Chapter 5
Groundwater and hydrogeologic units

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CENOZOIC HYDROGEOLOGIC UNITS

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PRECAMBRIAN HYDROGEOLOGIC UNITS

SUMMARY OF GROUNDWATER FLOW IN THE GGRB

Water saturates much of the Greater Green River Basin (GGRB) stratigraphic succession (**Plate 1a**). The stratigraphic boundaries are defined by perceived differences in rock type and by consistency of succession, and the geological formations are delineated by the stratigraphic boundaries. Rocks forming pathways through which groundwater can flow relatively quickly (aquifers) or rocks through which water can flow only relatively slowly (semi-confining units) or extremely slowly (confining units) may compose one geologic formation or part of a formation, or may comprise all or parts of several formations: the hydrogeologic unit boundaries and the geologic unit boundaries may not coincide. As thus defined, most individual hydrogeologic units—aquifers, semi-confining units, and confining units—are mixed within a geologic formation or group of formations, and the dominant hydrogeologic unit determines how the formation or group of formations behaves hydrologically as a whole. Thus, in this chapter, the term *hydrogeologic unit* denotes a formation, part of a formation, or group of formations that behaves as an aquifer or a semi-confining or confining unit.

Entries in this chapter are *hydrogeologic units*, and each entry describes the hydrogeology of the geologic units or rock-stratigraphic units within that hydrologic unit in the various structural basins and uplifted areas of the GGRB. Tertiary and older hydrogeologic units are arranged in stratigraphic order, and some are grouped in *aquifer systems* as described in Chapter 4. These aquifer systems are shown on **Plate 1b**, right column:

- *Green River Basin lower Tertiary aquifer system*
- *Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system*
- *Mesaverde aquifer system*
- *Upper Paleozoic aquifers*
- *Upper Paleozoic confining units*
- *Lower-Middle Paleozoic aquifer system*

Cenozoic hydrogeologic units (**Figures 5-1** and **5-2**) are grouped as Quaternary hydrogeologic units and Tertiary hydrogeologic units. Quaternary hydrogeologic units, mostly unconsolidated sedimentary deposits, are described by type of deposit (corresponding to GIS geologic unit designations of **Appendix 1** and **Plates 2** and **3**) and basin of occurrence. Tertiary hydrogeologic units are described in great detail, because they are by far the most important source of groundwater for human use in the GGRB, and because data about them are the most plentiful. These units are grouped as upper Tertiary and lower Tertiary hydrogeologic units, and the lower Tertiary units are grouped again as aquifer systems by basin of occurrence (**Figures 5-1** and **5-2**). Mesozoic hydrogeologic units are not further grouped, except those in the Mesaverde aquifer system (**Figure 5-3**). Paleozoic hydrogeologic units (**Figure 5-4**) are grouped as Upper Paleozoic aquifers, Upper Paleozoic confining units, and the Lower-Middle Paleozoic aquifer system. The Precambrian hydrogeologic units are not further grouped.

Groundwater in the GGRB occurs under both unconfined (water-table) and confined (artesian) conditions. Under unconfined conditions, permeable material extends from the land surface to the saturated zone, allowing vertical movement of water. Aquifers in Quaternary unconsolidated deposits consisting of alluvium, dune sand (eolian), lacustrine, and gravel deposits generally are unconfined. In some locations, shallow aquifers in other hydrogeologic units also may be unconfined.

Confined (artesian) aquifers are composed of permeable rock or sediment confined by relatively impermeable rocks or deposits (semi-confining or confining units). Water in a confined aquifer is under hydraulic pressure and will rise above the top of the aquifer when the overlying confining bed is penetrated (for example, by a well) or fractured (for example, at a spring). Under sufficient hydraulic pressure, water from a well completed in a confined (artesian) aquifer will flow to the land surface even though the aquifer is deeply buried. Most aquifers in Tertiary and deeper hydrogeologic units in the GGRB contain water under artesian conditions (except at or near the surface, especially where formations are exposed). Throughout the GGRB, the water-level depth in both unconfined and confined wells generally is less than 200 feet, but the drilling depth to confined aquifers may be much greater

(Welder and McGreevy, 1966, p. 3; Welder, 1968 p. 2; Whitehead, 1996, figure 68).

