Chapter 2
Study area

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The Greater Green River Basin (GGRB) includes the Green River Basin, the Great Divide Basin, and the Little Snake River Basin (**Figure 1-1**). The project boundary is determined by the distal river drainage basin divides. The drainage basin boundaries overlap several geologic features within the GGRB. The continental divide marks the northern and eastern boundaries of the GGRB; it bifurcates and reconverges around the Great Divide Basin (**Figure 1-1**). **Figure 2-1** shows the townships and ranges in the GGRB.

The Wyoming portion of the GGRB, as delineated using GIS databases, has an area of 20,792 square miles (13,306,700 acres). The Wyoming GGRB covers 21.3 percent of the area of the state. The adjacent 3,821 square miles (2,445,900 acres) of the Colorado and Utah GGRB added to the Wyoming GGRB area gives a total basin area of 24,613 square miles (15,752,500 acres) (**Figures 1-1** and **2-2**).

Surface elevations in the Wyoming GGRB range from 13,804 feet above mean sea level on Gannett Peak – the highest point in Wyoming, in the central Wind River Range – to 6,040 feet above mean sea level, measured as the high-water level in Flaming Gorge Reservoir on the Green River at the Wyoming-Utah border. The lowest elevation within the internal drainage of the Great Divide Basin is 6,647 feet above mean sea level.

In 2007, the population of the Wyoming GGRB was estimated at 54,760 (WWC Engineering, 2007), giving an average population density of 2.6 per square mile.

Average annual precipitation in the GGRB ranges from less than 7 inches in central basin areas to nearly 60 inches in the high mountain areas above 10,000 feet in elevation (**Figure 2-3**). Most of the lowest parts of the central basin areas receive between 6 and 15 inches of precipitation annually. The highland and mountain areas receive 21 to 59 inches.

Vegetation in the basin areas is mixed-grassland and sagebrush steppe, sagebrush, scrub/brush lands, and high-altitude desert, ranging to alpine forest and alpine tundra on the higher mountains. At lower elevations in the basin, the vegetation includes abundant sagebrush, saltbush, greasewood, and desert shrub. Forested areas contain lodgepole pine, spruce, fir, and aspen.

GEOLOGIC SETTING: STRUCTURE

The GGRB is bounded by the Overthrust Belt to the west, the Hoback Basin to the northwest, the Wind River Range and Granite Mountains to the north, the Rawlins Uplift to the east, the Sierra Madre to the east-southeast, the southern Sand Wash Basin in Colorado to the south-southeast, and the Uinta Mountains in Utah to the south. Within the GGRB, the Rock Springs Uplift and Bridger Basin are located in the Green River Basin proper; the Wamsutter Arch separates the Great Divide Basin from the Washakie Basin; and Cherokee Ridge separates the Washakie Basin from the Sand Wash Basin (**Figure 2-2**).

The basin topography follows undulations on the Precambrian basement surface, formed by folding and faulting of the earth's crust under compressional stress that began and was most intense during the Sevier and Laramide orogenies. As shown in **Figure 2-4**, some Precambrian basement areas in the GGRB downwarped (subsided) and formed structural basins, while adjacent areas upwarped to form mountains, uplifts, and structural arches and ridges. Sediments eroded from the upwarped areas were deposited over the pre-Laramide sediments within the new structural basins.

The maximum measured structural offset of Precambrian basement rocks in the GGRB is on a Laramide fold-thrust fault in the northern Green River Basin near Pinedale, where the rocks are structurally offset by approximately 44,000 feet. The Precambrian surface, more than 30,000 feet below sea level in the deepest part of the structural basin, is faulted against Precambrian rocks uplifted to nearly 14,000 feet at the top of the Wind River Range (**Figure 2-4**).

Figure 2-5 is a geologic cross section across southwestern Wyoming, from the Overthrust Belt eastward across the Moxa Arch, Green River Basin, Rock Springs Uplift, and Washakie Basin.

The cross section shows the Precambrian basement rocks overlain by varying thicknesses of Paleozoic to Cenozoic formations; some large-scale geologic structures; and major faults. The structural basins are depressions in the crust in which thicker sedimentary rock units accumulated. The uplifts and structural arches mark where the crust upwarped, and associated folding and faulting.

Overthrust Belt. The Overthrust Belt is a large, elongate fold-thrust complex located in southwestern Wyoming and adjacent areas of Idaho and Utah. It is a region of complex structural deformation of Paleozoic and Mesozoic units: folding, reverse faulting, thrust faulting, and overthrust faulting; and a later phase (beginning in the late Tertiary) of overprinted normal faulting that has continued to the present day. The thrust sheets were generally transported eastward during the Sevier Orogeny (Late Jurassic to Eocene). The north–south trending, parallel thrust faults of the Overthrust Belt are generally younger to the east. The Moxa Arch is a parallel fold structure east of the Overthrust Belt in the western Green River Basin (**Figures 2-2** and **2-5**).

Green River Basin. The Wyoming Green River Basin has an area of approximately 14,700 square miles. West of the Rock Springs Uplift, the local depression of the Green River Basin between the uplift and the Moxa Arch shows a depth of more than 25,000 feet below land surface on the Precambrian basement contours (more than 20,000 feet below mean sea level) (**Figures 2-2**, **2-4**, and **2-5**).

Figure 2-4 shows a structural depression in the Pinedale area deeper than 35,000 feet below land surface on the Precambrian basement contours (more than 30,000 feet below mean sea level). The structural trend on this deepest part of the Green River Basin is northwest–southeast, semi-parallel to the northwest–southeast structural trend of the Wind River Range (**Figure 2-4**).

Great Divide Basin. The Great Divide Basin has an area of approximately 3,500 square miles. Elevations range from 6,647 feet above mean sea level near basin center (Sec. 32, T.24N., R.94W.) to more than 8,000 feet in the adjacent highlands (Collentine et al., 1981). **Figure 2-4** shows the Great Divide Basin with a structural depth more than 25,000 feet below ground surface on the Precambrian basement contours (more than 20,000 feet below mean sea level). The deepest parts of the Great Divide Basin are located in the northwestern and southeastern basin; their structural trend is approximately west-northwest (**Figure 2-4**).

Washakie Basin. The Washakie Basin has an area of approximately 2,600 square miles. Elevations range from approximately 6,100 feet above mean sea level to approximately 8,700 feet at Pine Butte in the southwestern basin (Collentine et al., 1981). **Figure 2-4** shows a structural depth of more than 20,000 feet below land surface on the Precambrian basement contours (more than 15,000 feet below mean sea level in the central basin). This deepest part of the Washakie Basin is oriented north–south in structural trend (**Figure 2-4**), parallel to the major structural trend of the Rock Springs Uplift (**Figure 2-4**).

Rock Springs Uplift. The Rock Springs Uplift has an area of approximately 1,750 square miles (50 miles by 35 miles). Elevations range from approximately 6,200 feet above mean sea level on Bitter Creek to 8,680 feet above mean sea level at Aspen Mountain on the southern half of the uplift and to more than 7,500 feet in the Leucite Hills (Collentine et al., 1981). The maximum structural uplift of the Rock Springs Uplift is estimated at 17,000 feet (Love, 1961a). The Precambrian basement rocks lie about 8,000 feet below land surface (less than 2,000 feet below mean sea level) in the central Baxter Basin area of the Rock Springs Uplift. The Rock Springs Uplift is a doubly-plunging, anticlinal fold (dome) structure with a north–south major structural trend.

The deepest and oldest geologic formation exposed at land surface in the core of the Rock Springs Uplift is the Upper Cretaceous Baxter Shale. The surface exposure includes the Baxter Basin area (**Plate 2**). A north–south trending reverse fault, east side upthrown, lies along the west flank of the Rock Springs Uplift (**Figure 2-5**); it is associated with the compressional stress and anticlinal folding that formed the uplift during the Laramide Orogeny. Most of the structural doming of the Rock Springs Uplift occurred after Eocene time (Surdam and Jiao, 2007).

Sierra Madre. The Sierra Madre ranges in elevation from 6,330 feet above mean sea level on the Little Snake River to 11,007 feet on Bridger Peak (Collentine et al., 1981). Precambrian basement rock units are exposed in the uplifted core of the Sierra Madre, and Miocene formations unconformably overlie and blanket the flanks of this mountain uplift (**Plate 2**).

GEOLOGIC SETTING: ROCK UNITS

This section describes the geologic characteristics of the geologic units in the GGRB, or rock-stratigraphic units that are grouped in these geologic units, and introduces their hydrologic character. Some of these geologic descriptions are taken directly from Mason and Miller (2005) and Bartos et al. (2006), with minor modifications. Other geologic descriptions are summarized from Welder and McGreevy (1966), Welder (1968), Lines and Glass (1975), Ahern et al. (1981), Collentine et al. (1981), and Love and Christiansen (1985).

The 170 digital GIS geologic units that compose the GGRB are introduced in Chapter 1, described in detail in **Appendix 1** as constituents of the hydrogeologic units described in Chapter 5, and shown on **Plate 2**. In this section, the order of geologic units in **Appendix 1** and **Plate 7**, and the order of the grouped rock-stratigraphic units presented on **Plate 1a**, are generally followed.

Plate 1a is a stratigraphic chart correlating the geologic formations in the subareas of the Wyoming GGRB: areas of the Green River Basin, Great Divide Basin, and Washakie Basin, and the uplifts that separate and border them. In the Wyoming Green River Basin, the Paleozoic formations have an average combined thickness of about 5,000 feet and a maximum combined thickness estimated at 9,800 feet. The Mesozoic formations have an average combined thickness of about 12,000 feet and a maximum combined thickness estimated at 29,000 feet. Of the Cenozoic rocks in the basin, the Paleocene-Eocene formations have an average combined thickness of between 5,000 and 8,000 feet and a maximum combined thickness estimated at more than 12,000 feet.

CENOZOIC UNITS

Quaternary geologic units

As shown as outcrop on **Plate 2** and **Plate 3**, Quaternary deposits include unconsolidated alluvial and colluvial sediments, landslide deposits, dune sand (eolian), lacustrine sediments, glacial deposits, gravel pediment and fan deposits, undivided surficial deposits, and terrace gravels, as well as consolidated uppermost Pliocene to Quaternary alkalic extrusive and intrusive igneous rocks (Welder and McGreevy, 1966, sheet 3; Welder, 1968, sheet 2; Lowry et al., 1973, sheet 3; Love and Christiansen, 1985). Quaternary unconsolidated deposits in the basin are generally less than 100 feet thick and are present in many areas of the GGRB (**Figures 3-2** and **3-6**; **Plate 2**). Elsewhere in the GGRB, Quaternary bedrock formations are exposed at the land surface (for example, outcrops on mountain uplifts and along basin margins) or are buried by soil (for example, central basin areas).

Alluvium and colluvium. The Quaternary alluvial/colluvial deposits in the GGRB are interbedded and unconsolidated mixtures of clay, silt, sand, and gravel located along stream and river channels. They are commonly less than 50 feet thick, although locally they may exceed 100 feet in thickness. The alluvial/colluvial deposits unconformably overlie bedrock formations or older unconsolidated deposits.

Quaternary alluvium and colluvium occur in the major drainages of the GGRB: the Green River, Little Snake River, New Fork River, Hams Fork River, Blacks Fork River, Henry's Fork River, and Big Sandy River (**Figure 1-1**; **Plate 2**). These surficial unconsolidated sedimentary deposits are also present in many of the minor stream drainages (**Plate 3**) (Love and Christiansen, 1985), and consist of mixtures of clay, silt, mud, sand, and gravel, with coarser materials and cobbles near the higher elevations and uplifted areas (Berry, 1960; Lowry et al., 1973). Welder (1968, sheet 2) and Welder and McGreevy (1966, sheet 3) indicated that alluvium and colluvium generally range in thickness from 0 to 50 feet in the GGRB. Alluvium and colluvium may be a source of sand and gravel for construction materials (Harris and Meyer, 1986; Harris, 1996).

The groundwater in the alluvial deposits is commonly connected hydrologically to local surface-water streams, and is unconfined. The groundwater quality in the alluvial deposits is similar to that of the associated surface water. Shallow groundwater flow is generally intergranular porous flow in this unconsolidated sediment, and flow direction is predominantly controlled by topography. In general, larger grain size in the alluvial deposits correlates with greater permeability and a higher rate of groundwater flow. The Wyoming Framework Water Plan (WWC Engineering, 2007) classifies the alluvial deposits as a major aquifer, in areas where the deposits are sufficiently permeable and water-saturated.

Landslide deposits. Quaternary landslide deposits have been mapped throughout the GGRB as part of a geologic hazards evaluation. Because they cover small areas, the deposits cannot be easily seen on **Plate 2**. Detailed landslide maps at a scale of 1:100,000 may be consulted at the WSGS in Laramie to investigate local deposits. The composition, size, and distribution of landslide materials depend on the lithology of their source formation(s) and processes of transport. Berry (1960) reported that their thickness is as great as 200 feet on the Rawlins Uplift. He also indicated that while the deposits do not yield water to wells, small springs commonly occur at the base of the deposits. Some of these deposits are saturated and can produce enough water locally for stock or domestic use.

Dune sand and loess (eolian) deposits. Quaternary eolian (wind-blown) sand and loess (silt) deposits are found in many parts of the GGRB (**Plate 2**). These deposits can be as much as 30 feet thick in the Green River Structural Basin (Welder, 1968, sheet 2) and to as much as 70 feet in the Great Divide and Washakie Basins (Welder and McGreevy, 1966, sheet 3). The most striking example is the Killpecker Dune Field east of the Eden area (**Figure 1-1**; **Plate 2**): it contains both active and dormant sand dunes, and covers 170 square miles (Ahlbrandt, 1974, p. 51) in an east-west band starting a few miles east of Eden and continuing eastward for more than 50 miles. The sand in the dune field originates primarily from the Laney Member of the Green River Formation (Gibbons et al., 1990, p. G12). The dune field has been active intermittently during the past 20,000 years, and has recorded climatic fluctuations associated with glaciation periods (Gibbons et al., 1990, p. G12).

Holocene to Pleistocene windblown deposits in most of the GGRB are generally less than 100 feet thick, but locally can be more than 100 feet thick. Small, unmapped eolian deposits in the GGRB range from 1 to 10 feet thick.

The sand dune deposits are oriented dominantly west–east or southwest–northeast, which corresponds to the present-day prevailing wind directions. Locally, the basal eolian deposits may contain shallow groundwater as perched and unconfined groundwater, especially where the permeable eolian deposits overlie weathered low-permeability bedrock strata (shale, mudstone, and claystone) of Tertiary to Cretaceous age. In an actively migrating sand dune, the dune may incorporate quantities of snow on the lee side of the dune during winter. During warmer summer months, this subsurface snow interbedded with sand will gradually melt and provide groundwater to the eolian deposits.

Playa lake and other lacustrine deposits. As shown on **Plate 2**, the Quaternary playa lake and other lacustrine (lake) deposits are found mainly in the Great Divide and Washakie Basins, but some deposits are mapped in the north-central Green River Basin (Love and Christiansen, 1985) and north of the Rawlins Uplift in the Lost Soldier-Separation Flats area (Gaylord, 1982; Case et al., 1998). Welder and McGreevy (1966, sheet 3) described the lacustrine deposits in the Great Divide Basin as consisting of clay, silt, and sand mixtures that are less than about 25 feet thick and unlikely to yield usable groundwater in most areas. The deposits in the Separation Flats area may be a source of sodium salt evaporates (Harris et al., 1985).

Glacial deposits. Small Quaternary glacial deposits are present in the Overthrust Belt, Wind River Range, Sierra Madre, and Uinta Mountains (**Plate 2**) (Love and Christiansen, 1985). Lowry et al.

(1973, sheet 3) described these glacial materials as poorly sorted mixtures of clay, silt, sand, gravel (pebbles to boulders), and larger blocks. These glacial deposits may be a source of sand and gravel construction materials (Harris and Meyer, 1986; Harris, 1996).

Alkalic extrusive and intrusive igneous rocks. Pliocene to Upper Pleistocene igneous rocks in the Leucite Hills area comprise volcanic cones, necks, plugs, lava flows, and sheets located on the northern Rock Springs Uplift (Osterwald et al., 1966, p. 152) (**Plate 2**). These rocks are lamproites, silica-poor and highly potassium-rich. Their mineralogy and petrology are described by Hausel (2006, p. 22ff.).

There are also a few remnant volcanic rocks in the Green River Basin, including the Badgers Teeth (the volcanic neck in Sec. 7, T.21N., R.107W.), and Pilot Butte (the flat-topped mesa in Sec. 11, T.19N., R.106W.) (Osterwald et al., 1966, p. 152–154). These 1.25-million-year-old, leucite-bearing extrusive and intrusive igneous rocks (Love and Christiansen, 1985) consist predominantly of wyomingite and orendite (Osterwald et al., 1966, p. 152). These rocks intrude and unconformably overlie the erosional surface at the top of the Tertiary Green River and Wasatch Formations and Upper Cretaceous formations, (Osterwald et al., 1966, p. 152).

