Light-brown to brown, well-sorted, unconsolidated sand, silt, and clay veneer on undissected surfaces underlain mainly by basin-fill deposits. Marked, in part, by multiple strand lines that outline limit of dwindling glacial lake. Thickness unknown; probably less than 2 m (from O'Neill and Christiansen, 2002, 2004).

PLEISTOCENE

Qos OBSIDIAN SAND DEPOSITS OF THE OBSIDIAN SAND PLAIN (PLEISTOCENE) – Gray to light-gray, well-sorted, gravelly sand, dominantly obsidian in composition, with large pebbles and small cobbles of rhyolite and welded tuff. Unconsolidated and cross-bedded. Forms a large, low-gradient, compound alluvial fan in the West Yellowstone Basin; 40-100 ft thick. Deposited during the interglacial period between Bull Lake and Pinedale glaciations. Underlain by a layer of clay 3-9 m thick that formed in a lake behind Bull Lake till (after Richmond, 1964).

Qfd FLOOD DEPOSITS (PLEISTOCENE) – Moderately to moderately well-sorted, poorly stratified, coarse boulder gravel with abundant gneiss and basalt boulders more than 3 feet in diameter. Boulders are sub-angular to sub-rounded and commonly display percussion spalls. Although the bouldery surfaces of these deposits suggest moraines, all the boulders are about the same size and they occur in longitudinal and mid-channel bars up to 50 feet high in valley bottoms; 3-15 m thick. Probably a decent aquifer. (after Pierce, 1979)

Qafo OLDER ALLUVIAL FAN DEPOSITS (PLEISTOCENE) – Fans, dominated by streamflow deposition, that are now perched above the modern stream channels. Most of these were deposited in outwash fans during Pinedale glaciation. Some were deposited against ice margins.

Qdfo OLDER DEBRIS-FLOW FAN DEPOSITS (PLEISTOCENE) – Older debris-flow fans perched above the modern drainages. Most formed during the Pinedale recession.

Qgt GLACIAL TILL (PLEISTOCENE) – Unsorted, mostly unstratified clay, silt, sand, and gravel with subrounded boulders up to 3 m in diameter. Till is mostly found in thin ground moraine deposits overlying bedrock, but also occurs in some thicker end and lateral moraine deposits. Till is often characterized by large, subrounded, exotic boulders that have been transported some distance, and by hummocky topography. Poor drainage with swampy areas and numerous springs, and subangular clasts distinguish it in the field from kame deposits (Qgk, Qgkg, Qgks). Till usually forms a poor aquifer, and in the Cooke City area, no domestic wells are completed in it (Metesh and others, 1999).

Qgl GLACIAL LAKE DEPOSIT (PLEISTOCENE) – Glacial lake deposits shown only in the Tom Miner and Cinnabar Basins and along the Yellowstone Valley where they consist of varved silt and clay.

Qgk KAME DEPOSITS (PLEISTOCENE) – Moderately well- to well-sorted. Sub-rounded to well-rounded, well-stratified sand, pebbles, and boulders deposited by streams flowing within and on glaciers. Topographic surfaces tend to be hummocky and contain ridges and kettles, unlike the surfaces of older alluvium (Qao). Generally not as well sorted as Qao. Distinguished in the field from glacial till (Qgt) by the roundness of the clasts and by its well-drained nature. Where these deposits are extensive, such as upstream of Frenchy's Meadow on Slough Creek, this unit is probably an important aquifer. However, these deposits are all isolated and discontinuous, and have also been dissected and drained by modern streams; 6 m to more than 60 m thick.

Qgkg KAME DEPOSITS DOMINATED BY BOULDERS AND COBBLES (PLEISTOCENE)

Qgks KAME DEPOSITS DOMINATED BY SAND AND PEBBLES (PLEISTOCENE)

Qtr TRAVERTINE DEPOSIT (PLEISTOCENE) – Cream-colored, finely crystalline calcium carbonate in travertine deposits on the east side of the Yellowstone Valley above Gardiner have been quarried for many years for decorative stone. Two distinct U-Th ages have been reported for this travertine: 19.57+/- 0.12 ka and 22.64+/-0.17 ka (Pierce and others, 1991). Modern travertine deposits at LaDuke Hot Springs and at Chico Hot Springs are too small to show at the scale of this map.

Qlc LAVA CREEK TUFF, UNDIVIDED (PLEISTOCENE) – Welded ash flows. Shown in Yellowstone National Park (after U.S. Geological Survey, 1972a; Kellogg and Williams, 2000).

Qlcu LAVA CREEK TUFF, UPPER MEMBER, INFORMAL (PLEISTOCENE) – Light-gray, locally pale-red, fine-grained to aphanitic, densely welded ash-flow tuff, with phenocrysts composing as much as 20 percent of rock (from O'Neill and Christiansen, 2004).

Qlcl LAVA CREEK TUFF, LOWER MEMBER, INFORMAL (PLEISTOCENE) – Ash-flow tuff lithologically similar to overlying upper member; the two members are separated by a partially welded tuff locally associated with a sorted and bedded crystal ash several cm thick (from O'Neill and Christiansen, 2004).

Qba BASALT (PLEISTOCENE) – Basalt flows in the Gardiner area (after Van Gosen and others, 1993).

Qpcu PLATEAU RHYOLITE, CENTRAL PLATEAU MEMBER, UPPER PART (PLEISTOCENE) – Rhyolitic flows erupted from vents in the Yellowstone Caldera; flows contain abundant phenocrysts of mainly quartz and sanidine; absence of plagioclase phenocrysts distinguishes this rock. Maximum thickness about 300 m (from O'Neill and Christiansen, 2004).

TERTIARY

Thr HUCKLEBERRY RIDGE TUFF, UNDIVIDED (PLIOCENE) – Tuff, mapped in the Gravelly Range where it thins dramatically to less than 1 m in the north, and in the northern Gallatin Mountains.

Thru HUCKLEBERRY RIDGE TUFF, UPPER MEMBER, INFORMAL (PLIOCENE) Pinkish-gray, gray to brown welded tuff containing abundant phenocrysts of sanidine and quartz (25 and 10 percent, respectively); uppermost part is locally nonwelded, light-pink on weathered surfaces; contains noncompacted pumice fragments.

Thrl HUCKLEBERRY RIDGE TUFF, LOWER MEMBER, INFORMAL (PLIOCENE) – Medium- to dark-gray welded tuff with sparse (less than 5 percent) phenocrysts; base of unit is a vitrophyre overlain by densely welded tuff grading to partially welded at the top.

Tav ABSAROKA GROUP VOLCANIC ROCKS, UNDIVIDED (OLIGOCENE AND EOCENE) – Includes andesite flows and andesite epiclastic deposits. Thickness unknown, but as much as 600 m in the map area.