Welder (1968, sheet 2) considered there to be no potential for groundwater development from these igneous rocks in the Green River Basin, and Welder and McGreevy (1966, sheet 3) reported the potential for groundwater development in the Great Divide Basin area (Rock Springs Uplift) as unknown, but likely very poor. A few springs are reported near the base of this geologic unit; and where these rocks are sufficiently permeable with fractures and water-saturated, they may yield some small amount of water to local wells. This geologic unit is an unclassified aquifer.

Gravel, pediment, and fan deposits. There are Quaternary gravel, pediment, and alluvial fan deposits in widely scattered areas of the GGRB, including parts of the Great Divide Basin and the Wamsutter Arch area. Welder and McGreevy (1966, sheet 3) considered the potential for groundwater development from these deposits unknown, but probably poor because the deposits are generally topographically high and likely well-drained.

Undivided surficial deposits. The Quaternary undivided surficial deposits mainly consist of alluvium, colluvium, and glacial and landslide deposits (Love and Christiansen, 1985). The groundwater development potential is probably good where these deposits are sufficiently thick, permeable, and water-saturated.

Terrace gravel deposits. The Pliocene-Pleistocene-Holocene terrace gravel deposits are located along uplands bordering principal streams of the GGRB (**Plate 2**). The deposits consist predominantly of sand and gravel (cobble-boulder sizes), and some gravel is derived from older sedimentary and crystalline rocks (Lowry et al., 1973). Lowry et al. (1973, sheet 3) reported that the deposits are generally less than 20 feet thick, but locally may exceed 100 feet. These terrace gravel deposits may be a source of sand and gravel construction materials (Harris and Meyer, 1986; Harris, 1996). Some of the thin deposits are water-saturated and locally may yield enough water for stock-watering or domestic use.

Upper Tertiary geologic and rock-stratigraphic units

Undifferentiated Miocene rocks and the Browns Park Formation are present in the GGRB (**Plate 2**). Bradley (1964, p. A56) reported that because younger Tertiary rocks in southwestern Wyoming are predominantly white or very light colored, generally tuffaceous and sandy, and lacking in age-diagnostic fossils, a diversity of opinions exists regarding the Miocene formation's identity, geologic age, and correlations. Other upper Tertiary aquifers (this report) include the Oligocene Bishop Conglomerate and White River Formation – the Oligocene is considered lower Tertiary on **Plate 1a**. Whitehead (1996, p. 111) reported that the Upper Tertiary aquifers (Pliocene and Miocene only, by Whitehead's definition) are less extensive than the Lower Tertiary aquifers (Oligocene, Eocene, and Paleocene, by Whitehead's definition) in the GGRB, but commonly have greater permeability and are important local sources of groundwater.

Upper Tertiary intrusive igneous rocks. The upper Tertiary (Miocene-Pliocene) igneous intrusive rocks consist mainly of plutonic porphyries of felsic, intermediate, and basaltic compositions (Tweto, 1976; Stoeser et al., 2005). These igneous rocks are exposed in the Elkhead Mountains east of the Sand Wash Basin (Tweto, 1976), along the western flank of the Park Range in Colorado.

Upper Miocene rocks (undivided). The upper Miocene rocks (undivided) predominantly consist of interbedded sandstone and claystone. As shown on **Plate 2** and **Plate 3**, the upper Miocene rocks located along the southern flank of the Wind River Range consist of arkosic, siliceous claystone, sandstone, and conglomerate that are locally radioactive (Love and Christiansen, 1985). These rocks were originally defined as the Miocene-Pliocene South Pass Formation and may include some older rocks of Eocene age (Love and Christiansen, 1985).

East of the Wind River Range in the Granite Mountains area (**Plates 2** and **3**), the upper Miocene rocks consist of arkosic siltstone, sandstone, and conglomerate interbedded with light-colored tuffaceous and radioactive claystone and thin white cherty limestone beds (Love and Christiansen, 1985).

The upper Miocene rocks in the Sierra Madre consist of white to greenish gray, tuffaceous claystone, siltstone, and sandstone with local beds of conglomerate (Love and Christiansen, 1985). The upper part of these rocks was considered the North Park Formation, but since Love et al. (1993), this upper part has been considered the upper part of the Browns Park Formation.

Miocene rocks (undivided). The many different formation names applied to the upper Tertiary rocks (**Plate 1** and **Plate 2**) of the GGRB have caused confusion about the stratigraphic nomenclature of the area. McGrew (1951, p. 56) interpreted that the widespread Miocene sheet deposits were the Browns Park Formation, and that in Miocene time they covered the eastern GGRB. McGrew suggested that lithologic differences between the Miocene rocks of the Granite Mountains and the eastern GGRB are locally attributed to different sediment sources. Pipiringos (1955; 1961) considered McGrew's (1951) Miocene depositional sheet to have left remnants of the Browns Park Formation in the north-central Great Divide Basin.

Love (1961b) named the undifferentiated Miocene rocks in the Granite Mountains the *Miocene Split Rock Formation* and overlying *Pliocene Moonstone Formation*. The name *Split Rock Formation* was abandoned by Denson (1965), who replaced the names *Moonstone Formation* and *upper Split Rock Formation* with *Ogallala Formation* (Pliocene and late Miocene). In addition, Denson replaced *lower Split Rock Formation* with the Miocene *Arikaree Formation* and the *upper part of the Oligocene White River Formation*.

Denson and Harshman (1969) and Lowry et al. (1973) mapped the Split Rock Formation of Love (1961b; 1970) as the Ogallala Formation. Whitcomb and Lowry (1968) mapped the Miocene unit as the Moonstone and Arikaree Formations. Love et al. (1993) assigned the age of the Arikaree Formation to early Miocene and late Oligocene, and the age of the Ogallala Formation to late Miocene. Because of the disagreement in the stratigraphic formation names in the area, this report refers to these rocks in the Granite Mountains area as Miocene rocks (undivided).

In the Granite Mountains area, the Miocene rocks (Split Rock Formation of Love (1961b; 1970); Ogallala Formation of Denson (1965)) consist of gray to white sandstone, siltstone, and tuff that contain white pumicite and pumiceous limestone beds (Denson, 1965). These fine-grained rocks grade laterally toward the highlands into coarse-grained sandstone, conglomerate, and gravel. These rocks contain a large percentage of volcanic ash. The formation was deposited by a combination of fluvial, lacustrine, and eolian environments.

The Miocene formations (undivided) in the Rawlins Uplift area (**Figure 2-2**; **Plate 2**) have not been mapped with a formal name. Berry (1960) suggested that the Browns Park Formation likely covered the Rawlins area, but he did not correlate the Browns Park to the Miocene-Pliocene rocks on the eastern Rawlins Uplift. Berry (1960) and Welder and McGreevy (1966) considered the Upper Tertiary rocks at the Rawlins Uplift to be of Miocene-Pliocene age. Love and Christiansen (1985) defined these rocks as Miocene age because of a change in defining Miocene time. Love et al. (1993) defined the rocks as the Split Rock Formation. Because the name *Split Rock Formation* had been abandoned by Denson (1965), this memorandum refers to these rocks as Miocene rocks (undivided).

On the Rawlins Uplift, the Miocene rocks consist of gray to brown sandstone with beds and lenses of conglomerate (Berry, 1960). This sandstone is locally tuffaceous, cross-bedded, and calcareous ranging from calcareous sandstone to sandy limestone. The conglomerate contains chert and quartz pebbles, with occasional Precambrian cobbles. The basal conglomerate contains Precambrian-, Paleozoic-, and Mesozoic-derived pebbles, cobbles, and boulders in a fine- to coarse-grained yellow-brown sandstone matrix that is calcareous to partly tuffaceous. Berry (1960) also described thin beds of light-gray tuffaceous limestone that contains grains of chert, quartz, and feldspar, and pebbles derived from Precambrian rocks. Berry noted a maximum thickness of approximately 624 feet.

Browns Park Formation. The Miocene Browns Park Formation is a rock-stratigraphic unit present in the southern Washakie Basin (**Plate 2**) (Bradley, 1964, plate 1; Love et al., 1993) and contains a mixture of fluvial and eolian deposits. Love and Christiansen (1985) mapped the Browns Park Formation as the Late Miocene-age North Park Formation. Vine and Prichard (1959) used the name "North Park (?) Formation" to describe the Miocene rocks of the Miller Hill area on the northern flank of the Sierra Madre. No fossils have been found to determine the age of the formation, and they believed it could be either the Browns Park Formation or North Park Formation. Montagne (1991) combined the two units as the Browns Park Formation because of the difficulty in establishing a mapping boundary between the two units in the field. The stratigraphic question remains to be settled, but the hydrogeologic unit described herein is considered the Browns Park Formation.

The Browns Park Formation is mapped as Miocene rocks by Love and Christiansen (1985). According to Hansen (1986, p. 28), the Browns Park Formation in the eastern Uinta Mountains area "consists chiefly of light-colored to nearly white, loosely cemented, generally calcareous sandstone and light-gray to white, vitric and ashy to earthy, friable to firm, rhyolitic tuff." Bradley (1964, p. A56) described the Miocene rocks (undivided) on the Rock Springs Uplift as similar lithologically to the Browns Park Formation. The Miocene rocks (undivided), which contain the Browns Park aquifer, were likely deposited by a mixture of eolian and fluvial processes. Welder and McGreevy (1966, sheet 3) considered the potential for groundwater development of the Browns Park Formation largely unknown, but probably favorable.

The Browns Park Formation has varicolored (gray, green, tan, or white) calcareous to siliceous to tuffaceous, siltstone and sandstone beds that contain white pumicite beds, white chalcedonic and algal lacustral limestone ledges, and agillaceous lacustrine rocks (Powell, 1876; Hansen, 1984; Honey and Izett, 1988; Montagne, 1991). Along the flanks of the uplifts, a conglomerate layer (sometimes referred to as the "basal conglomerate") is present and derived predominantly from Precambrian rocks in a cross-bedded calcareous sandy matrix (Powell, 1876; Hansen, 1984; Honey and Izett, 1989; Montagne, 1991). The Browns Park was likely deposited by a mixture of fluvial, lacustrine, and eolian processes. The Browns Park Formation is a source of uranium; major producing areas are the Poison Basin Uranium District west of Baggs and the Ketchum Buttes Uranium District northeast of Baggs (Vine and Prichard, 1954, 1959; Harris et al., 1985; Harris, 1996).

Basalt flows and intrusive igneous rocks. In the eastern GGRB, the few outcrops of Miocene basalt flows and intrusive igneous rocks are located east of Savery Creek and along the western flank of the Sierra Madre (**Plate 2**). The basalt flows were extruded and associated intrusive igneous rocks were emplaced contemporaneously with the deposition of the Miocene Browns Park Formation (Love and Christiansen, 1985). These igneous units may yield small quantities of water locally to wells, but most of these igneous rock outcrops are well-drained highlands with little groundwater retention. This geologic unit is an unclassified aquifer.

Lower Tertiary geologic and rock-stratigraphic units

The lower Tertiary aquifers are the most widely used source of groundwater in the Wyoming GGRB. Rocks containing these aquifers occur at or near the surface in more than 75 percent of the Wyoming GGRB (see **Figures 3-2** and **3-6**; **Plate 2**). The lower Tertiary aquifers include the Eocene Ice Point Conglomerate, Bridger, Washakie, Wagon Bed, Green River, Battle Spring, and Wasatch Formations and the Paleocene Fort Union Formation. The stratigraphy of GGRB Eocene formations is highly complex; it records interfingering lithologies deposited in the ancient Lake Gosiute environment (Green River and Wasatch Formations). Fluctuations of the ancient lake level from early to middle Eocene time led to a complex intertonguing of lacustrine and fluvial deposits in the GGRB. These lake-level fluctuations also affected lacustrine water quality during accumulation of the sedimentary deposits in the basin. During times when water levels were low, mineral salts such as trona, nahcolite, shortite, dawsonite, and halite were deposited from high-salinity (brine) lake water within the sediment of the Green River Formation. The later dissolution of these mineral salts into the groundwater has adversely affected groundwater quality in many of the Eocene members/tongues/formations of the GGRB. During times when the lake level was high, when fresh water flowed from ancient rivers through Eocene Lake Gosiute, the evaporite minerals did not form within the lacustrine deposits of the Green River Formation.

Roehler (1991a, p. B1) noted that the stratigraphic nomenclature of the intertonguing Eocene Wasatch and Green River Formations has been repeatedly revised in the GGRB since Hayden (1869a,b) first named these formations. Many new tongue/member names of both formations have been defined and abandoned. For other members/tongues, the stratigraphic and geographic boundaries have been changed. In this report, the Eocene nomenclature from Love et al. (1993) is used. **Plate 1a** shows the correlation of Eocene units across the GGRB and adjacent areas. Roehler (1991a, p. B12) summarized a more detailed stratigraphic correlation for the Wasatch/Green River Formations to the member and bed level.

Bishop Conglomerate. In Sweetwater County, the Oligocene Bishop Conglomerate is present on the southwestern flank of the Rock Springs Uplift, on Pine Mountain, and in the southeastern and southwestern Green River Basin. The Bishop Conglomerate was first named by Powell (1876) for its exposure on Bishop Mountain (now Pine Mountain) in south-central Sweetwater County, near the Wyoming-Utah border. Bradley (1936, p. 172) reported that the Bishop Conglomerate consists predominantly of red, poorly sorted boulders and gravel derived from the Precambrian Uinta Mountain Group, interbedded with gray, cherty limestone, and white to greenish-gray quartzite. As indicated by the source sediment contained in the Bishop Conglomerate, the formation was deposited by relatively quick-flowing streams flowing northward off the Uinta Mountains in Oligocene time.

Upper conglomerate member of the White River Formation. The upper conglomerate member of the Oligocene White River Formation is composed of light gray, soft, conglomeratic tuffaceous medium-grained sandstone and conglomerate of Precambrian clasts (Love and Christiansen, 1985). The upper conglomerate member is limited in area and may yield limited quantities of usable groundwater to wells in the outcrop areas where the member is sufficiently water saturated.

White River Formation. The Oligocene White River Formation occurs only in the north-central Great Divide Basin and along the flanks of the Wind River Range and Granite Mountains (**Plate 2**). The White River Formation is stratigraphically equivalent to the Bishop Conglomerate, which is a conglomeratic, up-paleogradient depositional facies of the White River Formation.

Oligocene and Upper and Middle Eocene rocks. The Oligocene and Upper and Middle Eocene rocks consist of light-gray volcanic tuff, arkosic sandstone, and lenticular conglomerate (Love and Christiansen, 1985). The rocks are located along the southern flank of the Wind River Range and north of the Rock Springs Uplift. They may yield limited quantities of usable groundwater to wells in local areas where the rocks are sufficiently water saturated.

Ice Point Conglomerate. The Ice Point Conglomerate crops out in two small locations (less than one-quarter square miles each) in Sweetwater County (Sec. 4, T.26N., R.95W. and Sec. 17, T.26N., R.96W.), and consists mainly of angular rock fragments (pebbles to boulders 10 feet in diameter) derived from Paleozoic formations in the Wind River Range in a matrix of brown to golden-yellow, arkosic, poorly cemented sandstone (Love, 1970, p. C59). The conglomerate is present in the GGRB only in the Great Divide Basin. The groundwater resources of the Ice Point Conglomerate are limited to the small outcrop areas of the formation, and the unit may yield limited quantities of water to wells where it is sufficiently water saturated.

Washakie Formation. The Middle to Upper Eocene Washakie Formation consists of fluvial sedimentary rocks in the Washakie Basin. Before Roehler (1973c) amended the stratigraphic nomenclature, the Middle to Late Eocene rocks in the Washakie Basin were assigned to various formations such as the Bridger Formation, undivided Bridger and Uinta Formations, or Washakie Formation. The Washakie Formation is exposed in an area of approximately 680 square miles in the central Washakie Basin, where its maximum thickness is about 3,200 feet (Roehler, 1973c, p. 12). The formation is predominantly a sequence of irregularly interbedded gray and green mudstone; gray, green, or brown tuffaceous and arkosic sandstone; and minor thin beds of tuff, limestone, conglomerate, shale, and siltstone (Roehler, 1973c). Roehler divided the Washakie Formation into two members: the upper Adobe Town Member (2,300 feet thick) and the lower Kinney Rim Member (900 feet thick). The two members in the Washakie Basin are separated by a basin-wide unconformity and by minor differences in lithology. The water-saturated portions of the formation are considered the Washakie aquifer.

Bridger Formation. The Eocene Bridger Formation is located in the Green River Basin and in small areas north of the Rock Springs Uplift and in the north-central Great Divide Basin (Love and Christiansen, 1985). It is exposed at the ground surface in southwestern and west-central Sweetwater County. The Eocene Bridger Formation is similar and partly time equivalent to the Washakie Formation, described above (Roehler, 1973c, p. 9). The Bridger aquifer is the water-saturated portion of the formation.

The Bridger Formation consists mostly of light gray to dark greenish and grayish brown, sandy, tuffaceous mudstone interbedded with beds and lenses of gray to brownish gray, cross bedded, medium-grained, tuffaceous, muddy sandstone; interbedded marlstone and limestone; and some volcanic-ash beds (Bradley, 1964, p. A49). Love (1939, p. 109–110) reported that eruptions of the volcanic Absaroka Range were likely the source of the incorporated volcanic material. Koenig (1960, p. 164-165) reported that the formation mostly consists of floodplain sediments, and that channel, lacustrine, deltaic, lignitic, and volcanic deposits occur to a lesser extent. He suggested that almost all of the sediments in the Bridger Formation, except the thin calcareous layers of lacustrine origin, had volcanic origins (Koenig, 1960, p. 168). Bradley (1964, p. A49) agreed with Koenig (1960) that many tuffaceous beds are present in the Bridger Formation, and also noted a substantial percentage of clastic material.

The thickness of the Bridger Formation ranges from approximately 500 to 2,300 feet in the Green River Basin (Ahern et al., 1981). Highly mineralized groundwater is present in most of this area, except possibly in sandstone beds overlain by Quaternary alluvial or gravel deposits (Welder, 1968, sheet 2).

Crooks Gap Conglomerate. The Eocene to Oligocene(?) Crooks Gap Conglomerate consists mainly of large granite boulders or blocks (up to 20 feet in diameter) embedded in a matrix of pink to gray, arkosic sandstone and siltstone (Love, 1970, p. C39). Reynolds (1976) interpreted the eastern portion of the conglomerate as possibly Oligocene in age. The Crooks Gap Conglomerate occurs in northeastern Sweetwater County (**Plate 2**), about 5 miles west of Bairoil. The conglomerate outcrop area in Sweetwater County only covers about one quarter of a square mile, but extends northward into adjacent Fremont County (Love and Christiansen, 1985). Love (1970, pl. 6) suggested that most of the conglomerate in Sweetwater County has eroded away. The Crooks Gap Conglomerate in the GGRB probably does not contain usable quantities of groundwater, although it may yield small quantities of groundwater to shallow wells locally.

Green River Formation. F.V. Hayden (1869a,b, p. 90; p 190–191 of the 1873 reprint) named the Eocene Green River Formation ("Green River Shales"), a rock-stratigraphic unit, for exposures along the Green River, west of Rock Springs, Wyoming Territory. The formation was deposited in Eocene Lake Gosiute in southwestern Wyoming. At its maximum extent, Lake Gosiute flooded most of the GGRB (Bradley, 1964, p. A36). The Green River Formation is composed of "a huge lens of fine-grained generally calcareous sedimentary rock embedded in a thick body of somewhat sandy mudstone that fills a large intermontane basin" (Bradley, 1964, p. A18). Regional Eocene climatic changes directly influenced the depositional environment and composition of stratigraphic units in ancient Lake Gosiute (Roehler, 1992a, p. E45).

The Green River Formation is divided into at least five members and one tongue: the Laney, Godiva Rim, Wilkins Peak, Tipton Shale, and Farson Sandstone Members, and the Luman Tongue (Love et al., 1993). Roehler (1992a, p. E45) postulated that the Laney Member was deposited in a wet, hot climate; the Wilkins Peak Member was deposited in a dry, hot climate; the Tipton Shale Member was deposited in a moist, warm/hot climate; and the Luman Tongue was deposited in a moist, warm climate. The Farson Sandstone Member was deposited concurrently with the Tipton Shale Member.

Laney Member. Schultz (1920, p. 27-28) named the Eocene Laney Member of the Green River Formation for exposures along the Laney Rim (now called DeLaney Rim) in the Washakie Basin. The water-saturated parts of the unit form the Laney aquifer. The Laney Member is exposed at the ground surface in a broad, north–south trending swath in the Green River Basin; in an arcuate exposure around the margin of the Washakie Basin; and to a lesser extent, north of the Rock Springs Uplift and in the northern Great Divide Basin (**Plate 2**). Bradley (1961) described the Laney Member as a "massive to thinly laminated buff, gray, and brown, marlstone, shale, and muddy sandstone; white to brown tuff and tuffaceous sandstone; low grade to rich beds of oil shale and, in shore facies, algal deposits and oolite beds." The Laney Member was deposited in Eocene Lake Gosiute during a humid period when the freshwater lake had a flow outlet (Bradley, 1964, p. A2). The Laney Member is as much as 1,900 feet thick (Bradley, 1961).

Godiva Rim Member. Roehler (1991b, p. C2) defined the Eocene Godiva Rim Member, a rock-stratigraphic unit, of the Green River Formation as a sequence of rock that intertongues with the Cathedral Bluffs Tongue of the Wasatch Formation within the Washakie Basin and Sand Wash Basin (Colorado). Love and Christiansen (1985) included this member in the lower part of the Laney Member in the Washakie Basin. The Godiva Rim Member was deposited along the eastern extent of Eocene Lake Gosiute during the lake's east–west expansions and contractions across the Washakie Basin (Roehler, 1991b, p. C5). Roehler (1991b, p. C5) reported the member as composed of interbedded oil shale, mudstone, siltstone, sandstone, and limestone. The thickness of the Godiva Rim Member is as much as 100 feet or more in the Washakie Basin (Roehler, 1992a, p. E42). The member thins northward across the Wamsutter Arch in the subsurface and pinches out within the Great Divide Basin (Roehler, 1992a, p. E42). The Godiva Rim Member is exposed around the margin of the Washakie Basin (**Plates 2** and **3**).

Wilkins Peak Member. Love and Christiansen (1985) mapped the Eocene Wilkins Peak Member as a single unit and as a combined unit with the Tipton Shale Member (**Plates 2** and **3**; **Appendix 1**). The Wilkins Peak Member crops out along the western edge of the Green River Basin, in a very small area north of the Rock Springs Uplift, and in the southeastern GGRB around the north and west margin of the Washakie Basin and south of the Rock Springs Uplift (**Plates 2** and **3**). Bradley (1961) reported that the Wilkins Peak Member consists of green-gray to white dolomitic mudstone, marlstone, and oil shale that is locally thin-bedded; and white to brown volcanic tuff, tuffaceous sandstone, marlstone, and thick beds of evaporite minerals, including several laterally extensive trona beds.

The Wilkins Peak Member was deposited in a dry, hot climate (Roehler, 1992a, p. E45), when the saline lake did not have a flow outlet (Bradley, 1964, p. A1). These restricted lake conditions caused the deposition of abundant evaporite mineral deposits, including trona [Na_2CO_3•$NaHCO_3$•$2H_2O$], in the GGRB. The thick trona beds of the Wilkins Peak Member located in western Sweetwater County are the world's largest known source of natural sodium carbonate.

In addition to the trona beds, black sodium-carbonate brine with high levels of humic and fulvic acids and under confined (artesian) pressure is present at shallow depth in the Farson-Eden area (Dyni, 1996, p. 22). This brine could yield economic quantities of soda ash and organic acids. This black brine in the Wilkins Peak Member is seemingly present only in the Farson-Eden area, but it is possible that other black brines may occur locally in the Wilkins Peak Member in other parts of the GGRB. Welder (1968, sheet 2) reported that the Wilkins Peak Member is as much as 1,400 feet thick, and Welder and McGreevy (1966, sheet 3) reported that it is as much as 1,200 feet thick in the Washakie and Great Divide basins. The Wilkins Peak Member is considered an aquifer where it is sufficiently water saturated and of acceptable quality.

Tipton Shale Member. As discussed above for the Wilkins Peak Member, Love and Christiansen (1985) show the Eocene Tipton Shale Member of the Green River Formation as a combined map unit with the Wilkins Peak Member in some areas of the GGRB. In other areas, the Tipton Shale Member is mapped as a single unit (**Plates 2** and **3**). The Tipton Shale crops out in the southeastern Green River Basin, around the margin of the Washakie Basin, in the west-central Great Divide Basin, and on the northern and southern Rock Springs Uplift (**Plates 2** and **3**).

The upper half of the Tipton Shale Member consists of light-blue-gray, organic-rich marlstone; the lower half is brown to buff soft shale and organic marlstone, with laterally extensive algal beds that are characteristic of the middle part and of shoreline deposition (Bradley, 1961). The Tipton Shale Member was deposited during warm/moist or hot/moist times when ancient Lake Gosiute was freshwater with a flow outlet (Bradley, 1964, p. A1; Roehler, 1992a, p. E45). The Tipton Shale Member is as much as 400 feet thick (Welder, 1968, sheet 2; Welder and McGreevy, 1966, sheet 3). The Tipton aquifer is the water-saturated portions of the Tipton Shale Member.

Farson Sandstone Member. The Eocene Farson Sandstone Member of the Green River Formation has been assigned several different names by stratigraphic workers over the years. Donavan (1950) assigned it to the Fontenelle Tongue of the Green River Formation, Oriel (1961) to the New Fork Tongue of the Wasatch Formation, Lawrence (1963) also to the Fontenelle Tongue, and Sullivan (1980) to the Tipton Shale Member of the Green River Formation. In 1991, Roehler (1991a) proposed that rock units with these former stratigraphic names be assigned to his newly proposed Alkali Creek Tongue of the Wasatch Formation and Farson Sandstone Member of the Green River Formation, and recommended abandoning the older New Fork Tongue and Fontenelle Tongue names. Roehler (1991a, p. B19) described the Farson Sandstone Member as gray, tan, and brown sandstone with thin interbedded gray shale and siltstone and local conglomerate, of lacustrine origin located stratigraphically between the Rife Bed and Scheggs Bed of the Tipton Shale Member.

The Wind River Range is apparently the source of the sediment of the Farson Sandstone Member. The Farson Sandstone was deposited predominantly as lacustrine fan deltas formed in the northwest part of Eocene Lake Gosiute during deposition of the Tipton Shale Member (Roehler, 1991a, p. B19-B20). At the type section on the east slopes of White Mountain southeast of Farson, Wyoming, the Farson Sandstone Member is 256 feet thick (Roehler, 1991a, p. B21). The sandstone thickens to the north toward the Wind River Range and is more than 400 feet thick in the Farson area, but thins and pinches out to the east, west, and south (Roehler, 1992, p. E33). The Farson aquifer is the water-saturated portion of the Farson Sandstone.

Luman Tongue. The Eocene Luman Tongue of the Green River Formation crops out in a thin band around the northern and western margins of the Washakie Basin; in a small area in the southeastern corner of the Green River Basin south of the Rock Springs Uplift; and in the central Great Divide Basin (**Plate 2**). Bradley (1961) described the Luman Tongue as a sequence of brown, flaky shale, oil shale, marlstone, carbonaceous shale, and limy sandstone beds that locally contain a few thin coal beds. Roehler (1992a, p. E28-E29) suggested that the Luman Tongue was deposited predominantly in a freshwater lake environment. The lake formed in a subsiding trough along the north flank of the Uinta Mountain uplift; and, during deposition of the Luman Tongue, it expanded to 13 to 40 miles wide (north–south) north of the Uintas and transgressed eastward to the Great Divide and Washakie basins, where it was more than 60 miles wide (Roehler, 1992a, p. E29). The thickness of the Luman Tongue exceeds 400 feet, with a maximum thickness of 455 feet reported in the southwestern Washakie Basin (T.13N., R.100W.) (Roehler, 1992a, p. E29). The Luman aquifer is the water-saturated portion of the Luman Tongue.

Granitic conglomerate above or in upper part of Wasatch Formation. The Eocene granitic conglomerate is located above or in the upper part of Wasatch Formation and consists of giant granite boulders and blocks in an arkosic sandstone matrix (Love and Christiansen, 1985). This geologic unit is small in area and is only present along the western flank of Wind River Range in the northern Green River Basin (Love and Christiansen, 1985).

Wasatch Formation. The Eocene Wasatch Formation, which contains the Wasatch aquifer, consists predominantly of fluvial, alluvial, and lacustrine-deltaic sediments contemporaneous with the lake deposits of the Green River Formation in the GGRB. During the Early-Middle Eocene, ancient Lake Gosiute repeatedly expanded and contracted as its water level rose and fell. Fluvial sediments of the Wasatch Formation were deposited around the lake basin margins, which narrowed when the lake expanded and widened when the lake contracted (Bradley, 1964, p. A18). The Wasatch Formation is divided into several member/tongue units within the GGRB. The Cathedral Bluffs Tongue, Niland Tongue, and main body occupy large areas of the GGRB. The Diamictite and sandstone, New Fork Tongue, Alkali Creek Tongue, La Barge Member, and Chappo Member occupy smaller areas.

Cathedral Bluffs Tongue. The Eocene Cathedral Bluffs Tongue of the Wasatch Formation occurs in the Green River Basin at or near land surface around Pine Mountain, in the Jack Morrow Hills, in a band around the margin of the Washakie Basin, and in the northwestern Great Divide Basin (**Plate 2**). The Cathedral Bluffs Tongue intertongues with other Eocene rock units (Roehler, 1992a, p. E37-E38). Roehler (1992a, p. E37) described the Cathedral Bluffs Tongue as variegated (mostly red), fluvial-deposition sediment that intertongues toward the center of the GGRB predominantly with the lacustrine rock units of the Wilkins Peak Member of the Green River Formation. Bradley (1961) described the rocks of the Cathedral Bluffs Tongue as gray and greenish gray sandy mudstone banded with pink and red beds and interbedded with massive lenses and beds of brown to yellowish muddy sandstone, which form badland slopes in outcrop. Roehler (1992a, p. E38) reported that the Cathedral Bluffs Tongue is as much as 2,000 feet thick.

Diamictite and sandstone. The Eocene Diamictite and sandstone unit in the Wasatch Formation consists of diamictite (mudstone matrix-supported pebble-cobble-boulder conglomerate) and sandstone that grades eastward into other members of the formation (Love and Christiansen, 1985). The conglomerate clasts consist of Paleozoic and Mesozoic rocks eroded from the actively uplifting mountains of the Overthrust Belt and deposited eastward into the Green River Basin. This Wasatch unit is present along the eastern flank of the Overthrust Belt and in the northwestern Green River Basin in Lincoln and Sublette counties.

New Fork Tongue of the Wasatch Formation and Fontenelle Tongue or Member of the Green River Formation. The Eocene New Fork Tongue of the Wasatch Formation consists of dull red and green mudstone, brown sandstone, and thin limestone beds that merge southward in T.23N., Sweetwater County, with other units (Love and Christiansen, 1985). The Eocene Fontenelle Tongue (or Member) of the Green River Formation consists of alternating, 350-foot-thick, buff to brown, fine- to coarse-grained sandstone, thin-bedded to thick-bedded to blocky, interbedded with green and gray mudstone as a basal member of the Green River Formation (Love and Christiansen, 1985). Roehler (1991g) redefined the stratigraphy of the Green River and Wasatch Formations, and recommended that the stratigraphic name *Fontenelle Tongue* (or Member) be abandoned.

Alkali Creek Tongue. See *Farson Sandstone Member*, page 2-12.

Niland Tongue. In Sweetwater County, the Eocene Niland Tongue of the Wasatch Formation crops out east of Pine Mountain, in the extreme southeastern Green River Basin, along the northern margin of the Washakie Basin, and in the central Great Divide Basin (**Plate 2**). Bradley (1961) reported that near the Washakie Basin, the Niland Tongue is gray mudstone and gray to white lenticular sandstone interbedded with carbonaceous shale and some sub-bituminous coal beds. Roehler (1992a, p. E30) reported that the Niland Tongue has approximately the same area as the Luman Tongue of the Green River Formation, and ranges in thickness to more than 400 feet. Roehler interpreted the depositional environment of the tongue as a dry period during the Early Eocene, when the former large, ancient Luman Lake had retreated and divided into many small freshwater lakes, swamps, and floodplains (Roehler, 1992a, p. E30). The water-saturated portion of the Niland Tongue is the Niland aquifer.

Main body of the Wasatch Formation. The Eocene main body of the Wasatch Formation crops out along the western margin of the Green River Basin, on the flanks of the Rock Springs Uplift, on the Wamsutter Arch, and in the southern Great Divide Basin (**Plates 2** and **3**). Masursky (1962, p. 10-11) suggested that the Battle Spring Formation as mapped by Pipiringos (1955, 1961) was an up-paleogradient (towards the Granite Mountains), fluvial depositional facies of the main body of the Wasatch Formation. Love (1970, p. C33-C34) agreed with this interpretation. The Battle Spring Formation is exposed in most of the eastern Great Divide Basin (**Plates 2** and **3**).