Tavb ABSAROKA VOLCANICS, VENT BRECCIA FACIES (EOCENE)

Tr RHYOLITE (EOCENE?) – Massive, porphyritic rhyolite with large quartz and feldspar phenocrysts in a chocolate-brown, glassy matrix.

Tae ANDESITE, EPICLASTIC, OF HYALITE PEAK VOLCANICS (EOCENE) – Well- to poorly stratified. This unit is thought to be correlative with the Sepulcher Formation of the Washburn Group as mapped by the U.S. Geological Survey (1972a) near the northern boundary of Yellowstone National Park (after Chadwick, 1982).

Tanf ANDESITE FLOWS OF HYALITE PEAK VOLCANICS (EOCENE) – Commonly autobrecciated; includes some epiclastic lenses. Unit thought to be correlative with the Mount Wallace Formation of the Sunlight Group as mapped by the U.S. Geological Survey (1972a) near northern boundary of the Park (after Chadwick, 1982).

Tbi INTRUSIVE BRECCIA (EOCENE) – Tuff breccia dike on Ash Mountain (Wedow and others, 1975).

Tbr BRECCIA PIPE (EOCENE) – Formed by explosion and collapse. Mapped by Elliott (1979)

Tda DACITE, INTRUSIVE (EOCENE) – Light- to medium-gray and brownish-gray, dense porphyritic dacite. Phenocrysts are euhedral plagioclase, hornblende, and biotite.

Tdaf DACITE FLOWS (EOCENE) – Reddish to gray, altered hornblende porphyry with sparse feldspar laths. Appears massive in hand specimen, but from a distance flow geometry is apparent. Some flow breccia. Unit mapped west of Yellowstone River.

Tfi FELSIC INTRUSIVE ROCKS (EOCENE) – Mostly porphyritic rocks of rhyolitic and dacitic composition. Includes Ti, Tdp, Td, and Trd of Wedow and others (1975) and Tds, Trp, Tlp, Trl, Trh, and Trpq of Elliott (1979).

Tfpy FELSIC PYROCLASTIC ROCKS (EOCENE) – Includes thin planar, pumiceous beds that are interpreted to represent air-fall deposition. These beds also contain a few andesite pebbles. Also included is welded tuff containing large phenocrysts of quartz and feldspar. These latter beds are altered to mottled purple and gray bentonitic clay that contains sand-size grains of quartz, biotite, and lithic fragments.

Ti INTRUSIVE ROCKS, UNDIVIDED (EOCENE) – Dikes, sills, and irregular-shaped bodies; andesite, quartz latite, dacite, and rhyolite; commonly porphyritic (after Van Gosen and others, 1993).

Tmi MAFIC INTRUSIVE ROCKS (EOCENE) – Mostly of andesitic and basaltic composition. Includes Tia of Wedow and others (1975) and Tds, Ttp, and Ta of Elliott (1979).

Tit INTRUSIVE TUFF (EOCENE) – Occurs on Ash Mountain. Welded trachyrhyolite tuff; probably related to and the same age as the Slough Creek Tuff Member of the Mount Wallace Formation (after Wedow and others, 1975).

Tlf LANGFORD FORMATION (EOCENE) – Light-colored andesitic volcaniclastic rocks with a few andesite lava flows interbedded. Dominated by well-rounded, loosely consolidated pebble-boulder conglomerate. Petrified wood locally abundant (after U.S. Geological Survey, 1972a).

Twp WAPITI FORMATION (EOCENE) – Dark-colored andesitic and basaltic volcaniclastic rocks with a few thin lava flows. Mostly sub-angular to rounded, crudely layered, unsorted, lithologically heterogenous conglomerate. Petrified wood locally abundant (after U.S. Geological Survey, 1972a).

Tm MOUNT WALLACE FORMATION (EOCENE) – Andesite and basalt lava flows and flow breccias. The two main flow sequences are often separated by the Slough Creek Tuff Member (Tms) (Wedlow and others, 1975).

Tms SLOUGH CREEK TUFF MEMBER, MOUNT WALLACE FORMATION (EOCENE) – Light-colored ash-flow tuff; welded and non-welded, but mostly non-welded in this area.

Twa WASHBURN GROUP (EOCENE) – Cathedral Cliffs and Lamar River Formations, undivided, and equivalent to Tc, Tlr, and Tlrf of U.S. Geological Survey (1972a), Tlc of Elliott (1979), and Te, Tvb, f, and Tv of Wedow and others (1975). Light and dark andesitic rocks, mostly volcanoclastic. In Hellroaring Creek drainage, the base of this unit contains abundant volcanic ash, and was misidentified as Wapiti Formation and Quaternary sediments by Wedow and others (1975). This tuffaceous unit is probably the same one (Tfpy) mapped by Berg and others (1999) at the base of the Eocene volcanic sequence in the Gardiner Valley.

Twaf LAVA FLOWS IN THE WASHBURN GROUP (EOCENE) – Mostly andesite.

Twav VENT FACIES OF THE WASHBURN GROUP (EOCENE) – Discrete light- and dark-colored pyroclastic sequences of dominantly crystal tuff breccia and subordinate lava flows and flow breccias, laharic deposits, agglomerates, and ash-flow tuff (after Wedow and others, 1975).

Tgr GRAVEL (TERTIARY) – Pebble and cobble conglomerate; age uncertain, but underlies the Huckleberry Ridge Tuff of Pliocene age.

CRETACEOUS

Kv VOLCANIC ROCKS, UNDIVIDED

Ks SEDIMENTARY ROCKS, UNDIVIDED

Klv LIVINGSTON FORMATION (UPPER CRETACEOUS) – Unit mapped as undivided in some areas of map; elsewhere divided into three informal members.

Klvu LIVINGSTON GROUP, UPPER MEMBER, INFORMAL – Cobble and boulder conglomerate composed of well-rounded volcanic clasts in matrix of coarse-grained volcaniclastic sandstone; upper part is predominantly sandstone; lower contact is conformable. Thickness as much as 80 m (Kellogg and Williams, 2000).

Klvm LIVINGSTON GROUP, MIDDLE MEMBER, INFORMAL – Brown, maroon, and gray dacite to basalt flows, autoclastic breccia, tuff breccia, and welded tuff; minor interlayered volcaniclastic sandstone; lower contact is conformable. Estimated thickness 300 to 450 m (Kellogg and Williams, 2000).

Klvl LIVINGSTON GROUP, LOWER MEMBER, INFORMAL – Complexly intertonguing units of dark-green to dark-brown, medium- to coarse-grained, locally pebbly volcaniclastic sandstone, olivine basalt, mudflow breccia, volcaniclastic conglomerate, and mudstone; conformable with underlying Everts Formation. Thickness ranges from about 60 to 210 m (Kellogg and Williams, 2000).

Klc LANDSLIDE CREEK FORMATION (UPPER CRETACEOUS) – Overall dark, somber colors of brown, olive-drab, and gray conglomeratic sandstones, mudstones, and claystones. Conglomerate clasts up to cobble size are common. Andesite grains are common in all grain sizes; swelling bentonite beds occur throughout the formation, and all mudstones and claystones are bentonitic. Fossil plant debris and dinosaur bone fragments common. Formation prone to landslides. At least 396 m thick, and possibly as much as 701 m (Fraser and others, 1969). Contains youngest Cretaceous beds of the Yellowstone region; named for beds within Yellowstone Park (Fraser and others, 1969), but equivalent to all or part of Livingston Group in northern part of study area.

Kevtc EVERTS, EAGLE, AND TELEGRAPH CREEK FORMATIONS, UNDIVIDED (UPPER CRETACEOUS)

Kevv EVERTS FORMATION THROUGH VIRGELLE MEMBER OF EAGLE FORMATION, UNDIVIDED (UPPER CRETACEOUS)

Kevt EVERTS FORMATION (UPPER CRETACEOUS) – Light- to medium-gray, fine- to medium-grained, cross-stratified, calcareous, locally tuffaceous sandstone with abundant heavy-mineral grains, and olive-gray to dark-gray siltstone, mudstone, and shale. Lower part of formation is dominantly fine grained beds; upper part is dominantly sandstone 366 m (Ruppel, 1972).

Ke EAGLE FORMATION (UPPER CRETACEOUS) – Consists of a prominent, thick, light-gray, white-weathering, thick-bedded, cross-stratified, medium-grained basal sandstone as much as 48 m thick called the Virgelle Sandstone Member, overlain by as much as 195 m of lenticular sandstones interbedded with dark-gray carbonaceous shale and thin to thick coal beds. Coals were formerly mined at Electric Coal Field north of Gardiner. A white-weathering sandstone up to 6 m thick commonly marks the top of the formation above the highest coal bed.

Ktc TELEGRAPH CREEK FORMATION (UPPER CRETACEOUS) – Medium-gray to yellowish-gray, blocky, silty and sandy mudstone transitional into overlying Virgelle Sandstone member of Eagle Formation. As much as 91 m thick (Ruppel, 1972).

Kco CODY SHALE (UPPER CRETACEOUS) – Medium- to dark-gray, silty mudstone and shale in lower and upper parts, with a middle 15-m-thick interval of gray to brown-gray, rusty-weathering, partly cross-stratified, glauconitic, fine-grained sandstone with interbeds of dark gray shale; equivalent to Eldridge Creek Member of Cody in Livingston area. Upper shale interval contains numerous very thin sandstone beds. Formation as much as 366 m thick (Ruppel, 1972).

Kf FRONTIER FORMATION (UPPER CRETACEOUS) – Gray- and brownish-gray-weathering, commonly iron-stained, fine-grained sandstone with abundant grains of heavy minerals; thin- to thick-bedded with ripple bed forms and animal burrows and trails on bedding-plane surfaces; locally calcareous, locally glauconitic; fish scales on some bedding planes; small rusty ironstone concretions in some sandstone beds; interbedded with dark-gray silty to clayey shale. On Cinnabar Mountain, the sandstone occurs in two approximately 15-m-thick intervals separated by approximately 118 m of silty shale with thin laminae of sandstone. Elsewhere in the map area, only the upper sandstone is present, owing to structural thinning and/or faulting. This upper sandstone is overlain by a prominent whitish porcellanite everywhere but at Cinnabar Mountain. This porcellanite and the resistant underlying sandstone form a distinct outcrop in the area. Formation thickness at Cinnabar Mountain is 498 ft (Fraser and others, 1969); elsewhere thickness is only 12 m to 30 m (Ruppel, 1972).

Km MOWRY FORMATION (LOWER CRETACEOUS) – Medium- to dark-gray, clayey to siliceous mudstone and shale commonly weathering a lighter blue-gray; interbedded with thin beds and laminae of fine-grained sandstone; several whitish to yellow, non-swelling bentonite beds a few inches to 1 m thick; fish scales common on bedding planes, especially in upper part. Thickness as much as 98 m at Cinnabar Mountain (Fraser and others, 1969).

Kmdt MUDDY AND THERMOPOLIS FORMATIONS, UNDIVIDED (LOWER CRETACEOUS)

Kmd MUDDY FORMATION (LOWER CRETACEOUS) – Gray to grayish-brown, fine-grained, cross-stratified; uppermost beds commonly coarse-grained and contain black chert pebbles; thickness as much as 34 m (Fraser and others, 1969). Some authors place this sandstone as an upper member of the Thermopolis Formation.

Kt THERMOPOLIS FORMATION (LOWER CRETACEOUS) – Contains a basal sandstone overlain by marine shale. Ruppel (1972) and other authors commonly include the overlying Muddy Formation within the Thermopolis, largely based on relative thickness of the sandstone at this stratigraphic position. The basal sandstone is light gray, commonly with small rusty-colored iron specks, quartzose, fine grained, well sorted, and commonly cross-stratified; small marine trace fossils common on bedding plane surfaces; thickness about 100 ft. Overlying shale is dark gray, fissile, and about 85 m thick at Cinnabar Mountain (Fraser and others, 1969). The basal sandstone is equivalent to the Fall River Sandstone of eastern Wyoming and Montana and to the upper sandstone of the Cloverly Formation of western Wyoming. The marine shale is equivalent to the Skull Creek Shale of Wyoming and Montana.

Kk KOOTENAI FORMATION (LOWER CRETACEOUS) – Contains a 15- to 18-m-thick basal chert conglomerate or conglomeratic sandstone overlain by red, purple-gray, and tan mudstones and shales with lenses of fine- to medium-grained sandstone. Upper part of formation is the distinctive gastropod limestone, a light-gray, 6- to 9-m-thick interval locally composed almost entirely of gastropod shells. Light-gray shale forms the upper 6 m of the formation (Ruppel, 1972). Formation is equivalent to the middle and lower parts of the Cloverly Formation of western Wyoming.

JURASSIC

Js SEDIMENTARY ROCKS, UNDIVIDED (JURASSIC) – Contains rocks elsewhere assigned to the Upper Jurassic Morrison Formation and the Upper and Middle Jurassic Ellis Group.

Jm MORRISON FORMATION (UPPER JURASSIC) – Predominantly dull red and gray-green mudstones. A few beds of gray limestone, 0.3- to 0.6-m thick occur in the lower part of the formation; yellow-brown-weathering, fine-grained quartzose sandstones and thin siltstones occur in the upper part of the formation. Uppermost part of the formation contains dark-gray shales and numerous sandstone interbeds with locally abundant fossil wood (Ruppel, 1972). The formation is about 61 m thick, but poorly exposed, usually forming a swale between the resistant Swift Formation below and the Kootenai Formation above.