The upper part of the main body of the Wasatch Formation intertongues with some tongues and members of the Green River Formation. The lower part of the main body of the Wasatch Formation is older than Lake Gosiute and underlies the Green River Formation, rather than intertonguing with it. Love and Christiansen (1985) reported the main body of the Wasatch Formation in southwest Wyoming as drab sandstone, drab to variegated claystone and siltstone, and locally derived conglomerate around basin margins.

Like the rest of the Wasatch Formation in the GGRB, most of the main body of the Wasatch Formation is fluvial sediment deposited up-paleogradient of Eocene Lake Gosiute. The main body of the Wasatch Formation in the GGRB ranges from less than 1,000 feet thick across the northern and middle Rock Springs Uplift (it has been eroded from the central uplift) to more than 4,000 feet thick in parts of the Green River Basin and Washakie Basin (Roehler, 1992a, p. E26-E27). The Wasatch Formation produces natural gas via both conventional and coal bed natural gas (CBNG) extraction methods in southwestern Wyoming (De Bruin, 2002; Wyoming Oil and Gas Conservation Commission, 2004).

La Barge and Chappo Members. The Eocene La Barge and Paleocene-Eocene Chappo Members of the Wasatch Formation consist of red, gray, and brown mudstone; conglomerate; and yellow sandstone (Love and Christiansen, 1985). At about T.35N. in Sublette County and in the northern

Green River Basin, the La Barge Member thins and pinches out northward (Love and Christiansen, 1985). The lower part of the Chappo Member is Paleocene (Love and Christiansen, 1985).
Almy Formation. Veatch (1907) and Schultz (1914, p. 71-72) described the Almy Formation, a rock-stratigraphic unit, as overlying the Evanston Formation and underlying the Knight Formation in Uinta County and Lincoln County. The Almy and Knight formation names have been abandoned. The Almy Formation is now identified with the basal conglomerate in the lower part of the Wasatch Formation main body.

Transitional unit between Battle Spring and Wasatch Formations. This Eocene transitional unit between the Battle Spring and Wasatch Formations consists of interbedded and interfingering lithologies of the Battle Spring and Wasatch Formations (Love and Christiansen, 1985). The lithology of this unit includes medium- to fine-grained mixtures of sandstone and pebbly sandstone interbedded with mudstone and claystone. This transitional unit between the two formations crops out only in the Great Divide Basin (**Plate 2**).

Battle Spring Formation. The Paleocene to Eocene Battle Spring Formation consists of light gray to brown, coarse-grained to pebbly, feldspar-rich (arkosic) sandstone interbedded with small quantities of green claystone/mudstone containing abundant large, angular quartz grains (Pipiringos, 1955; Bradley, 1961). At its thickest, the Battle Spring Formation is 3,300 to 4,500 feet thick. It unconformably overlies the Fort Union Formation and interfingers laterally with the Wasatch and Green River Formations (Pipiringos, 1955; Welder and McGreevy, 1966, sheet 3). The Battle Spring is stratigraphically equivalent and lithologically similar to locally derived basin-margin conglomerate of the Wasatch Formation; it merges southward in the Great Divide Basin into the main body of the Wasatch Formation (Love and Christiansen, 1985).

The presence of high concentrations of uranium in the Tertiary formations and groundwaters of the Great Divide Basin has been known for years. An example of this is the Lost Creek schroeckingerite deposit located in secs. 29, 30, 31, 32, and 33, T.26N., R.94W., and sec. 25, T.26N., R.95W. in the north-central Great Divide Basin. The uranium ore schroeckingerite, $NaCa_3(UO_2)(CO_3)_3(SO_4)F \cdot 10H_2O$, is a green-yellow to yellow platy mineral. Sheridan et al. (1961, p. 428) interpreted the schroeckingerite ore deposit as probably formed by crystallization from uraniferous groundwater during evaporation. Sheridan et al. (1961, p. 429) speculated that the uranium in the Tertiary groundwater probably came from a nearby high-grade deposit such as pitchblende (uranium oxide) or uraninite (uranium dioxide).

The Great Divide Basin also has uranium-bearing Tertiary coal beds. These coals are more widespread in the basin than the schroeckingerite deposit, but the uranium content of the coals is much lower. Groundwater likely contained the uranium concentrated within these coal beds. Masursky (1962, p. B93-B95) identified three potential sources for the uranium in the groundwaters of the Great Divide Basin: hydrothermal solutions associated with Middle Eocene volcanic rocks, uranium leached from volcanic ash in nearby tuffaceous Miocene rocks, and uranium leached from sediment originating in the Granite Mountains area. Sediments of the Battle Spring Formation were derived from the Granite Mountains, and contain 0.0005 to 0.001 percent uranium (Masursky, 1962, p. B95).

On the basis of fossil pollen evidence from wells penetrating it, the lower part of the formation is Paleocene (Love, 1970). The Battle Spring was deposited in lacustrine deltaic and fluvial environments (Pipiringos, 1955), and is exposed as a large outcrop area covering much of the northeastern Great Divide Basin, mostly in northeastern Sweetwater County and in several small areas of western Carbon County (**Plate 2**).

Pass Peak Formation and equivalents. The Eocene Pass Peak Formation and equivalents include the Lookout Mountain Conglomerate Member of the Wasatch Formation. South of the Gros Ventre Mountains, it consists of gold-bearing quartzite conglomerate and intertongues southward with sandstones and claystones of the Diamictite and sandstone unit of the Wasatch Formation (Love and Christiansen, 1985). The Pass Peak Formation crops out in a small area of the far northern Green River Basin and along the northern Overthrust Belt in Sublette County (**Plate 2**).

Conglomerate of Roaring Creek. The Paleocene(?) to Eocene(?) Conglomerate of Roaring Creek is a red and gray conglomerate containing gravel-sized clasts of Mesozoic, Paleozoic, and Precambrian rocks (Love and Christiansen, 1985). The age of the formation has not been determined but is considered approximately Paleocene to Eocene; this conglomerate is older than the main body of the Eocene Wasatch Formation (Love and Christiansen, 1985). The Conglomerate of Roaring Creek is exposed in a few outcrops in the northernmost Wind River Range and northern Sublette County (**Plate 2**).

Hoback Formation. The Paleocene Hoback Formation consists of interbedded drab and gray sandstone and claystone; locally, the formation contains thick beds of red and gray conglomerate (Love and Christiansen, 1985). The Hoback Formation is exposed only in two small outcrops in the northern Green River Basin in west-central Sublette County (**Plate 2**).

Devils Basin Formation. The Late Paleocene Devils Basin Formation consists of light gray sandstone interbedded with green and gray claystone, and sparse coal and carbonaceous shale (Love and Christiansen, 1985). The Devils Basin Formation is exposed only in one small outcrop in the northern Green River Basin in north-central Sublette County (**Plate 2**). The Devils Basin Formation is stratigraphically equivalent to the upper Fort Union Formation.

Fort Union Formation. The Paleocene Fort Union Formation, which contains the Fort Union aquifer, crops out encircling the Rock Springs Uplift, along part of the southern boundary of Sweetwater County, in the north-central Great Divide Basin, and along the eastern margins of the Great Divide, Washakie, and Sand Wash basins (**Plate 2**). The Fort Union Formation consists of brown to gray sandstone, gray to black shale, and thin coal beds (Love and Christiansen, 1985). The formation was deposited during the Laramide Orogeny, when mountain ranges such as the Wind River Range, Sierra Madre, and Granite Mountains were actively uplifting contemporaneously with the subsidence of the adjacent structural basins. Love (1970, p. C115) suggested that during the Paleocene, as the Great Divide Basin was subsiding, the sediment derived from uplift areas filled the basin fast enough that the land surface in the basin remained at a nearly constant elevation.

The warm and humid Fort Union paleoenvironment maintained a similar depositional environment of rivers, swamps, wetlands, and floodplains during the Paleocene. These organic-rich swamps formed the multiple coal beds in the Fort Union Formation. The Fort Union Formation can be as much as 2,500 feet thick or more in the Green River Basin (Welder, 1968, sheet 2), and 700 to about 2,700 feet thick in the Great Divide and Washakie basins (Welder and McGreevy, 1966, sheet 3).

Numerous small coal mines and prospects have been constructed since the 1800s, and some large-scale mining operations have been proposed for the Fort Union in the Wamsutter Arch and Washakie Basin (Jones, 1991). Two active coal mines in the Fort Union Formation currently operate in eastern Sweetwater County. The Fort Union produces natural gas via both conventional and CBNG extraction methods in southwestern Wyoming (De Bruin, 2002; Wyoming Oil and Gas Conservation Commission, 2004). The Fort Union Formation in the Great Divide Basin contains uranium deposits (Harris et al., 1985; Harris, 1996).

Pinyon Conglomerate. The Upper Cretaceous to Paleocene Pinyon Conglomerate consists of brown gold-bearing quartzite conglomerate interbedded with brown and gray sandstone (Love and Christiansen, 1985). The basal part of the conglomerate in northeastern Jackson Hole has been dated at about 67 million years before the present (Ma), but farther to the south the entire sequence is Paleocene (55–66 Ma) (Love and Christiansen, 1985). The Pinyon Conglomerate is exposed only in two small outcrops in the northern Green River Basin in north-central Sublette County (**Plate 2**).

Evanston Formation. The Upper Cretaceous-Paleocene Evanston Formation consists of gray siltstone, minor red sandstone, and lignite/coal beds (Love and Christiansen, 1985). The formation is Paleocene, with an Upper Cretaceous basal unit. It is located in the Overthrust Belt and southwestern Green River Basin, in Uinta and Lincoln counties (**Plate 2**). Eastward into the Green River Basin, the Evanston Formation grades into and correlates with the uppermost part of the Upper Cretaceous Lance Formation and Paleocene Fort Union Formation.

MESOZOIC UNITS

Mesozoic rock outcrops account for approximately 12 percent of the surface exposures in the Wyoming GGRB.

Upper Cretaceous geologic and rock-stratigraphic units

Upper Cretaceous rocks occur at or near land surface in a wide belt around the Rock Springs Uplift, in a small area in the extreme northeast corner of Sweetwater County, and in a thin band along the Wyoming-Utah border east of Flaming Gorge (**Plate 2**). In all other parts of the GGRB, Upper Cretaceous formations are deeply buried by younger formations (2,000 feet to more than 12,000 feet below the land surface).

Lance Formation. The Upper Cretaceous Lance Formation, which contains portions of the Lance-Fox Hills aquifer, is exposed in outcrop around the eastern margins of the Rock Springs Uplift, the Great Divide Basin, and the Washakie Basin (**Plate 2**). The Lance Formation consists of dark gray and brown carbonaceous shale; medium to light brown, very fine- to fine-grained, clayey, calcareous sandstone; and coal and lignite beds (Berry, 1960; Welder and McGreevy, 1966). The sediment of the Lance is believed to have accumulated in a fluvial depositional environment. The Lance is as much as 4,540 feet thick in the Rawlins Uplift area (Berry, 1960). There have been some small coal mines, prospects, and proposed mines in the Lance Formation west and north of the Rawlins Uplift (Jones, 1991). The Lance produces natural gas in the Washakie Basin (De Bruin, 2002). The Lance is laterally equivalent to the Harebell Formation, which is located in the northwestern Green River Basin and Gros Ventre Range (**Plate 1a**).

Fox Hills Sandstone. The Upper Cretaceous Fox Hills Sandstone, which contains portions of the Lance-Fox Hills aquifer, is exposed only in one small outcrop in the eastern Great Divide Basin, but is present in the subsurface of the eastern GGRB. The formation is often mapped with the Lewis Shale (Lowry et al., 1973; Love and Christiansen, 1985). The Fox Hills Sandstone consists of yellow-gray, very fine- to fine-grained sandstone with a few beds of olive gray to dark gray sandy shale, thin carbonaceous shale, and thin impure coal beds (Gill et al., 1970). The formation is described as a shallow-marine, barrier-bar, and beach deposit that records the sedimentary transition from the underlying marine Lewis Shale to the overlying fluvial Lance Formation. The Fox Hills Sandstone represents the last marine deposition in the eastern GGRB. Gill et al. (1970) reported the formation thickness as ranging from 200 to 700 feet.

Fox Hills Sandstone and Lewis Shale. This combined Upper Cretaceous Fox Hills Sandstone and Lewis Shale geologic unit is exposed along the eastern flank of the Rock Springs Uplift and in a few small outcrop areas in the eastern Great Divide Basin. See descriptions of the separate units, above and below.

Lewis Shale. The Upper Cretaceous Lewis Shale, which contains the Lewis confining units, crops out extensively along and near the eastern boundary of the GGRB (**Plate 2**). The Lewis marine shale is a gradational sedimentary transition from the underlying Almond Formation (Mesaverde Group) to the overlying Fox Hills Sandstone (**Plate 1a**). The middle sandy lithology, defined as the Dad Sandstone Member (Gill et al., 1970), is interpreted as a lower tongue of the Fox Hills Sandstone. The Lewis Shale consists of a dark gray to olive gray to buff, silty to sandy shale with dark-gray to brown carbonaceous deposits, fossiliferous limestone, siltstone concretions, very fine- to medium-grained, yellow-gray to brown sandstone, and yellow-gray siltstone (Berry, 1960; Welder and McGreevy, 1966; Gill et al., 1970; Lowry et al., 1973). The formation thickness is difficult to determine because of the gradational contact with the Fox Hills Sandstone; in some places, these two formations are mapped together, and in others they are mapped separately. Gill et al. (1970) reported the Lewis Shale as 2,300 to 2,600 feet thick in the eastern GGRB. The Lewis Shale produces natural gas in the Washakie Basin and on the Wamsutter Arch (De Bruin, 2002).

Mesaverde Group. The Upper Cretaceous Mesaverde Group, which contains the Mesaverde aquifer, occurs at or near the land surface between the basins and uplifts of the GGRB. The Mesaverde Group is in gradational contact with the underlying Baxter, Cody, and Steele Shales and with the overlying Lewis Shale. It is present in the Lamont area east of Bairoil, where some of the Mesaverde was eroded before and after deposition of the Teapot Sandstone Member of the Mesaverde Group (Reynolds, 1966, 1967). Reynolds (1966, 1967) inferred that the Mesaverde Group had eroded completely in areas north and west of Lamont and Bairoil.

In the Rock Springs Uplift area, the Mesaverde Group comprises the Almond Formation, Ericson Sandstone, Rock Springs Formation, and Blair Formation, in descending order. The total combined thickness of the Mesaverde Group in the Rock Springs Uplift area is approximately 1,300-5,200 feet (Ahern et al., 1981). In the eastern Rawlins Uplift area, the Mesaverde Group comprises the Almond Formation, Pine Ridge Sandstone, Allen Ridge Formation, and Haystacks Mountains Formation, in descending order (Gill et al., 1970). The Ericson Sandstone grades eastward from the Rock Springs Uplift into the Pine Ridge Sandstone (Teapot Sandstone Member equivalent) and Allen Ridge Formation (Love et al., 1993); the Rock Springs Formation grades eastward into the Haystack Mountains Formation; and the Blair Formation grades eastward into stratigraphically equivalent upper parts of the Cody and Steele Shales.

The Mesaverde Group (undivided) in northwestern Carbon County consists of light gray to brown, very fine- to medium-grained sandstone interbedded with gray to dark gray shale, siltstone, lenses of carbonaceous shale, thin lenses of lignite, and thick beds of coal (Berry, 1960; Reynolds, 1966; Welder and McGreevy, 1966). Reynolds (1966, 1967) reported that the Teapot Sandstone Member (Pine Ridge Sandstone) consists of a lower light-gray to white sandstone and upper red-brown to white weathered carbonaceous siltstone and sandstone beds. Reynolds inferred that the Mesaverde Group was deposited in littoral, shallow marine, brackish, and non-marine environments. Berry (1960) and Welder and McGreevy (1966) reported a maximum thickness of 2,800 feet.

There have been many small coal mines, prospects, and proposed mines in the Mesaverde Group in western Carbon County (Jones, 1991). The Mesaverde Group produces natural gas via both conventional and CBNG extraction methods, in the Washakie Basin and on the Wamsutter Arch (De Bruin, 2002). In the Washakie Basin, the production zones are in the Almond Formation and the Ericson Sandstone (De Bruin, 2002).

Almond Formation. The Upper Cretaceous Almond Formation of the Mesaverde Group intertongues with, and is gradational with, the overlying Lewis Shale (Gill et al., 1970). Schultz (1909) described the Almond Coal Group, and Sears (1926) elevated it to formation rank. The Almond Formation consists of interbedded sandstone, siltstone, shale, and coal (Welder and McGreevy, 1966; Gill et al., 1970). The very-fine-grained sandstone is white to pale yellow-gray to dusky yellow, and weathers to brown (Schultz, 1909; Gill et al., 1970). The shale beds are dark gray to olive gray or brown-gray to brown-black, and are carbonaceous to coaly (Schultz, 1909; Gill et al., 1970). Gill et al. inferred that the lower part is fluvial sandstone, shale, and coal, and the upper part is shallow-water marine sandstone, lagoonal or brackish-water rocks, and marine shale (tongues of Lewis Shale). The Almond Formation is generally less than 600 feet thick; on the Rock Springs Uplift, the Almond is as much as 1,000 feet thick (Ahern et al., 1981).

Pine Ridge Sandstone. In Carbon County, the Upper Cretaceous Pine Ridge Sandstone of the Mesaverde Group consists of white to pale yellow-gray to light gray, fine- to medium-grained, non-marine sandstone (Dobbin et al., 1929; Gill et al., 1970). Gill et al. correlate the Pine Ridge with the Teapot Sandstone Member of the Mesaverde Formation. The Pine Ridge Sandstone locally contains beds of light gray carbonaceous shale, gray sandy shale, and impure coal beds (Dobbin et al., 1929; Gill et al., 1970). Gill et al. interpreted the sandstone as a fluvial deposit in the eastward-regressive tongue of the Mesaverde Group, with a thickness of 60 to 450 feet.

Allen Ridge Formation. In Carbon County, the Upper Cretaceous Allen Ridge Formation of the Mesaverde Group consists of an upper zone of red-brown carbonaceous shale, shallow-water marine sandstone, and dark brown-gray ironstone-bearing shale; a middle zone of fossiliferous shale, siltstone, and sandstone; and a lower zone of a brown to rusty-brown fluvial sandstone and shale sequences containing many carbonaceous shale interbeds, very sparse coal beds, and many ironstone concretions (Bergstrom, 1959; Gill et al., 1970). Gill et al. interpreted the unit as entirely non-marine in the Great Divide and Washakie Basins, and reported a formation thickness of as much as 1,275 feet.

Haystack Mountains Formation. The Upper Cretaceous Haystack Mountains Formation is the lowest and oldest formation of the Mesaverde Group in Carbon County. The formation is in gradational contact with the underlying Steele Shale in this area. Gill et al. (1970) defined three sandstone members of the unit: the Hatfield (upper), O'Brien Spring (middle), and Tapers Ranch (basal) Sandstone Members. The Haystack Mountains Formation consists of pale yellow-gray, very-fine- to fine-grained sandstone interbedded with gray to brown-gray shale and sandy shale containing fossiliferous concretions of ironstone, limestone, or argillaceous sandstone (Gill et al., 1970). The sandstone beds are interpreted as near-shore to off-shore marine deposits, and the shale beds as deep marine deposits. The formation ranges in thickness from 850 feet to 2,550 feet (Gill et al., 1970).

Ericson Sandstone. The Upper Cretaceous Ericson Sandstone underlies the Almond Formation on the Rock Springs Uplift in Sweetwater County. The Ericson consists of white massive sandstone, with lenticular chert-grit conglomerate in the upper part of the formation (Love and Christiansen, 1985). The Ericson Sandstone on the Rock Springs Uplift is approximately 400 to 700 feet thick (Ahern et al., 1981).

Rock Springs Formation. The Upper Cretaceous Rock Springs Formation underlies the Ericson Sandstone on the Rock Springs Uplift in Sweetwater County. The Rock Springs consists of white to brown sandstone, shale, and claystone with numerous coal beds (Love and Christiansen, 1985). On the Rock Springs Uplift, the Rock Springs Formation is approximately 900 to 1,700 feet thick (Ahern et al., 1981).

Blair Formation. The Upper Cretaceous Blair Formation underlies the Rock Springs Formation on the Rock Springs Uplift in Sweetwater County. The oldest and lowest formation of the Mesaverde Group on the Rock Springs Uplift, the Blair consists of drab yellow to brown sandstone and interbedded sandy shale (Love and Christiansen, 1985). The thickness of the Blair Formation on the Rock Springs Uplift is approximately 900 to 1,800 feet (Ahern et al., 1981).

Adaville Formation. The Upper Cretaceous Adaville Formation consists of gray sandstone, siltstone, and carbonaceous claystone; it is conglomeratic in the upper part and coal-bearing in the lower part (Love and Christiansen, 1985). As shown on **Plate 1a**, the Adaville Formation overlies the Hilliard Shale in the far western GGRB, and the top of the Adaville is an unconformity. The Adaville is laterally equivalent to the lower part of the Mesaverde Group and part of the Sohare Formation. The Adaville Formation is exposed in the eastern Overthrust Belt and western Green River Basin mostly in Uinta and Lincoln counties and in a few outcrop areas in southwestern Sublette County.

Sohare Formation and Bacon Ridge Sandstone. The Upper Cretaceous Sohare Formation and Bacon Ridge Sandstone are exposed only in two small outcrop areas in the northern Green River Basin, near Pinedale in north-central Sublette County. The Sohare Formation, which overlies the Bacon Ridge Sandstone, consists of gray and brown lenticular sandstone and shale with some thin coal beds (Love and Christiansen, 1985). The underlying Bacon Ridge Sandstone is composed of gray to tan marine sandstone and thick coal beds, with a gold-bearing quartzite conglomerate in the lower part (Love and Christiansen, 1985). The Sohare Formation and Bacon Ridge Sandstone are stratigraphically above the Cody Shale and Frontier Sandstone in the western Green River Basin, and are laterally equivalent to most of the Cody Shale eastward (**Plate 1a**).

Hilliard Shale. The Upper Cretaceous Hilliard Shale consists of dark gray to tan claystone, siltstone, and sandy shale (Love and Christiansen, 1985). The Hilliard Shale underlies the Adaville Formation and overlies the Frontier Formation in the far western GGRB (**Plate 1a**). The Hilliard Shale is laterally equivalent to the upper Blind Bull Formation, lower Sohare Formation, Bacon Ridge Sandstone, Baxter Shale, Cody Shale, Steele Shale, and Niobrara Formation. The Hilliard Shale and equivalent shale units (the upper part of the Baxter-Mowry confining unit) form an Upper Cretaceous regional shale confining unit above the Frontier Formation aquifer and below the Mesaverde aquifer. The Hilliard Shale is exposed in the eastern Overthrust Belt, mostly in Uinta and Lincoln counties.

Blind Bull Formation. The Upper Cretaceous Blind Bull Formation consists of gray to tan conglomeratic sandstone, siltstone, claystone, coal, and bentonite (Love and Christiansen, 1985). The Blind Bull Formation is a lateral equivalent of the Adaville Formation, Hilliard Shale, and Frontier Formation (**Plate 1a**), and crops out in the eastern part of the northern Overthrust Belt in northeastern Lincoln County and western Sublette County.

Baxter Shale. The Upper Cretaceous Baxter Shale underlies Sweetwater County and adjacent GGRB areas, but crops out only in the Baxter Basin, the structural apex of the Rock Springs Uplift (**Plate 2**). Freethey and Cordy (1991, p. C44) described the Baxter Shale as predominantly marine shale, mudstone, and claystone interbedded with minor thin sandstone. The thickness of the Baxter Shale on the Rock Springs Uplift varies from approximately 2,700 feet to 4,500 feet (Ahern et al., 1981). The Baxter Shale is stratigraphically equivalent to the Hilliard, Cody, and Steele Shales and the Niobrara Formation. These Upper Cretaceous regional marine shale units, which form the uppermost part of the Baxter-Mowry confining unit, act as a regional confining unit for the overlying Mesaverde aquifer and underlying Frontier Formation aquifer in the GGRB.

Cody Shale. The Upper Cretaceous Cody Shale is equivalent to the Steele Shale (upper Cody) and Niobrara Formation (lower Cody). The Cody is mapped in northwestern Carbon County, where the Steele Shale and Niobrara Formation are difficult to identify individually (Weitz and Love, 1952; Reynolds, 1966; Gill et al., 1970). The Cody Shale is gray marine shale with interbedded thin gray sandstone and siltstone (Weitz and Love, 1952; Weimer and Guyton, 1961; Welder and McGreevy, 1966). Weitz and Love described a smoky gray, limy shale located at the base of Cody. The Cody Shale contains minor interbedded bentonite (Weimer and Guyton, 1961, Welder and McGreevy, 1966). Weimer and Guyton (1961) inferred that the Cody Shale is 4,500 feet thick.

Steele Shale and Niobrara Formation. This geologic unit (**Plate 2**) combines the Upper Cretaceous overlying Steele Shale and underlying Niobrara Formation in areas where the two formations are difficult to distinguish from each other, but where the unit was not mapped as Cody Shale. This geologic unit is considered to be equivalent to the Cody Shale.

Steele Shale. The Upper Cretaceous Steele Shale occurs in the eastern and northeastern GGRB, although it cannot be differentiated from the underlying Niobrara Formation in northwestern Carbon County, and the combined units are mapped as Cody Shale. The Steele has gradational contacts with the overlying Mesaverde Formation and underlying Niobrara Formation. The Steele is a dark gray shale with locally interbedded layers of limestone, sandstone, siltstone, and bentonite (Dobbin et al., 1929; Weitz and Love, 1952; Berry, 1960; Harshman, 1968, 1972; Gill et al., 1970; Naftz and Barclay, 1991). Sandstone is more common in the upper part of Steele Shale. The formation was deposited as a marine shale. The thickness of the Steele ranges from 2,300 to 5,000 feet, depending on where the upper and lower gradational contacts are identified (Gill et al., 1970). The Steele Shale produces oil and natural gas in Carbon County, with two named production zones – the Shannon and Sussex Sandstones (De Bruin, 2002). The Washakie Basin area produces mostly natural gas from the Steele; areas east of the GGRB in Carbon County produce mostly oil (De Bruin, 2002).

Niobrara Formation. The Upper Cretaceous Niobrara Formation is present in the northeastern GGRB, although in northwestern Carbon County the Niobrara cannot be differentiated from the overlying Steele Shale, and the units are combined and mapped as Cody Shale. The Niobrara – a dark-gray calcareous shale with interbedded light-colored layers of limestone, chalk, and sandstone – is in gradational contact with the overlying Steele Shale (Dobbin et al., 1929; Weitz and Love, 1952; Berry, 1960; Harshman, 1968, 1972). The formation contains some thin layers of white crystalline calcite (Dobbin et al., 1929). Hale (1961) observed that the Niobrara Formation is lighter in color and more calcareous than the overlying Steele Shale. The Niobrara was deposited in a marine environment and is as much as 2,000 feet thick in the Washakie Basin (Welder and McGreevy, 1966). Some oil in western Carbon County and natural gas in the Washakie Basin are produced from the Niobrara (De Bruin, 2002).

Frontier Formation. The Upper Cretaceous Frontier Formation, which forms a marginal aquifer in parts of the Baxter-Mowry confining unit, is present throughout most of the GGRB and crops out on the flanks of the uplifts. The Frontier Formation is a dark gray shale with beds of sandstone in the upper part of the unit, described as the Wall Creek Sandstone Member by Merewether and Cobban (1972). In western Carbon County, the Frontier Formation consists of gray to grayish brown calcareous silty to sandy shale with bentonite beds and interbeds of fine-to medium-grained sandstone (Berry, 1960; Merewether and Cobban, 1972). Merewether and Cobban described the lower part of the formation as the Belle Fourche Shale Member. They reported an unnamed middle member composed of brownish gray carbonaceous siltstone and shale or silty, very-fine-grained to fine-grained sandstone.

The Frontier Formation was deposited in a shallow marine shelf environment as channel deposits and near-shore and offshore bars (Merewether et al., 1979). The formation ranges in thickness from 500 feet to 1,230 feet; the Wall Creek Sandstone Member is about 350 feet thick in western Carbon County (Merewether and Cobban, 1972).
The Frontier Formation produces petroleum in Carbon County (De Bruin, 2002). Most of the natural gas production from the Frontier occurs on the Rawlins Uplift and in the Washakie Basin, whereas most of the oil production from the formation occurs east of the GGRB (De Bruin, 2002).

Mowry Shale. The Upper Cretaceous (formerly considered Lower Cretaceous) Mowry Shale – a rock-stratigraphic unit included (with the Lower Cretaceous Muddy Sandstone and Thermopolis Shale) in the lower part of the Baxter-Mowry confining unit – is present throughout most of the GGRB, and crops out along the basin margins. The Mowry Shale is silvery gray to dark gray, hard siliceous shale containing abundant fish scales and bentonite beds (Love and Christiansen, 1985). It ranges in thickness from 110 feet to 525 feet (Welder and McGreevy, 1966; Harshman, 1972). In the eastern Overthrust Belt, the Mowry Shale is stratigraphically equivalent to the Lower Cretaceous Aspen Shale; in the western Overthrust Belt, it is equivalent to the Lower Cretaceous Sage Junction and Quealy formations (**Plate 1a**).

Lower Cretaceous geologic and rock-stratigraphic units

Lower Cretaceous geologic and rock-stratigraphic units are discussed in this section.

Thermopolis Shale and Muddy Sandstone. These rock stratigraphic units are included in the Frontier Formation, Mowry Shale, and Thermopolis Shale geologic unit, and in the Mowry and Thermopolis Shale geologic unit. The Lower Cretaceous Thermopolis Shale is present throughout most of the GGRB, and crops out near the basin margins.

It is a gray to black, soft shale with thin beds of sandstone, siltstone, and bentonite (Welder and McGreevy, 1966; Love and Christiansen, 1985). The Lower Cretaceous Muddy Sandstone, locally known as the Muddy Sandstone Member of the Thermopolis Shale, is a buff to gray, silty, fine- to medium-grained sandstone (Berry, 1960; Harshman, 1972). The Thermopolis Shale is predominantly marine. Curry (1962) indicated that the Muddy Sandstone is of shallow marine origin in some areas and of nonmarine origin in others. The Thermopolis Shale (including the Muddy Sandstone) is 100 to 250 feet thick (Lowry et al., 1973). In Carbon County, the Muddy Sandstone produces oil and natural gas; most of the natural gas production comes from southwestern Carbon County (De Bruin, 2002).

Sage Junction, Quealy, Cokeville, Thomas Fork, and Smiths Formations. The Lower Cretaceous Sage Junction, Quealy, Cokeville, Thomas Fork, and Smiths Formations are present only in the western Overthrust Belt of Wyoming; the Sage Junction and Quealy Formations are questionably Upper Cretaceous. These five formations are the western stratigraphic equivalents of the Aspen Shale and Bear River Formation, which are located in the eastern Overthrust Belt and western Green River Basin. In descending order, the Sage Junction Formation consists of gray and tan siltstone and sandstone; the Quealy Formation consists of variegated mudstone and tan sandstone; the Cokeville Formation consists of tan sandstone, claystone, limestone, bentonite, and coal; the Thomas Fork Formation is composed of variegated mudstone and gray sandstone; and the Smiths Formation consists of ferruginous black shale and tan to brown sandstone (Love and Christiansen, 1985).

Aspen Shale. The Lower Cretaceous Aspen Shale consists of light gray to dark gray, siliceous, tuffaceous shale and siltstone; thin bentonite beds; and quartzitic sandstone (Love and Christiansen, 1985). It is located in the eastern Overthrust Belt (**Plate 2**) and is considered Lower Cretaceous. However, it is considered stratigraphically equivalent to the Upper Cretaceous Mowry Shale in the area east of the Overthrust Belt and across Wyoming (**Plate 1a**).

Bear River Formation. The Lower Cretaceous Bear River Formation consists of black shale, interbedded fine-grained brown sandstone, thin limestone, and bentonite beds (Love and Christiansen, 1985). The Bear River Formation is located in the eastern Overthrust Belt (**Plate 2**) and is stratigraphically equivalent to the Muddy Sandstone Member and Thermopolis Shale of the GGRB eastward (**Plate 1a**).

Gannett Group. The Lower Cretaceous Gannett Group consists of red sandy mudstone, sandstone, and chert-pebble conglomerate – thin limestone and dark-gray shale in the upper part, more conglomeratic in the lower part (Love and Christiansen, 1985). The Gannett Group comprises five formations: in descending order they are the Smoot Formation (red mudstone and siltstone), Draney Limestone, Bechler Conglomerate, Peterson Limestone, and Ephraim Conglomerate (Love and Christiansen, 1985). Some Upper Jurassic fossils have been reported from the basal Ephraim Conglomerate (Love and Christiansen, 1985). The Gannett Group thickens to the north and west within the Wyoming Overthrust Belt and into southeastern Idaho. It is stratigraphically equivalent to the Cloverly Formation of the GGRB east of the Overthrust Belt (**Plate 1a**).