Je ELLIS GROUP (UPPER AND MIDDLE JURASSIC) – Three formations compose this group; they are generally mapped together although they often are easily recognized in the field. The upper formation, the *Swift Formation*, as much as 18 m thick, is a highly calcareous sandy coquina composed of varying amounts of fragmental shells, quartz sand, oolites, glauconite, and brown chert. The middle formation, the *Rierdon Formation*, as much as 18 m thick, is a resistant, light greenish gray- to reddish gray-weathering fossiliferous calcareous mudstone with a resistant, 0.3- to 2-m-thick, oolitic gray limestone at its base. The lower formation, the *Sawtooth Formation*, as much as 42 m thick, contains a lower red bed sequence, a middle fossiliferous limestone, and an upper siltstone and mudstone red bed sequence (after Ruppel, 1972).

JURASSIC AND TRIASSIC

JTRmd MORRISON FORMATION, UNDIVIDED (UPPER JURASSIC) THROUGH DINWOODY FORMATION (LOWER TRIASSIC) (after Van Gosen and others, 1993)

JTRed ELLIS GROUP (UPPER AND MIDDLE JURASSIC), AND WOODSIDE AND DINWOODY FORMATIONS (LOWER TRIASSIC) (after Van Gosen and others, 1993)

JURASSIC, TRIASSIC, AND PERMIAN

JTRPs SEDIMENTARY ROCKS, UNDIVIDED – Includes formations of Jurassic, Triassic, and Permian age that are elsewhere assigned to the Morrison Formation and Ellis Group (Jurassic), the Woodside and Dinwoody Formations (Triassic), and the Shedhorn and Phosphoria Formations (Permian).

TRIASSIC

TRwd WOODSIDE AND DINWOODY FORMATIONS, UNDIVIDED (LOWER TRIASSIC) (after O'Neill and Christiansen, 2002, 2004)

TRw WOODSIDE FORMATION (LOWER TRIASSIC) – Grayish-red to reddish-brown mudstones and thin lenticular micaceous fine-grained sandstone; as much as 100 ft thick and forms open, rolling, reddish to bright red slopes. Locally, a ledge of fine-grained quartzose sandstone as much as 15 m thick forms the top of the mapped unit; this sandstone could be assigned to the Upper Triassic Thaynes Formation (Ruppel, 1972).

TRd DINWOODY FORMATION (LOWER TRIASSIC) – Pale yellow-brown-weathering,thin-bedded limestone ranging from absent to 15 m. The formation is recognized by Ruppel (1972) south of Fawn Pass, but not farther east.

PALEOZOIC

Pzs SEDIMENTARY ROCKS, UNDIVIDED

PERMIAN

Psh SHEDHORN SANDSTONE AND PHOSPHORIA FORMATION – Throughout Yellowstone National Park and the north- and west-adjacent areas, chert-bearing and phosphatic sandstone beds are assigned to the Shedhorn Sandstone by Ruppel (1972), following the revised nomenclature of McKelvey and others (1959). The Shedhorn, as much as 35 m thick, is widely exposed north of the Park, with an outcrop pattern largely conforming to the underlying resistant Quadrant Sandstone. The yellow-gray- and yellow-brown-weathering sandstone contains a few interbeds of phosphate rock and common to abundant phosphatic oolites, glauconite, and nodular and tubular chert.

Pp PHOSPHORIA FORMATION – Although mapped separately from the Shedhorn Sandstone by some workers, Ruppel (1972) considers the phosphate beds (Phosphoria Formation) and the sandstone beds (Shedhorn Sandstone) to be essentially in facies relationship. In the Yellowstone National Park region, he assigns these beds to the Shedhorn because of the dominance of sandstone.

PENNSYLVANIAN

IPq QUADRANT SANDSTONE – Light yellow-brown, fine-grained quartzose cross-stratified sandstone in beds 0.2 to 1 m and as much as 2 m thick, interbedded in the upper half and basal part of the formation with light gray dolomite beds. Formation thickness ranges from 91 to 99 m thick (Ruppel, 1972).

PENNSYLVANIAN AND MISSISSIPPIAN

IPMqa QUADRANT SANDSTONE (PENNSYLVANIAN) AND AMSDEN FORMATION (LOWER PENNSYLVANIAN AND UPPER(?) MISSISSIPPIAN), UNDIVIDED

IPMa AMSDEN FORMATION (LOWER PENNSYLVANIAN AND UPPER(?) MISSISSIPPIAN) – Composed of pale red to pale yellow-orange mudstone, siltstone, and shale with thin interbeds of tan quartzose sandstone in the lower part, and grayish and pale red dolomitic shale with a few thin beds of dolomite in the upper part. Formation commonly forms moderately resistant red-stained outcrops beneath the overlying Quadrant Sandstone. A 0.2-ft-thick basal conglomerate commonly observed. Formation thickness ranges from 0 to 20 m (Ruppel, 1972), reflecting deposition on the strongly karsted post-Madison Group regional erosion.

MISSISSIPPIAN

Mm MADISON GROUP, UNDIVIDED (MISSISSIPPIAN) – Massive to thin-bedded, light gray-weathering, cherty limestone, commonly cliff-forming. Nearly all exposed sections are upper Madison Group Mission Canyon Formation; underlying beds of possible Lodgepole Formation exposed at Cinnabar Mountain. <u>Mission Canyon Formation</u>*:* generally massive, dolomitic, contains small to large cavities commonly lined or filled with white calcite; some large caves observed; several very thin zones of laterally discontinuous red stain on limestone; several zones of limestone breccia, commonly with associated white calcite masses; black, dark brown, or gray chert common as nodules, masses, and short stringers especially in one zone about 30 feet from top. <u>Lodgepole Formation</u>*:* thin-bedded, medium gray-weathering, with bedding-parallel stringers of dark gray chert. Maximum thickness of group is 335 m on Cinnabar Mountain (Wilson, 1934), but generally much thinner in area owing to faulting.

MISSISSIPPIAN AND DEVONIAN

MDtj THREE FORKS AND JEFFERSON FORMATIONS, UNDIVIDED (LOWER MISSISSIPPIAN AND MIDDLE DEVONIAN)

MDt THREE FORKS FORMATION ((LOWER MISSISSIPPIAN AND UPPER DEVONIAN) – Variable in composition throughout map area. In southern Gallatin Range, lower part composed of light-olive-colored, orange-weathering mudstone with minor thin, yellow-weathering limestone or dolomite; upper part composed of light-orange-gray dolomite. In eastern study area, these two units are lower and middle units with an upper unit of yellow-brown to greenish-gray mudstone grading upward into reddish and green-gray mudstone. At Cinnabar Mountain, the limestone unit weathers dark-reddish-brown and is exposed as erosional-remnant pinnacles and slabs. Formation is around 24 m thick in Gallatin Range, but 39 m thick in northeast corner of the park (Ruppel, 1972).