Cloverly Formation. The Lower Cretaceous Cloverly Formation, a rock-stratigraphic unit, which contains the Cloverly aquifer, is present throughout most of the GGRB, with outcrops near the uplift areas. The Cloverly Formation in the eastern GGRB consists of three recognizable lithologic units: an upper fine- to coarse-grained, white to buff to gray, quartz-rich sandstone; a middle sequence of green shale to gray carbonaceous shale with interbedded buff, fine-grained, well-cemented, silty sandstone and minor thin bentonite interbeds; and a lower light gray to white, fine- to medium-grained to conglomeratic sandstone with abundant chert pebbles (Dobbin et al., 1929; Berry, 1960; Harshman, 1972).

On the basis of fossil assemblages, Curry (1962, p. 118) inferred that terrestrial and freshwater depositional environments probably persisted during Early Cretaceous time in central Wyoming. Curry also stated that the uppermost sandy fluvial deposits of the Cloverly Formation were partially reworked by the transgressing Cretaceous sea (Curry, 1962, p. 118). The Cloverly Formation is as much as 200 feet thick in the eastern GGRB (Harshman, 1972).

Jurassic geologic and rock-stratigraphic units

Jurassic geologic and rock-stratigraphic units are discussed in this section.

Morrison Formation. The Upper Jurassic Morrison Formation, a rock-stratigraphic unit, is present throughout most of the GGRB in the subsurface, and crops out along the basin margins (**Plate 2**). It is included in several Jurassic-Lower Cretaceous geologic units. Love and Christiansen (1985) described the Morrison Formation in southern Wyoming as dull variegated claystone with interbedded white nodular limestone and gray silty sandstone. On the basis of fossil assemblages, Curry (1962, p. 118) inferred that the formation was deposited in non-marine and freshwater environments during the Late Jurassic. The Morrison Formation is thickest (325 feet) in the Rawlins Uplift area (Berry, 1960).

The Morrison is variously described as a minor aquifer or a confining unit; Chapter 5 (this report) includes the Morrison Formation in the Morrison and Sundance confining unit (**Plate 1b**). According to Freethey and Cordy (1991, p. C30), the extent of the Morrison aquifer in the GGRB is unknown; however, they inferred that the fine-grained character of the Morrison Formation makes the occurrence of an extensive aquifer unlikely. Locally, the Morrison contains interbedded sandstone that may act as an aquifer, but water produced from the formation is likely to be of poor quality, with a high TDS content.

Sundance Formation. Seven members of the Sundance Formation, a rock-stratigraphic unit, have been defined in the eastern GGRB: in descending order, they are the Windy Hill, Redwater Shale, Pine Butte, Lak, Hulett, Stockade Beaver Shale, and Canyon Springs Members (Pipiringos, 1968; Harshman, 1972). The uppermost Windy Hill Sandstone Member consists of a buff to gray, very-fine- to medium-grained, thin-bedded, limy oolitic sandstone or a fine- to coarse-grained, calcite-cemented sandstone with gray-green to dark gray shale partings (Pipiringos, 1968; Harshman, 1972).

The Redwater Shale Member consists of greenish or yellowish gray shale and clayey siltstone with locally lime-cemented coquinoid sandstone or sandy coquinoid limestone (Pipiringos, 1968; Harshman, 1972). The Pine Butte Member consists of greenish white, calcitic sandstone with interbedded greenish to yellowish-gray glauconitic siltstone and claystone/shale beds (Pipiringos, 1968; Harshman, 1972). The Lak Member is composed of pink to reddish brown to yellowish white fine- to medium-grained sandstone, sandy siltstone, and siltstone (Pipiringos, 1968; Harshman, 1972).

The Hulett Sandstone Member consists of buff to white, fine- to medium-grained sandstone with locally interbedded shale and glauconite (Pipiringos, 1968, Harshman, 1972). The Stockade Beaver Shale Member is composed of greenish gray to greenish yellow shale and siltstone (Pipiringos, 1968; Harshman, 1972). The basal Canyon Springs Sandstone Member consists of light gray fine-grained oolitic to yellowish white fine- to medium-grained sandstone with chert pebbles locally at the base (Pipiringos, 1968; Harshman, 1972).

To the west in Sweetwater County, the Sundance Formation is composed of the Windy Hill Sandstone, Redwater Shale, and Pine Butte Members. Freethey and Cordy (1991, p. C30) interpreted the Sundance depositional environment as predominantly marine and marginal marine. The Sundance was deposited during repeated sea transgressions and regressions as a complex sequence of interfingering non-marine, marginal marine, and marine beds in Jurassic time (Freethey and Cordy, 1991, p. C24, C28, C30). The Windy Hill Sandstone Member is not considered either continuous or thick enough to be a regional aquifer, but may produce highly mineralized water locally (Mason and Miller, 2005).

In Sweetwater County, the Sundance aquifer (**Plate 1b**) is identified as the Lak, Hulett Sandstone, Stockade Beaver Shale, and Canyon Springs Sandstone Members of the Sundance Formation

(Mason and Miller, 2005); the other members act as confining units. The Sundance aquifer is present throughout Sweetwater County.

The Sundance Formation was deposited in a marine environment and has a thickness of 195 to 365 feet (Pipiringos, 1968). The Sundance Formation produces oil and natural gas in northwestern and east-central Carbon County (De Bruin, 2002).

Gypsum Spring Formation. The Middle Jurassic Gypsum Spring Formation consists of interbedded red shale, dolomite, and gypsum (Love and Christiansen, 1985). Freethey and Cordy (1991, p. C22) reported that the confining unit was deposited in a marine to marginal marine environment along the depositional margins of a fluctuating shallow sea during Jurassic time. The Gypsum Spring Formation is located in the Overthrust Belt and western Green River Basin. Along the western border of Sweetwater County, the unit reaches a thickness of 600 feet, and it thins to pinch-out in the eastern Green River Basin (Freethey and Cordy, 1991, pl. 2). The Gypsum Spring is absent in the eastern quarter of Sweetwater County, and the formation is considered the lowest member of the Twin Creek Limestone in the Overthrust Belt.

Stump Formation. The Middle-Upper Jurassic Stump Formation consists of glauconitic siltstone, sandstone, and limestone (Love and Christiansen, 1985), and overlies the Preuss Sandstone/Redbeds. The Stump Formation is located in the Overthrust Belt and adjacent western Green River Basin.

Preuss Sandstone or Redbeds. The Middle Jurassic Preuss Sandstone or Preuss Redbeds consists of purple, maroon, and reddish-gray sandy siltstone and claystone; it commonly contains salt and gypsum in thick evaporite beds in some subsurface sections of the Overthrust Belt (Love and Christiansen, 1985). The formation is located in the Overthrust Belt and adjacent western Green River Basin.

Twin Creek Limestone. The Middle Jurassic Twin Creek Limestone consists of greenish gray shaly limestone and limy siltstone (Love and Christiansen, 1985). The Twin Creek Limestone includes the Gypsum Spring Formation as its lowest member (Gypsum Spring Member). The Twin Creek Limestone directly overlies the Nugget Sandstone in the Overthrust Belt and western Green River Basin.

Nugget Sandstone. The Triassic(?) to Jurassic Nugget Sandstone, a buff to white to pink, massive to coarsely cross bedded, well-sorted, very-fine- to coarse-grained, quartz-rich sandstone (Berry, 1960; Love and Christiansen, 1985), is present in most of the GGRB. The Nugget Sandstone is grouped with other rock-stratigraphic units on the geologic unit map (**Plate 2; Appendix 1**).

Pipiringos (1968) defined a lower Bell Springs Member of the Nugget Sandstone, which consists of red and gray sandstone with interbedded red, green, and pale purplish red to pale red siltstone and shale. Pipiringos (1957) interpreted the formation as of either eolian or subaqueous origin. Freethey and Cordy (1991, p. C17) suggested that the Nugget Sandstone was deposited under arid terrestrial conditions, and was mainly eolian in origin with locally minor fluvial components. In the Great Divide and Washakie basins, the Nugget Sandstone lies beneath more than 12,000 feet of younger rock formations (Freethey and Cordy, 1991, p. C19).

The saturated thickness of the Nugget aquifer (**Plate 1b**) is generally 100 to 500 feet in the eastern GGRB and more than 500 feet in western Carbon County (Freethey and Cordy, 1991, p. C18). Berry (1960) estimated the maximum thickness of the Nugget Sandstone on the Rawlins Uplift as 110 feet. The Nugget Sandstone produces oil and natural gas in the Overthrust Belt and GGRB, including northwestern and southwestern Carbon County, as well as east of the GGRB in east-central Carbon County (De Bruin, 2002).

Triassic geologic and rock-stratigraphic units

Triassic geologic and rock-stratigraphic units are discussed in this section.

Ankareh Formation. The Upper Triassic Ankareh Formation, a rock-stratigraphic unit, consists of red and maroon shale with interbedded purple limestone (Love and Christiansen, 1985). As shown on **Plate 1a**, the Ankareh Formation is a lateral equivalent of the upper part of the Chugwater Formation to the east in the GGRB. The Ankareh Formation directly underlies the Nugget Sandstone in the Overthrust Belt and adjacent Green River Basin.

Thaynes Limestone. The Lower-Upper Triassic Thaynes Limestone, a rock-stratigraphic unit, consists of gray limestone and interbedded limy siltstone (Love and Christiansen, 1985), and underlies the Ankareh Formation. The formation is located in the Overthrust Belt and adjacent Green River Basin, and is laterally equivalent to the middle part of the Chugwater Formation to the east in the GGRB (**Plate 1**).

Woodside Shale. The Lower Triassic Woodside Shale, a rock-stratigraphic unit, is composed of interbedded red siltstone and shale (Love and Christiansen, 1985), and underlies the Thaynes Limestone. The Woodside Formation is located in the Overthrust Belt and adjacent Green River Basin, and overlies the Dinwoody Formation. As shown on **Plate 1a**, the Woodside Shale is a lateral equivalent of the lower part of the Chugwater Formation to the east in the GGRB.

Chugwater Formation or Group. The Lower to Upper Triassic Chugwater Formation, a rock-stratigraphic unit, consists of interbedded red siltstone, shale, and fine-grained sandstone (Welder and McGreevy, 1966). The Alcova Limestone Member is present in the upper middle part of the formation in the eastern GGRB (Love and Christiansen, 1985).

The Chugwater Formation or Group occurs in the eastern GGRB, with outcrops near the uplifts. The Chugwater Group in some areas of Wyoming is divided into the Popo Agie Formation, Jelm Formation, Crow Mountain Sandstone, Alcova Limestone, and Red Peak Formation. The undivided Chugwater Formation consists of red shale and sandstone, with interbedded purple, pink, green, and buff beds and a few thin limestone and gypsum interbeds (Dobbin et al., 1929; Berry, 1960). The Chugwater is interpreted as having fluvial, lacustrine, eolian, and marine origins (Pipiringos and O'Sullivan, 1978). The maximum thickness is as much as 1,350 feet (Dobbin et al., 1929).

The Chugwater Formation or Group is a source of oil in northwestern Carbon County; and the Alcova Limestone (called *Thaynes* by oil producers) is a source of oil and natural gas in southwestern Carbon County (De Bruin, 2002). The Red Peak Formation of the Chugwater Group also produces natural gas in the Washakie Basin (De Bruin, 2002).

Dinwoody Formation. The Lower Triassic Dinwoody Formation, a rock-stratigraphic unit, is composed of olive-drab, thin-bedded, hard, dolomitic siltstone and interbedded green shale (Love and Christiansen, 1985). The Dinwoody is located in the Overthrust Belt, the western Green River Basin, and the Wind River Range (**Plate 2**). The Dinwoody Formation grades eastward into the stratigraphically equivalent upper Triassic part of the Permian-Lower Triassic Goose Egg Formation in the eastern GGRB (**Plate 1a**).

The Dinwoody Formation is described by Berry (1960) and Pipiringos and O'Sullivan (1978) as interbedded gray to olive-gray siltstone and shale. Pipiringos and O'Sullivan (1978) also described thin brown limestone beds near the base of this marine unit. Berry (1960) reported a thickness of 80 feet in the subsurface, with no recognizable outcrops on the Rawlins Uplift.

Upper Permian and Lower Triassic rock-stratigraphic units

Upper Permian (Paleozoic) and Lower Triassic (Mesozoic) formations underlie the structural basin areas of the GGRB and are exposed along the basin margins and adjacent uplifts (**Plate 2**). This sequence of rocks is complicated by intertonguing formations and by facies changes owing to repeated sea transgressions and regressions during the Permian-Triassic (McKelvey et al., 1959; Maughan, 1964).

In the western GGRB, the sequence includes the Dinwoody Formation, Ervay Member of the Park City Formation, Tosi Chert Member and Retort Phosphatic Shale Tongues of the Phosphoria

Formation, Franson Member of the Park City Formation, greenish gray shale that may or may not be a member of the Park City Formation, and the Grandeur Tongue of the Park City Formation (McKelvey et al., 1959). The "Phosphoria Formation and related rocks" on **Plate 1a** includes the Park City Formation.

The Permian-Triassic Goose Egg Formation is an interbedded sequence of medium red to orange siltstone and shale, gypsum, limestone, and dolomite. The Goose Egg was deposited in a marginal marine environment with high salinity and a warm, arid climate, such as a vast shallow lagoon or tidal flat bordering the sea. The Upper Goose Egg Formation in the eastern GGRB is equivalent to the Triassic Dinwoody Formation and upper parts of the Permian Park City/Phosphoria Formations in the western GGRB (Maughan, 1964).

PALEOZOIC UNITS

Paleozoic formations underlie Cenozoic and Mesozoic formations at depth throughout most of the GGRB. The Paleozoic formations are exposed along basin margins and in some of the uplifted areas (see **Figures 3-1 and 3-5**; **Plate 2**). Paleozoic rocks crop out in less than 1 percent of the area of the Wyoming GGRB (see **Figures 3-1 and 3-5**). Lindner-Lunsford et al. (1989, sheet 1) indicated that the depth to the top of Paleozoic rocks in Sweetwater County ranges between about 6,000 and 18,000 feet, where they are mapped. Geldon (2003b, p. B36) described the Paleozoic rocks in Sweetwater County as buried by 5,000 feet to more than 25,000 feet of younger geologic formations. Little hydrogeologic data are available for the deeply buried rocks in the GGRB. The sparse water data available indicate that groundwater in deeply buried Paleozoic units is unsuitable for most uses without treatment.

Mesozoic and Paleozoic rocks (undivided). The Mesozoic and Paleozoic rocks (undivided) geologic unit is composed of multiple geologic formations in areas of complex structure where mapping of individual geologic units is impractical. This unit is mapped only in a few small outcrop areas located along the western flank of the Sierra Madre and northeastern Great Divide Basin, south of the Granite Mountains in western Carbon County. On the western flank of the Sierra Madre, this combined geologic unit includes the Chugwater and Goose Egg Formations. On the south side of the Granite Mountains, the combined unit may include the Nugget Sandstone, Chugwater Formation, Goose Egg Formation, Tensleep Sandstone, and Amsden Formation.

Upper Paleozoic geologic and rock-stratigraphic units

The upper Paleozoic formations in the GGRB are present deep in the structural basin areas, and crop out along the basin margins (**Plate 2**). They consist of the Permian Phosphoria and Goose Egg (lower portion of Permian age) Formations, and the Pennsylvanian Tensleep Sandstone, Weber Sandstone, Morgan Formation, and Ranchester Limestone Member of the Amsden Formation (not shown on **Plate 1a**). The Phosphoria and Goose Egg Formations include interbedded sandstone, siltstone, gypsum, dolomite, limestone, shale, and phosphorite lithologies (Love and Christiansen, 1985). The Goose Egg Formation was deposited in shallow sea environments that periodically regressed, allowing erosion of exposed sediments (Sheldon, 1963, p. 60).

The Phosphoria Formation was deposited in deeper water in an area off the Permian continental shelf, with upwelling of deeper nutrient-rich marine waters. The Tensleep Sandstone consists of sandstone with thin interbeds of limestone and dolomite (Love and Christiansen, 1985). The name *Weber Sandstone* is used in northwest Colorado and Utah for the Pennsylvanian sandstone/carbonate lithologies in the Flaming Gorge area of Utah that are equivalent to the Tensleep Sandstone (Hansen, 1965).

Uplift and erosion of the ancestral Rocky Mountains during Pennsylvanian time provided abundant clastic sediment to shallow seas (Lageson et al., 1979, p. U18-U19) during the time the Tensleep Sandstone was deposited. The Ranchester Limestone Member of the Amsden Formation is a mixed interbedded sequence of cherty dolomite and limestone, sandstone, and shale (Sando et al., 1975, p. A32). The Morgan Formation is a stratigraphic name applied in Utah and northwest Colorado to the Mississippian-Pennsylvanian mixed carbonate/clastic sequence in the Flaming Gorge area, and is equivalent to the Ranchester Limestone Member of the Amsden Formation (Hansen, 1965). The Ranchester Limestone was deposited in a marine environment during the late Mississippian and early Pennsylvanian (Lageson et al., 1979, p. U13).

Phosphoria Formation and related rocks. The Permian Phosphoria Formation consists of an upper portion of dark gray to light gray chert and shale with black shale and phosphorite at top, and a lower portion of black shale, phosphorite, and cherty dolomite (Love and Christiansen, 1985). The Phosphoria Formation is located in the Overthrust Belt and western GGRB. Related and interbedded Permian rocks consist of brown sandstone and dolomite, cherty phosphatic and glauconitic dolomite, phosphatic sandstone and dolomite, and greenish-gray to black shale (Love and Christiansen, 1985). The intertonguing equivalents of portions of Phosphoria Formation are the Park City Formation (primarily cherty dolomite, limestone, and phosphatic gray shale) and the Shedhorn Sandstone (Love and Christiansen, 1985).

The Phosphoria Formation consists of a sequence of interbedded chert and phosphatic shale (McKelvey et al. (1959). The Tosi Chert Member is composed of thin dark- to light-colored chert beds. The Retort Phosphatic Shale Tongue includes soft, dark brownish gray, carbonaceous mudstone and pelletal phosphorite. The Phosphoria Formation in the area farther east of the Overthrust Belt is predominantly a shallow marine unit. The Tosi Chert Member and Retort Phosphatic Shale Tongue are each about 15 feet thick (McKelvey et al., 1959).

Park City Formation. The Permian Park City Formation (included in “Phosphoria Formation and related rocks” on **Plate 1a**) is composed of multiple sequences of carbonate rocks and locally a sequence of greenish gray siltstone. The Ervay Member is dolomite in its eastern extent and a limestone to the west. This marine unit is about 50 feet thick. The Franson Member consists of light gray and grayish brown limestone or dolomite, which locally is cherty or sandy, and includes calcareous sandstone. The Franson Member is a shallow marine deposit about 35 feet thick. The Grandeur Member consists of limestone/dolomite, cherty limestone or dolomite, carbonate sandstone, and carbonate siltstone. This member is also a marine unit, and is about 60 feet thick. The greenish gray siltstone that locally may be part of the Park City Formation is about 170 feet thick (McKelvey et al., 1959).

Wells Formation. The Pennsylvanian-Permian Wells Formation, a rock-stratigraphic unit, consists of red and white fine-grained, cross-bedded, calcareous to siliceous, quartz-rich sandstone and interbedded brown to dark gray, sandy to cherty limestone (Richards and Mansfield, 1912). The Wells Formation in the Overthrust Belt is stratigraphically equivalent to the Tensleep Sandstone and also to the Weber Sandstone and underlying Morgan Formation (**Plate 1a**) to the east in the Green River Basin.

Tensleep Sandstone. The Pennsylvanian Tensleep Sandstone, the rock-stratigraphic unit that contains the Tensleep-Weber aquifer, is present at depth in the GGRB and crops out along the basin margins and mountain flanks (**Plate 2**). The Tensleep is a white to buff, gray, and pink, fine to medium-grained sandstone with minor thin interbedded tan, white, gray, and pink, finely crystalline, dense limestone and dolomite beds (Dobbin et al., 1929; Berry, 1960; Mallory, 1967, 1975). The Tensleep Sandstone was primarily deposited as cross-bedded sand dunes, but was also deposited in associated nonmarine fluvial, marine beach, and shallow marine environments (Maughan, 1967; Mallory, 1975). The Tensleep Sandstone is 850 feet thick on the Rawlins Uplift (Berry, 1960).

Amsden Formation. The Mississippian-Pennsylvanian Amsden Formation, a rock-stratigraphic unit, is present at or near the surface on the flanks of mountain uplifts in the GGRB (**Plate 2**), and consists of three members: an upper Ranchester Limestone Member, middle Horseshoe Shale Member, and lower Darwin Sandstone Member (Mallory, 1967, 1975; Sando et al., 1975).

The upper Ranchester Limestone Member consists of an interbedded sequence of gray, tan, pink, or purple, dense or finely crystalline, cherty dolomite, dolomitic limestone, and limestone (Mallory, 1967, 1975; Sando et al., 1975). Some interbedded pink to dark red to green shale or shaly limestone is also present in the member, with interbedded white to gray, fine- to medium-grained sandstone, siltstone, and claystone (Mallory, 1967, 1975; Sando et al., 1975). The Ranchester Limestone Member is a marine deposit as much as 280 feet thick in Carbon County (Mallory, 1967, 1975; Sando et al., 1975).

The middle Horseshoe Shale Member is a red/purple or maroon shale, siltstone, and mudstone sequence, which is locally yellowish and light pinkish gray with minor interbeds and lenses of red, fine-grained calcareous sandstone, and silty, sandy, or argillaceous limestone (Mallory, 1967, 1975; Sando et al., 1975). Sando et al. described the Horseshoe Shale Member as composed mainly of fissile, platy or blocky siltstone, mudstone, and shale, deposited in a lagoonal environment. The Horseshoe Shale Member is as much as 150 feet thick in Carbon County (Mallory, 1967; Sando et al., 1975).

The lower Darwin Sandstone Member is a gray, white, or cream to salmon-colored, fine- to medium-grained quartz-rich sandstone with silica and local calcite cement (Mallory, 1967; Sando et al., 1975). The Darwin Sandstone was deposited as marine beaches, sand dunes, and sand bars along the margin of a sea transgressing eastward and covering fluvial deposits associated with the karst weathering zone at the top of the Madison Limestone (Mallory, 1967; Sando et al., 1975).

Round Valley Limestone. Pennsylvanian confining units in the GGRB include the Pennsylvanian Horseshoe Shale Member of the Amsden Formation and part of the Round Valley Limestone, a rock-stratigraphic unit. Geldon (2003b, p. B75 and B81) indicated that the combined thickness of Upper Paleozoic confining units (**Plate 1b**) is as much as 700 feet in the Flaming Gorge area. Geldon shows that these confining units are located mostly in the southern half of Sweetwater County but are absent in the northern half of Sweetwater County, with the exception of the northeastern Great Divide Basin.

Hansen (1965, p. 43) described the Round Valley Limestone exposed in the Flaming Gorge area as predominantly light gray to light bluish gray, hard and dense, thin-bedded to massive, cherty limestone. In southwestern Wyoming, Lageson et al. (1979, p. U24) described the dominant limestone facies of the Round Valley Limestone as gradational into the red mudstone and limestone facies of the Horseshoe Shale and Ranchester Limestone Members of the Amsden Formation in central Wyoming. These marine sedimentary units were deposited during a sea transgression eastward across Wyoming.

Madison Limestone. The Mississippian Madison Limestone, a rock-stratigraphic unit that contains much of the Madison aquifer, occurs at or near the surface around the mountain uplifts in the GGRB (**Plate 2**). Love and Christiansen (1985) described the Madison Limestone in Wyoming as blue-gray massive limestone and dolomite, and gray cherty limestone and dolomite. The Madison Limestone was deposited in a marine environment after a large part of the central Rocky Mountains was inundated from the north during latest Devonian to earliest Mississippian (Maughan, 1963, p. C26). The top zone of the Madison Limestone commonly includes a moderately- to well-developed paleokarst topography (Harshman, 1972; Sando et al., 1975), suggesting subaerial exposure and weathering prior to the deposition of overlying units. The Madison Limestone is a shallow to moderately deep marine deposit up to 500 feet thick (Maughan, 1963; Mallory, 1979).

The basal Madison Limestone is a dark brown or dark reddish brown arkosic sandstone and conglomerate that grades eastward into a fine-grained, red to brown sandstone on the Rawlins Uplift (Berry, 1960; Maughan, 1963; Harshman, 1972; Mallory, 1979). Sando and Sandberg (1987) believed that parts of this sandstone may be the Englewood Formation or Fremont Canyon Sandstone, although Macke (1993, p. M93) later suggested that these lithologies are actually the Cambrian Flathead Sandstone, which underlies the Madison on the

Rawlins Uplift. This sandstone was deposited in nearshore marine environments around emergent lowlands – the ancestral Rocky Mountains located in the southeastern Green River Basin and to the east (Mallory, 1979; Sando and Sandberg, 1987). Sando and Sandberg (1987) measured as much as 186 feet of Devonian Fremont Canyon Sandstone and as much as 45 feet of Devonian-Mississippian Englewood Formation in their study.

Lower Paleozoic rock-stratigraphic units

Lower Paleozoic rock-stratigraphic units are discussed in this section.

Darby Formation. Love and Christiansen (1985) described the Upper Devonian Darby Formation as composed of yellow and greenish gray shale and dolomitic siltstone underlain by fetid brown dolomite and limestone. The Darby Formation was also deposited in a marine environment, probably much smaller and shallower than the sea in which the overlying Madison Limestone was deposited.

Bighorn Dolomite. The Upper Ordovician Bighorn Dolomite consists of gray massive cliff-forming siliceous dolomite and local dolomitic limestone (Love and Christiansen, 1985). The Bighorn Dolomite is located in the Overthrust Belt and western Green River Basin. As shown in **Plate 1a**, the Bighorn Dolomite unconformably overlies the Cambrian formations, unconformably underlies the Devonian and Mississippian formations, and is completely absent from the eastern GGRB.

Cambrian rocks. Formations of Cambrian age in Carbon County generally are undifferentiated (**Plate 2**). The Cambrian formations exposed on the Rawlins Uplift are described as an upper sequence of red to reddish brown shale and green glauconitic sandstone, and a lower sequence of medium-grained quartzitic sandstone partly cemented by silica and partly conglomeratic (Berry, 1960; Welder and McGreevy, 1966). The upper part may correspond to the sandy facies of the Gros Ventre Formation and the lower part may correspond to the Flathead Sandstone, east of the Great Divide and Washakie basins, as reported by Keefer and Van Lieu (1966) for similar units in the eastern Wind River Basin. The limestone beds of the Gallatin Limestone and Gros Ventre Formation seem to be absent from the eastern GGRB. The lower sandstone beds represent marine beach and near-shore deposition as the sea transgressed the continent, and the upper unit includes a shallow marine and a non-marine unit (Keefer and Van Lieu, 1966). Berry (1960) reported that the Cambrian formations in the Rawlins Uplift area are as much as 600 feet thick.

Gallatin Limestone. The Upper Cambrian Gallatin Limestone consists of gray and tan limestone (Love and Christiansen, 1985) deposited in a marine carbonate shelf environment. The Gallatin Limestone is located in the Overthrust Belt and western Green River Basin. Undifferentiated Cambrian rocks in the Sweetwater County area of the GGRB are lithologically similar to the Gallatin Limestone, with the addition of micaceous shale and sandstone (Love and Christiansen, 1985).

Gros Ventre Formation. The Middle-Upper Cambrian Gros Ventre Formation consists of greenish gray micaceous shale (Love and Christiansen, 1985). Love and Christiansen (1985) described the Gros Ventre Formation in the Overthrust Belt as an upper Park Shale Member composed of soft, greenish gray micaceous shale; a middle Death Canyon Limestone Member consisting of blue-gray and yellow mottled, hard, dense limestone; and a lower Wolsey Shale Member composed of soft, green micaceous shale. The Gros Ventre Formation is located in the Overthrust Belt and western Green River Basin.

According to Keefer and Van Lieu (1966, p. B18), the strata of the Gros Ventre Formation represent deeper water, offshore marine deposits that accumulated contemporaneously with the marine beach and near-shore sandy deposits of the Flathead Sandstone as the sea transgressed eastward across the North American continent during the Cambrian. The Gros Ventre Formation thins to the east in the GGRB and is likely present as interbeds on the Rawlins Uplift, but is absent from the Sierra Madre. The Gros Ventre shale beds act as confining units. Where the Gros Ventre Formation in outcrop areas is sufficiently fractured and water-saturated, the upper and lower shale and middle limestone beds in the formation may yield small quantities of water to wells or springs via fracture flow.

Flathead Sandstone. Love and Christiansen (1985) described the lithology of the Flathead Sandstone in Wyoming as dull red quartzitic sandstone. According to Keefer and Van Lieu (1966, p. B15), the sediments composing the Flathead Sandstone eroded from adjacent Precambrian basement rock terrain and were deposited predominantly in the shore and near-shore environments of the transgressing Cambrian sea. In outcrop areas, where the Flathead Sandstone is sufficiently permeable (to porous or fracture flow) and water-saturated, this Cambrian formation is considered a major aquifer.

PRECAMBRIAN UNITS

The Precambrian rock units in the GGRB comprise a variety of igneous, metamorphic, and sedimentary rocks ranging in age from Proterozoic to Archean. The Precambrian rock units in most of Wyoming are older than the Precambrian units in Colorado and Utah as a result of the early crustal evolution of the North American continent. The Archean metamorphic and granitic rocks present in the Wind River Range are among the oldest in Wyoming. The Sierra Madre include a crustal suture zone with older Archean rocks to the north of the suture and younger Proterozoic rocks to the south (the Park Range in Colorado). The Uinta Mountain Group in Utah's Uinta Mountains is the youngest Precambrian rock unit in the GGRB; the group is a thick (more than 20,000 feet) sequence of sedimentary and metasedimentary lithologies.

Precambrian basement rocks generally act as the basal confining unit underlying the Paleozoic aquifer system in the structural basins of the GGRB. **Figure 2-4** shows the structural configuration of the Precambrian basement rocks in the GGRB, and **Figure 2-2** and **Plate 2** show the outcrop areas of Precambrian rocks in the GGRB. The depth from land surface to the top of the Precambrian ranges from 8,000 feet in the core of the Rock Springs Uplift to more than 35,000 feet in the deepest parts of the northern Green River Basin (**Figure 2-4**).

The Precambrian rock units yield little groundwater, except in the outcrop areas of the basement-cored mountain uplifts surrounding the basin. Generally, unweathered and unfractured Precambrian rock units show low primary permeability, with little to no porous or conduit flow of water. Shallow wells typically less than about 100 to 150 feet deep and constructed into fractured or weathered Precambrian rock units in outcrop areas with adequately developed fracture flow may yield limited amounts of good-quality water. Springs are also present in the Precambrian formation outcrop areas and typically exhibit fracture flow.

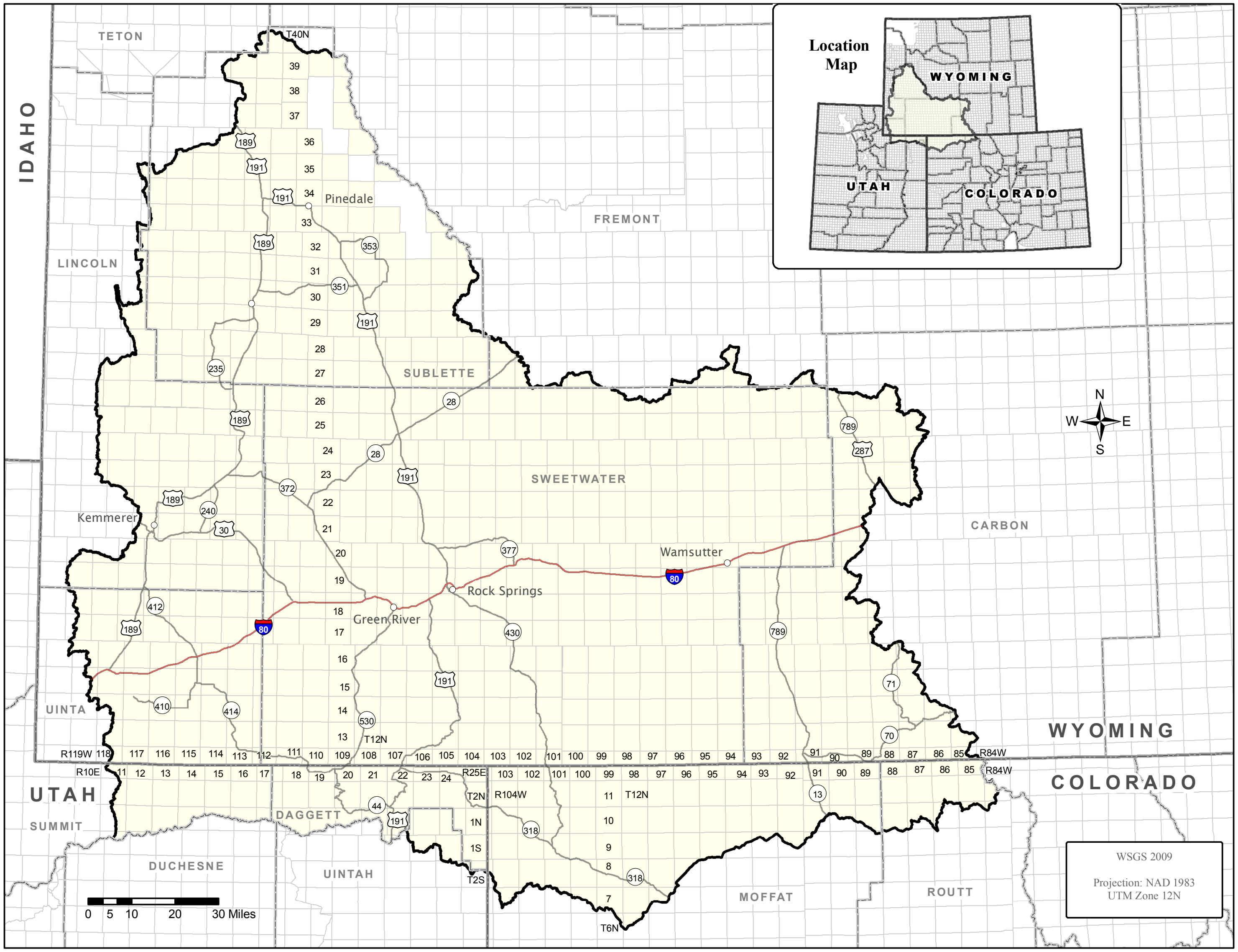

Figure 2-1. Township and range index map, Greater Green River Basin.