MISSISSIPPIAN, DEVONIAN, AND ORDOVICIAN

MDOs SEDIMENTARY ROCKS, UNDIVIDED (LOWER MISSISSIPPIAN, DEVONIAN AND ORDOVICIAN) – Includes Three Forks and Jefferson Formations and Big Horn Dolomite; shale, limestone, and dolomite.

DEVONIAN

Ds SEDIMENTARY ROCKS, UNDIVIDED – Includes rocks of Upper Devonian Three Forks and Jefferson Formations, and may include beds assignable to the Lower Devonian Maywood Formation in some localities.

Dj JEFFERSON FORMATION (UPPER DEVONIAN) – Brownish gray- to dark gray-weathering, medium- to dark-gray, fine-grained dolomitic limestone and sugary dolomite in beds ranging from a few cm to 1 m thick, or massive. Darker beds commonly fetid. Beds much lighter brown in eastern part of study area, with almost no dark, fetid-odor beds. Thin beds and laminae of yellowish-brown, silty dolomite and dolomitic siltstone occur sparsely throughout; four such beds occur at base of formation on Cinnabar Mountain. Distinctive thin, intersecting blade-like veins of white calcite at Cinnabar Mountain, especially in upper two-thirds of unit. Thickness highly variable in Yellowstone Park region, ranging from 35 m at Cinnabar Mountain (Wilson, 1934) to 73 m on Three Rivers Peak in the Gallatin Range, both outside this study area, and 38 m thick near Cooke City just east of the study area (Ruppel, 1972).

ORDOVICIAN

Ob BIG HORN DOLOMITE (ORDOVICIAN) – Light-tanish-gray dolomite that weathers yellowish-gray to very light gray with distinctive pitted surface. Generally massive, although Ruppel (1972) includes some thin-bedded dolomite in the unit; commonly cliff-forming. Dolomite is very fine grained or fine grained and locally chert-bearing in lenses as much as 2.5 cm thick and 1.5 m long. Thickness ranges from about 61 m in the Slough Creek and Soda Butte Creek areas to about 100 ft on Antler Peak in the Gallatin Range (Ruppel, 1972).

ORDOVICIAN AND CAMBRIAN

OCs SEDIMENTARY ROCKS, UNDIVIDED

OCsp BIG HORN DOLOMITE, SNOWY RANGE, AND PILGRIM FORMATIONS, UNDIVIDED (ORDOVICIAN AND UPPER CAMBRIAN) – Units mapped together where outcrops are poor and/or beds are steeply dipping. The Snowy Range Formation contains the youngest Cambrian rocks in the area. It is thin-bedded, light-gray limestone and gray shale. Three recognized members, in ascending order, are the Dry Creek Shale, Sage Limestone, and Grove Creek Limestone, but only the lower two have any significant outcrops in the area north of the Park (Ruppel, 1972). Dry Creek lithologies are dominantly strongly fissile, gray-green shale with minor thin interbeds of calcareous fine-grained sandstone, with glauconitic limestone and limestone pebble conglomerate in the upper few meters. Sage Limestone lithologies are dominantly thin wavy-laminated ("crinkly") brownish limestone and yellow-orange sandy limestone with numerous fossiliferous to coquina beds. The Pilgrim Formation and Big Horn Dolomite are described below.

CAMBRIAN

Cs SEDIMENTARY ROCKS, UNDIVIDED

Crlp RED LION AND PILGRIM FORMATIONS, UNDIVIDED (UPPER CAMBRIAN) – Red Lion Formation. Thin-bedded, medium-gray to tan, siliceous dolostone containing conspicuous orange-tan to reddish-tan, cherty stringers as thick as 2 cm; lower 7 m contains intraformational clasts as large as 5 mm long. Unconformably overlies Pilgrim Formation. Thickness about 40-60 m (Kellogg and Williams, 2000). Pilgrim Limestone. Light-gray weathering, cliff-forming limestone with three distinct subdivisions. *Lower unit*: "ribboned limestone"; medium-gray, very fine-grained, thin-bedded limestone with characteristic interbeds ("ribbons") of yellow- or orange-tan-weathering siltstone or silty limestone; other interbeds of oolitic, glauconitic, fossiliferous limestone. *Middle unit*: medium-gray, medium- to coarse-grained, glauconitic, fossiliferous limestone pebble conglomerate. *Upper unit*: oolitic, medium-grained limestone with characteristic yellow-gray to yellow-tan mottling; forms prominent cliffs. About 76 m thick in the Buffalo Creek, Slough Creek, and Soda Butte Creek areas, but thinner to the west (Ruppel, 1972). The formation hosts sinkholes, springs, and caverns, and been observed to transmit water through caverns near Lake Abundance, but the layer has been dissected and probably does not transmit water into Yellowstone National Park (Wedow and others, 1975).

Cpf PARK SHALE THROUGH FLATHEAD SANDSTONE, UNDIVIDED (UPPER CAMBRIAN)

Cp PARK SHALE (MIDDLE CAMBRIAN) – Gray-green shale interbedded with thin laminae of commonly rusty-weathering glauconitic limestone, and shelly limestone or coquina lenses. Shale is strongly fissile to papery in lower part becoming a more blocky mudstone upward. Thin beds of limestone pebble conglomerate occur locally in basal part. Generally poorly exposed in Gallatin Range; best outcrops, both outside this study area, are on Crowfoot Ridge and south of Mount Holmes (Ruppel, 1972). The upper few meters are well exposed below the Pilgrim Limestone along Slough Creek. Thickness ranges from about 27 to 36 m.

Cm MEAGHER LIMESTONE (MIDDLE CAMBRIAN) – Medium-gray to dark-gray, very fine-grained limestone that weathers lighter gray and is characteristically mottled with light-yellow-gray to light-orange, slightly coarser limestone. Thin-bedded in lower part, thick-bedded to massive in upper part, commonly forming cliffs. Gray-green shale interbeds common as are very thin white calcite veins. Thicknesses range from 118 m in Gallatin Range to 60 or fewer meters in the Buffalo and Slough Creek areas (Ruppel, 1972).

Cwf WOLSEY AND FLATHEAD FORMATIONS, UNDIVIDED (MIDDLE CAMBRIAN)

Cw WOLSEY SHALE (MIDDLE CAMBRIAN) – Greenish-gray, micaceous, fissile to blocky shale, with common thin interbeds of calcareous sandstone and glauconitic, sandy limestone bearing marine trace fossils. Poorly exposed throughout map area. Thickness ranges from 150 ft on Crowfoot Ridge to about 90 ft in the Cooke City area.

Cf FLATHEAD FORMATION (MIDDLE CAMBRIAN) – White to light-gray, fine- to medium-grained, well-sorted, quartzose sandstone; lower part commonly coarse-grained or pebble-conglomeratic, and stained reddish or brownish. Stratification commonly observed including cross beds and graded bedding. Upper part of formation may have thin interbeds of fissile green shale. Commonly not well exposed, and forms low rounded ledges. Thickness varies from about 30 m at Cooke City to 48 m on Crowfoot Ridge in the Gallatin Range (Ruppel, 1972).

PRECAMBRIAN

pCmy MYLONITE (AGE UNCERTAIN) – Occurs in two small outcrops along north border of map area along Tom Miner Creek.

PROTEROZOIC

XAmy MYLONITE (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) Age of mylonitization about 1.8 b.y., coeval with mylonitic rocks in the Madison Range (O'Neill and Christiansen, 2002, 2004)

XAgd GRANODIORITIC GNEISS (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Foliated granodiorite; unit occurs as intrusive sills that locally show crosscutting relationships and chilled margins. The rock is equigranular and composed of plagioclase, quartz, microcline, hornblende, and biotite (from O'Neill and Christiansen, 2002, 2004).

XAam AMPHIBOLITE (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Amphibolite dikes and sills in the Madison Range range from infolded, disjointed units to tabular sheets with sharp, planar contacts; mapped units were probably originally grabbroic intrusive rock. In the Centennial Range and Horn Mountains, amphibolite is green to greenish-brown, schistose to massive, generally fine grained, and locally porphyroblastic; actinolite makes up as much as 50-90 percent of rock (from O'Neill and Christiansen, 2002, 2004).

XAm MARBLE (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Massive, light-gray to cream-colored dolomitic marble interlayered with thin quartzite bands; schistosity defined by aligned chlorite and phlogopite, and flattened dolomite grains. In thin section, dolomite dominates the marble; calcite is associated with quartzite layers only; quartz is present generally as granular bands within marble (from O'Neill and Christiansen, 2002, 2004).

XAq QUARTZITE (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Light-green, poorly banded quartzite interfingering with adjacent biotite schist and marble; quartzite has been completely recrystallized and does not show clastic textures or graded bedding (from O'Neill and Christiansen, 2002, 2004).

XAms MICA SCHIST (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Interlayered rusty-yellow-weathering, quartz-rich muscovite schist and thin quartzite; locally contains abundant magnetite, chlorite, biotite, and poikiloblastic garnet (from O'Neill and Christiansen, 2002, 2004).

XAcs CHLORITE-BIOTITE SCHIST (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Well-banded chlorite-biotite schist and gneiss containing variable amounts of quartz and epidote; interlayered with green phyllonite, chloritic schist with quartz augen, and granulated amphibolite (from O'Neill and Christiansen, 2002, 2004).

XAbs BIOTITE SCHIST AND GNEISS (EARLY PALEOPROTEROZOIC(?) – LATE ARCHEAN) – Biotite-rich metamorphic rocks. Compositional layering defined by relative proportions of quartz, biotite, garnet, and muscovite. One- to 3-m-thick beds of biotite-rich metasandstone with well-preserved clastic textures separated by thinner beds of metapelite are common. Biotite schist is also interlayered with marble and is associated with chlorite-quartz schist and well-banded quartzite similar to banded cherts associated with iron formation (from O'Neill and Christiansen, 2002, 2004).

ARCHEAN

Adi DIORITIC GNEISS (MIDDLE ARCHEAN) – White-and-green-spotted, well-foliated plagioclase-hornblende-quartz rock occurs as thin sills and small stocks. Sills typically consist of 60-80 percent plagioclase, hornblende, and minor quartz; stocks are more felsic and include biotite and as much as 30 percent quartz (from O'Neill and Christiansen, 2002, 2004).

Ag GRANITE AND GRANITIC GNEISS (MIDDLE ARCHEAN) – Pink, foliated granitic rocks, showing weakly to strongly discordant contacts with adjacent rocks. Rock composition and texture is variable, ranging from medium-grained and equigranular with faint layering defined by aligned biotite, to highly folded and contorted leucogranite enclosing granodioritic xenoliths, to mafic, folded granite and granite gneiss (from O'Neill and Christiansen, 2002).

Agn	GNEISSIC ROCKS (MIDDLE ARCHEAN) – Mostly biotite granodiorite to biotite quartz monzonite gneiss (Casella and others, 1982). In this area, foliation usually strikes NNE, with variable dips. These crystalline rocks must transmit water through fractures, but to what extent this occurs is unknown. Joint and fracture systems are not obvious at the outcrop scale but are on air photos in some locations. A significant amount of water issues from these rocks at the Mineral Hill Mine just west of the study area (John Metesh, personal communication, 1999). Faults may also be important as ground-water conduits. North-northeast-striking faults along lower Buffalo Fork have the potential to transmit ground water into Yellowstone National Park. In Slough Creek near the Park boundary, metamorphic rocks are cut by circular faults associated with the Silvertip Structure (Courtis, 1965; Rubel and Romberg, 1971) that probably do not facilitate ground-water movement into the Park.
Ahga	HORNBLENDE-PLAGIOCLASE GNEISS AND AMPHIBOLITE (MIDDLE ARCHEAN) – Gray to black, medium-grained, hypidiomorphic equigranular, moderately to well-foliated; contains as much as 5 percent quartz and traces of zircon, opaque minerals, and apatite; locally garnetiferous. Plagioclase is typically An-30 and weathers white. Commonly contains white, migmatitic leucosomes of anorthosite as thick as 10 cm. Amphibolite envelopes around some metabasite intrusive bodies indicate at least some amphibolite was derived from intrusive rocks. Unit may include minor amounts of other Archean rocks (from Kellogg and Williams, 2002).
Aqfb	QUARTZ-FELDSPAR-BIOTITE GNEISS AND MIGMATITE (MIDDLE ARCHEAN) – Similar in composition to augen gneiss (not mapped) but lacks tectonite fabric; similar in texture to granite gneiss (Ag) but is less mafic and generally concordant.
Abs	BIOTITE SCHIST (MIDDLE ARCHEAN) – Black, dark-gray, and gray, fine- to medium-grained biotite-plagioclase-quartz, +/- hornblende, +/- microcline schist. Interpreted to be sheared mafic rock that equilibrated at lower amphibolite facies; not studied in detail. Crops out in Gallatin Canyon-Hell Roaring Lake (Spanish Peaks) area (from Kellogg and Williams, 2000).
At	TONALITIC GNEISS (MIDDLE ARCHEAN) – Tonalitic migmatite-gneiss and tonalitic biotite gneiss are highly variable both texturally and compositionally; gneiss includes amphibolitic migmatite breccia, leucotonalite gneiss, and dark-gray tonalitic biotite gneiss with moderate migmatite banding. Locally, tonalite gneiss is interlayered with a mixed gneiss composed of green quartzite, biotite-garnet gneiss, amphibolite and garnet amphibolite, and gedrite-cordierite-bearing gneiss. All tonalitic rocks consist of essential plagioclase, quartz, hornblende, and biotite with a granoblastic texture. Also included with these rocks is migmatitic granite gneiss characterized by granite leucosomes containing abundant microcline between thin layers enriched in plagioclase, biotite, and, locally, hornblende (from O'Neill and Christiansen, 2002, 2004).