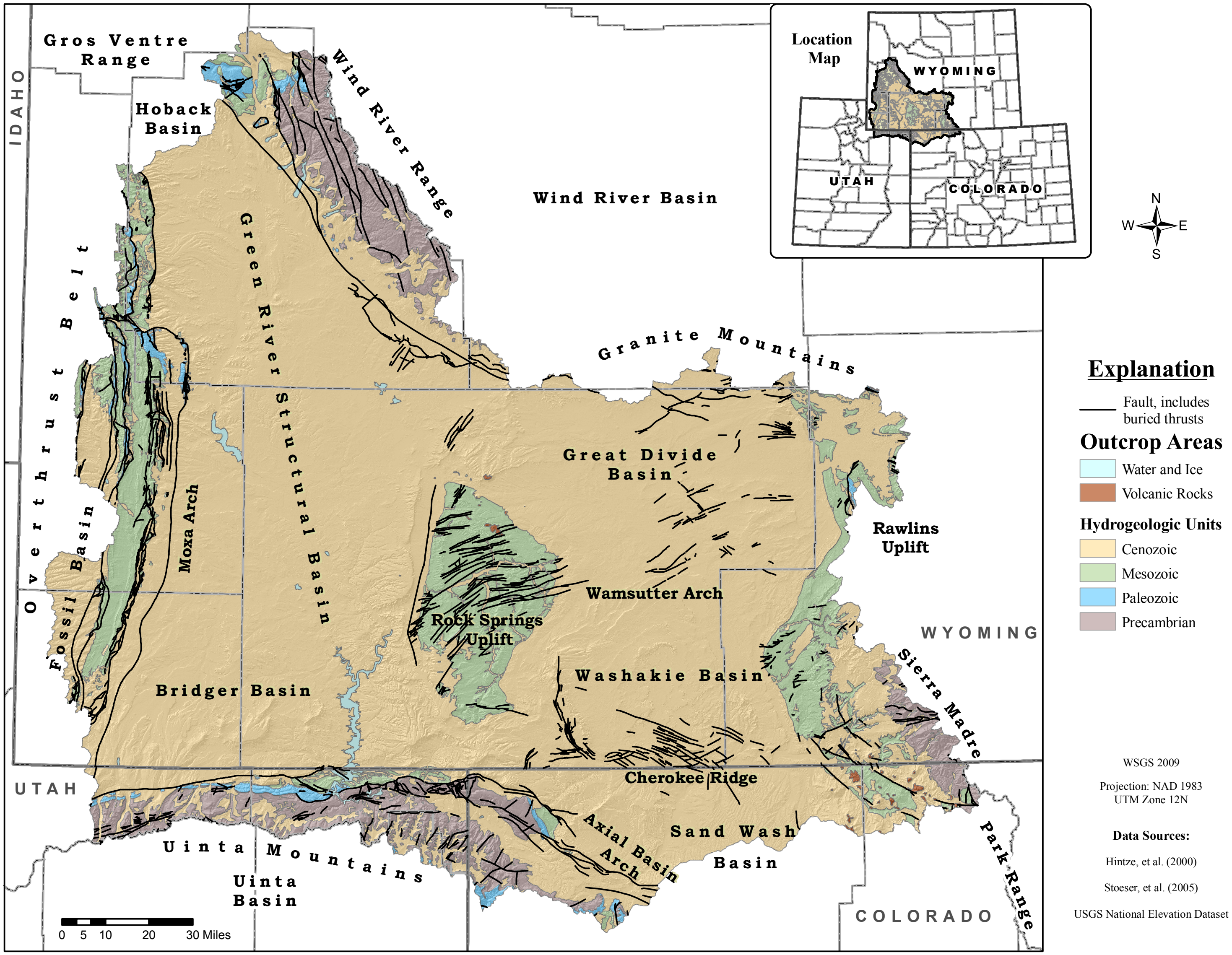

Figure 2-2. Geologic features, Greater Green River Basin.

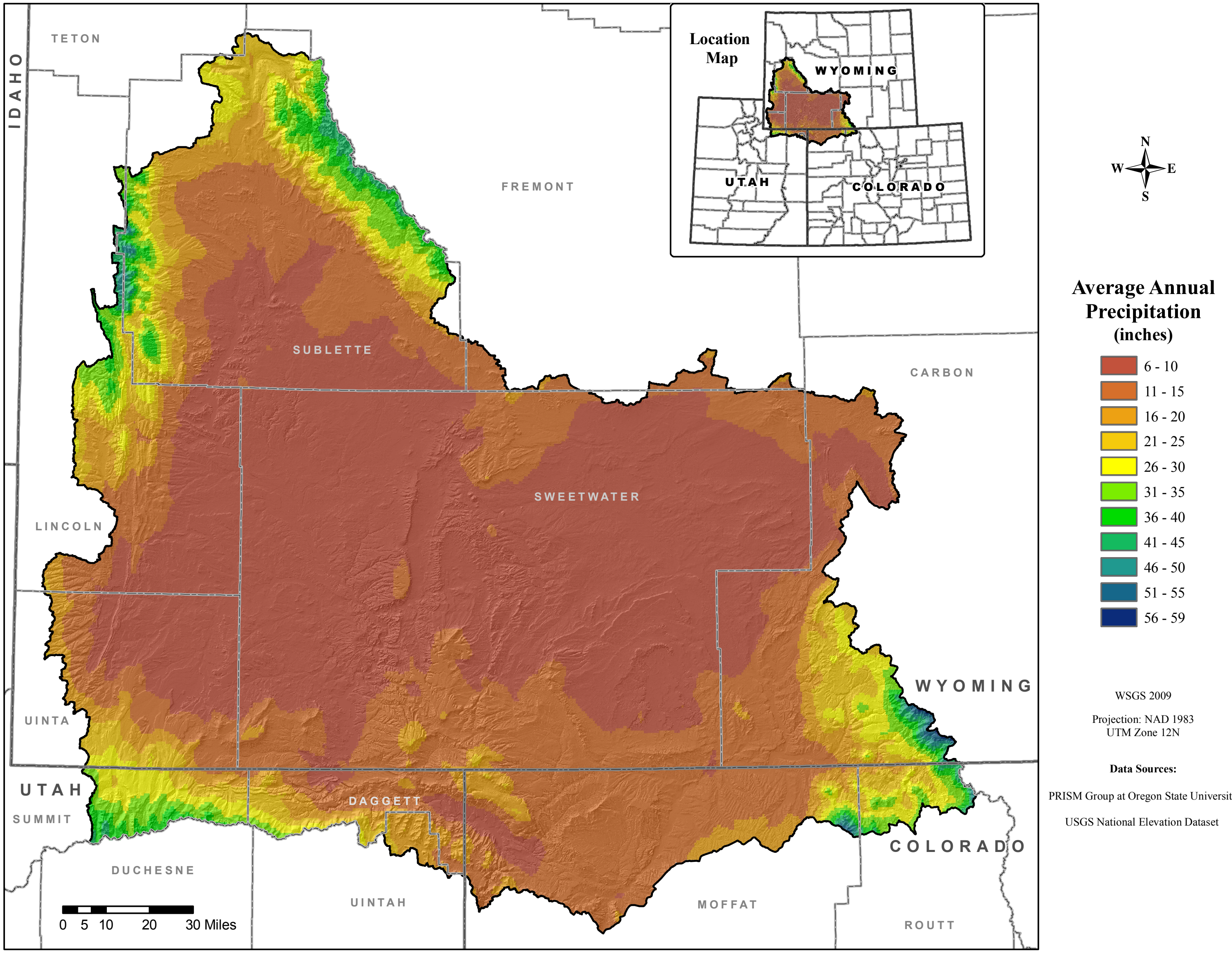

Figure 2-3. Average annual precipitation, Greater Green River Basin.

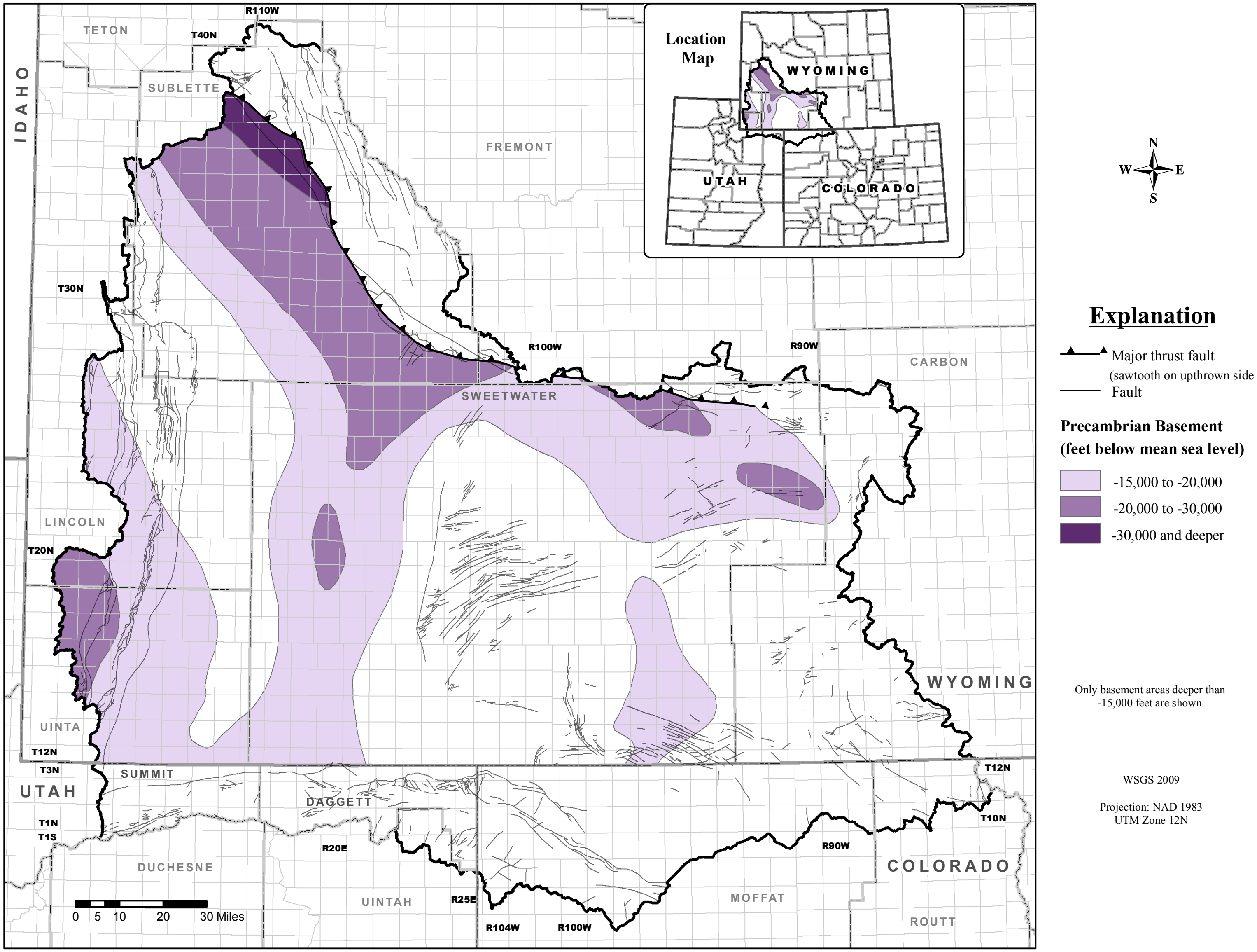

Figure 2-4. Precambrian basement structure, Wyoming Greater Green River Basin. *Modified from Blackstone (1993).*

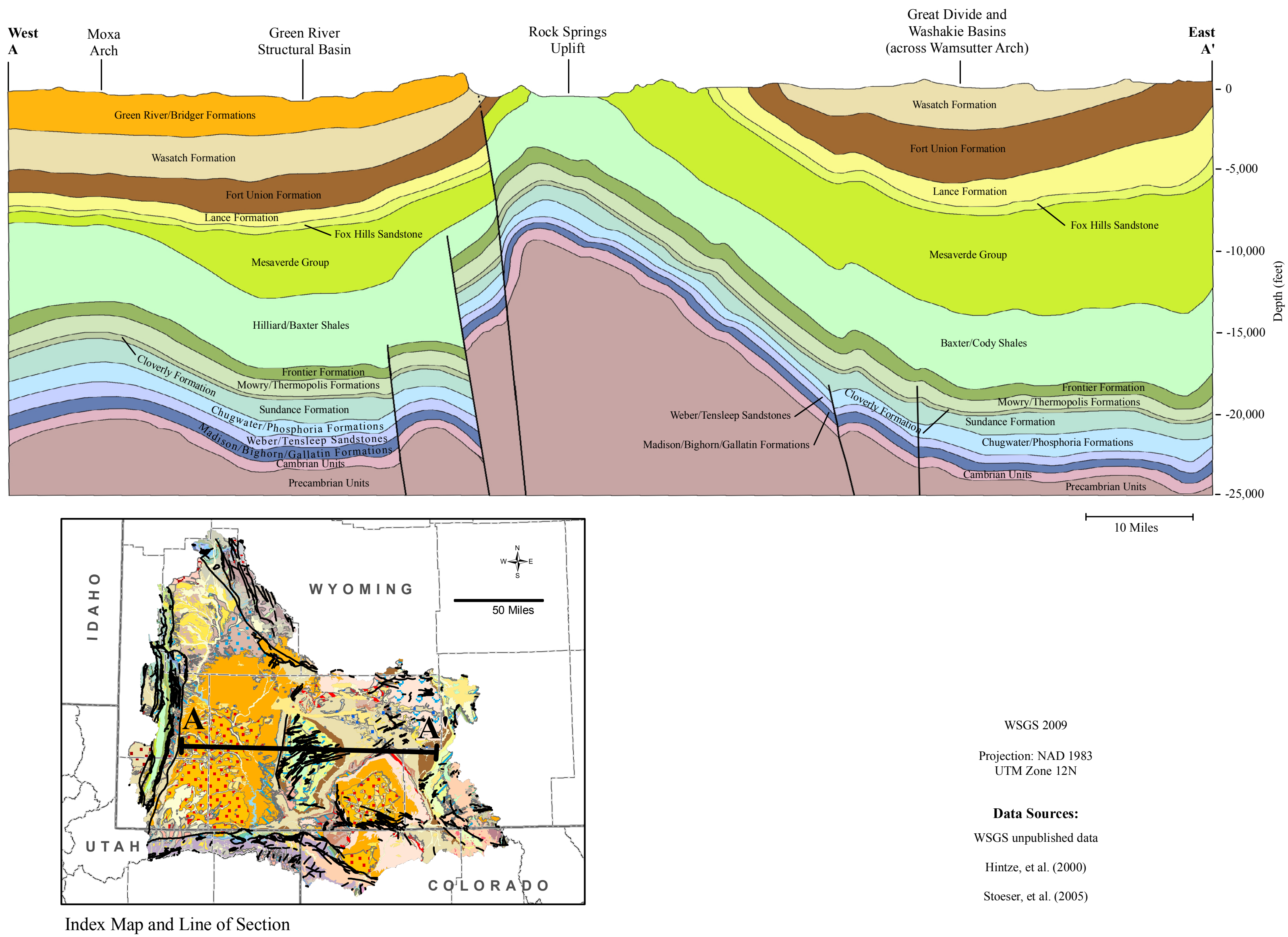

Figure 2-5. West–east geologic cross section, Wyoming Greater Green River Basin. *Cross section by Fred McLaughlin and Yuriy Ganshin, WSGS.*