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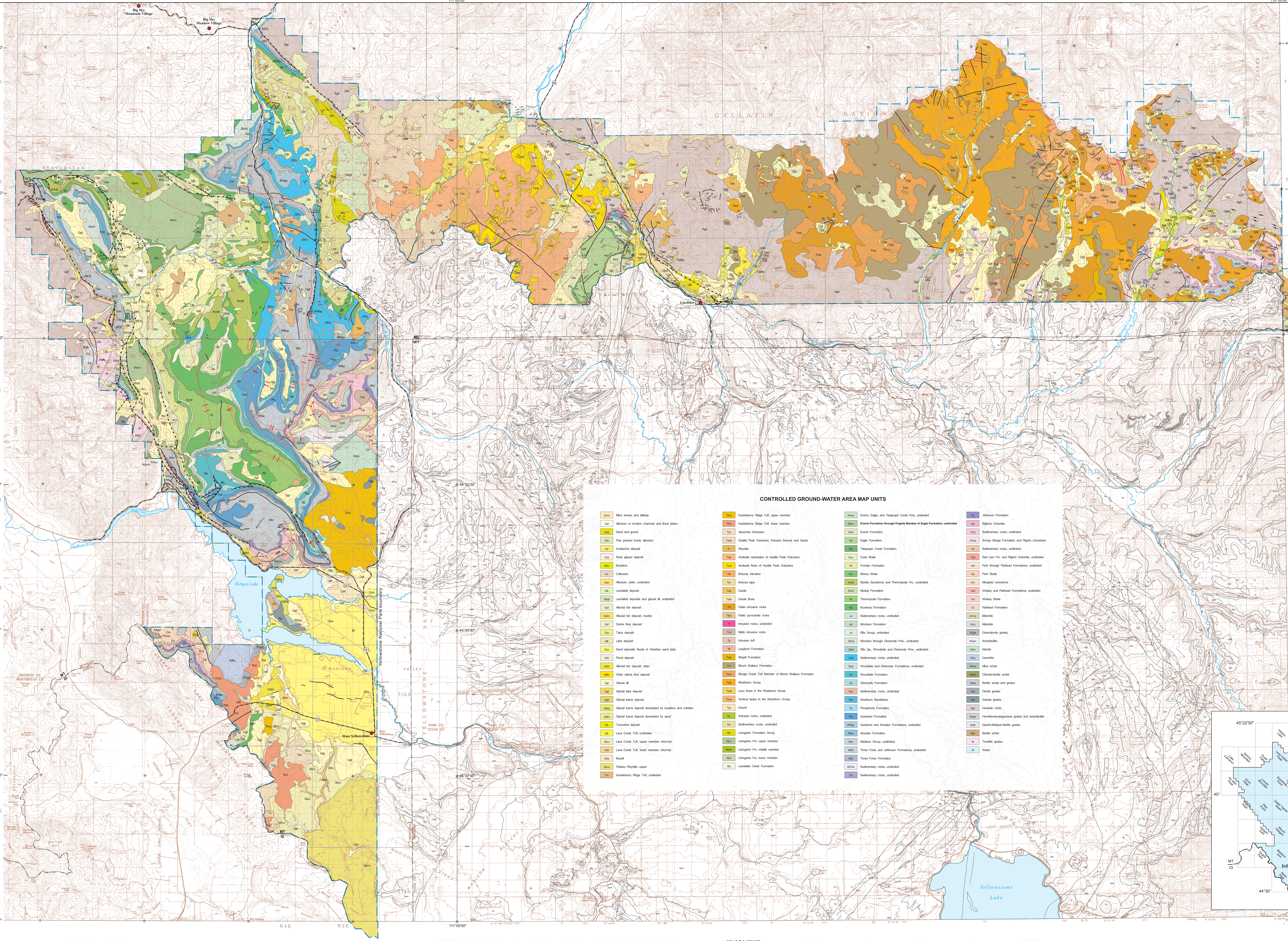

CONTROLLED GROUND-WATER AREA MAP UNITS

Symbol	Unit
Qmd	Mine dumps and tailings
Qal	Alluvium of modern channels and flood plains
Qsg	Sand and gravel
Qfa	Fine grained humic alluvium
Qa	Avalanche deposit
Qrg	Rock glacier deposit
Qbo	Boulders
Qc	Colluvium
Qao	Alluvium, older, undivided
Qls	Landslide deposit
Qlsgt	Landslide deposits and glacial till, undivided
Qaf	Alluvial fan deposit
Qafm	Alluvial fan deposit, muddy
Qdf	Debris flow deposit
Qta	Talus deposit
Qlk	Lake deposit
Qos	Sand deposits, fluvial of Obsidian sand plain
Qfd	Flood deposit
Qafo	Alluvial fan deposit, older
Qdfo	Older debris flow deposit
Qgt	Glacial till
Qgl	Glacial lake deposit
Qgk	Glacial kame deposit
Qgkg	Glacial kame deposit dominated by boulders and cobbles
Qgks	Glacial kame deposit dominated by sand
Qtr	Travertine deposit
Qlc	Lava Creek Tuff, undivided
Qlcu	Lava Creek Tuff, upper member, informal
Qlcl	Lava Creek Tuff, lower member, informal
Qba	Basalt
Qpcu	Plateau Rhyolite, upper
Thr	Huckleberry Ridge Tuff, undivided
Thru	Huckleberry Ridge Tuff, upper member
Thrl	Huckleberry Ridge Tuff, lower member
Tav	Absaroka Volcanics
Tavb	Hyalite Peak Volcanics, Volcanic breccia vent facies
Tr	Rhyolite
Tae	Andesite epiclastics of Hyalite Peak Volcanics
Tanf	Andesite flows of Hyalite Peak Volcanics
Tbi	Breccia, intrusive
Tbr	Breccia pipe
Tda	Dacite
Tdaf	Dacite flows
Tfi	Felsic intrusive rocks
Tfpy	Felsic pyroclastic rocks
Ti	Intrusive rocks, undivided
Tmi	Mafic intrusive rocks
Tit	Intrusive tuff
Tlf	Langford Formation
Twp	Wapiti Formation
Tm	Mount Wallace Formation
Tms	Slough Creek Tuff Member of Mount Wallace Formation
Twa	Washburn Group
Twaf	Lava flows in the Washburn Group
Twav	Vertical facies in the Washburn Group
Tgr	Gravel
Kv	Volcanic rocks, undivided
Ks	Sedimentary rocks, undivided
Klv	Livingston Formation Group
Klvu	Livingston Fm, upper member
Klvm	Livingston Fm, middle member
Klvl	Livingston Fm, lower member
Klc	Landslide Creek Formation
Kevtc	Everts, Eagle, and Telegraph Creek Fms, undivided
Kevv	**Everts Formation through Virgelle Member of Eagle Formation, undivided**
Kevt	Everts Formation
Ke	Eagle Formation
Ktc	Telegraph Creek Formation
Kco	Cody Shale
Kf	Frontier Formation
Km	Mowry Shale
Kmdt	Muddy Sandstone and Thermopolis Fm., undivided
Kmd	Muddy Formation
Kt	Thermopolis Formation
Kk	Kootenai Formation
Js	Sedimentary rocks, undivided
Jm	Morrison Formation
Je	Ellis Group, undivided
JTimd	Morrison through Dinwoody Fms., undivided
JTied	Ellis Gp., Woodside and Dinwoody Fms., undivided
JTiPs	Sedimentary rocks, undivided
Tiwd	Woodside and Dinwoody Formations, undivided
Tiw	Woodside Formation
Tid	Dinwoody Formation
Pzs	Sedimentary rocks, undivided
Psh	Shedhorn Sandstone
Pp	Phosphoria Formation
IPq	Quadrant Formation
IPMqa	Quadrant and Amsden Formations, undivided
IPMa	Amsden Formation
Mm	Madison Group, undivided
MDtj	Three Forks and Jefferson Formations, undivided
MDt	Three Forks Formation
MDOs	Sedimentary rocks, undivided
Ds	Sedimentary rocks, undivided
Dj	Jefferson Formation
Ob	Bighorn Dolomite
O€s	Sedimentary rocks, undivided
O€sp	Snowy Range Formation and Pilgrim Limestone
€s	Sedimentary rocks, undivided
€rlp	Red Lion Fm. and Pilgrim Dolomite, undivided
€pf	Park through Flathead Formations, undivided
€p	Park Shale
€m	Meagher Limestone
€wf	Wolsey and Flathead Formations, undivided
€w	Wolsey Shale
€f	Flathead Formation
p€my	Mylonite
Xmy	Mylonite
XAgd	Granodiorite gneiss
XAam	Amphibolite
XAm	Marble
XAq	Quartzite
XAms	Mica schist
XAcs	Chlorite-biotite schist
XAbs	Biotite schist and gneiss
Adi	Diorite gneiss
Ag	Granite gneiss
Agn	Gneissic rocks
Ahga	Hornblende-plagioclase gneiss and amphibolite
Aqfb	Quartz-feldspar-biotite gneiss
Abs	Biotite schist
At	Tonalitic gneiss
W	Water

Sources of Geologic Data:

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Geologic Symbols

Fault: dashed where approximately located, dotted where concealed.

Thrust fault: dashed where approximately located, dotted where concealed, teeth on upper plate.

Axis of anticlinal fold; dotted where concealed.

Axis of synclinal fold; dotted where concealed.

54 Strike and dip of bedding.

Strike of vertical joint.

38 Strike and dip of inclined foliation.

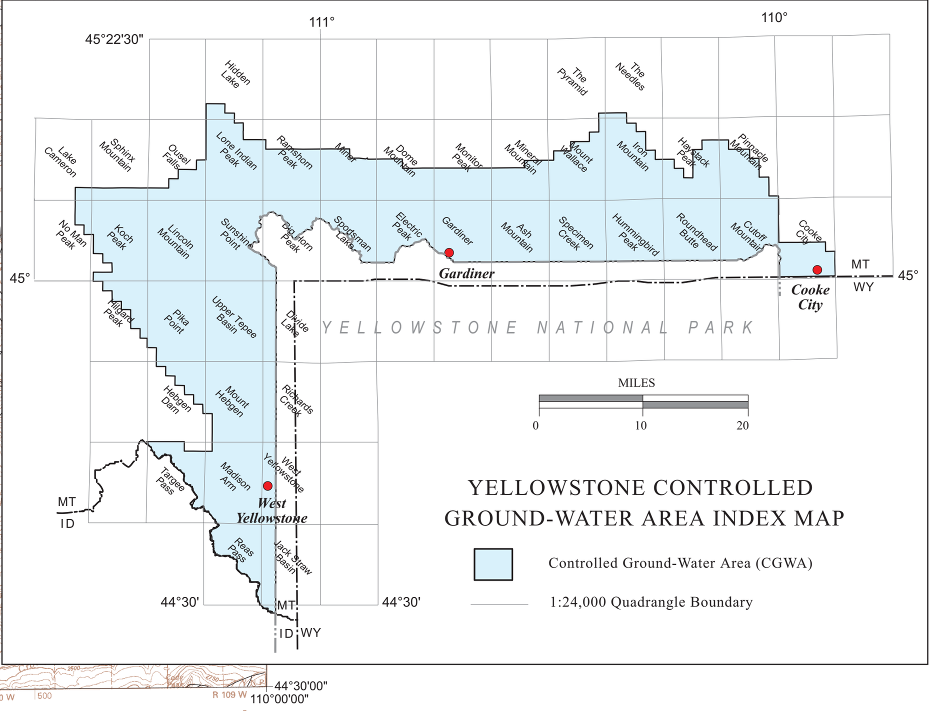
76 Strike and dip of vertical foliation.

Mafic dike.

Felsic dike.

Study area boundary

Geologic data for Yellowstone National Park area are from: U.S. Geological Survey, 1972, Geologic map of Yellowstone National Park: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-711, scale 1:125,000. For digital data, contact: Yellowstone Center for Resources, Spacial Analysis Center, P.O. Box 168, Yellowstone National Park, WY 82190.



YELLOWSTONE CONTROLLED GROUND-WATER AREA INDEX MAP

Controlled Ground-Water Area (CGWA)

1:24,000 Quadrangle Boundary

SCALE 1:100 000

KILOMETERS

MILES

MBMG Open File 557

Geologic Map of the Yellowstone National Park Controlled Ground-Water Study Area

Compiled and mapped by Jeffrey D. Lonn,
Karen W. Porter, and John J. Metesh
GIS Preparation by Paul Thale
Cartography by Susan M. Smith

2007

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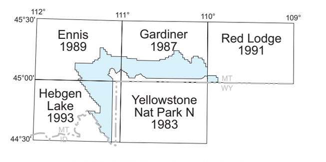
Primary support for this map was provided by the National Park Service. Additional support was provided by the Custer National Forest, the Gallatin National Forest, the U.S. Geological Survey's STATEMAP program, and the Montana Bureau of Mines and Geology.

Base from U.S. Geological Survey
30' x 60' topographic quadrangles
Projection: UTM zone 12; 1927 NAD



1:100,000 Quadrangle Index

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