Appendix 1 presents stratigraphic and lithologic descriptions of all geologic units in the GGRB. Mapped geologic units in the GGRB are shown on **Plate 2**. Measurement of spring discharge, well-yield, and other hydraulic properties of geologic units are grouped in the text of this chapter and on **Plates 4** through **6** on the basis of the principal tectonic features of the GGRB identified on **Figure 5-5**. Information about areas adjacent to the Wyoming GGRB in Colorado and Utah is shown on many figures in Chapters 5 and 6 – areas south of the Uinta Uplift in Utah and Colorado, and the southern Washakie Basin (Middle Park) in Colorado. These figures were modified from reports on regions of the Upper Colorado River Basin that include the GGRB. Much of the data used in Chapters 5 and 6 was obtained from U.S. Geological Survey reports and the USGS National Water Information System (NWIS) Web site (U.S. Geological Survey, 2008b); the rest was obtained from various federal, state, and local government agencies, and consulting engineers' reports.

CENOZOIC HYDROGEOLOGIC UNITS

Cenozoic hydrogeologic units are described in this section of the report. Cenozoic hydrogeologic units are divided into two groups (Quaternary and Tertiary hydrogeologic units) for descriptive purposes.

Quaternary hydrogeologic units

Quaternary hydrogeologic units in the GGRB correspond to unconsolidated geologic units described in **Appendix 1**, mapped on **Plates 2** and **3**, and charted on **Plate 7**: alluvium and colluvium; landslide deposits; dune sand (eolian) deposits; lacustrine sediments; glacial deposits; gravel, pediment, and fan deposits; terrace gravels; undivided surficial deposits; and igneous extrusive and intrusive rocks (Welder and McGreevy, 1966, sheet 3; Welder, 1968, sheet 2; Lowry et al., 1973, sheet 3; Love and Christiansen, 1985).

Undifferentiated unconsolidated deposits occur in the Green River Basin region of the GGRB. Spring-discharge measurements from the USGS National Water Information System (NWIS) database were reviewed for this study. The three measured discharges from the springs ranged from 2 to 150 gallons per minute (gpm), with a median discharge of 7 gpm.

Alluvium and colluvium deposits. Alluvium and colluvium are found in minor and major drainages throughout the GGRB (**Plate 2**). These unconsolidated surficial deposits are composed primarily of clay, silt, sand, and gravel. Coarser deposits – cobbles and boulders – occur in some locations, especially near the mountains. These deposits have been reported to range in thickness from 0 to about 50 feet in the Green River, Great Divide, and Washakie basins (Welder and McGreevy, 1966, sheet 3; Welder, 1968, sheet 2). Alluvium in these basins may contain alluvial aquifers where saturated. Alluvial aquifers generally are hydraulically connected with streams.

Well yields are directly related to the size and sorting of the materials composing the deposits, and to the saturated thickness of the deposits. Recharge to alluvial aquifers is from direct infiltration of precipitation on the deposits and from streamflow. In the GGRB, alluvial aquifers are local, unconfined aquifers that generally have small areal extent along streams. Alluvium along the Little Snake River has been shown to be in direct connection with the stream (Huntoon et al., 1993). Groundwater flow in most alluvial aquifers is toward streams or in the direction of streamflow.

Well-yield measurements, spring-discharge, and other hydraulic properties from the USGS NWIS database and many other sources were reviewed and summarized for the GGRB (**Plate 4**). In the Green River Basin, four measurements of discharge from springs were available from the USGS NWIS database, and ranged from 20 to 300 gpm with a median discharge of 138 gpm. One measurement of yield for one flowing well was available from the USGS NWIS database and was 4 gpm. Measurements of yield for 30 pumped wells were available from the USGS NWIS database and ranged from 0.2 to 85 gpm with a median yield of 5 gpm. Well-yield values from other sources ranged from 5 to 97 gpm with a median yield of 22 gpm. Welder (1968) reported that wells completed in alluvial aquifers in the Green River Basin generally yield less than 10 gpm, but higher yields were available along perennial streams where deposits composing the aquifers consist of clean sand and gravel.

Some irrigation wells in the Farson-Eden area reportedly yield at least several hundred gpm (Ahern et al., 1981, p. 70). Nine measurements of specific capacity for alluvium in the Green River Basin were available from all sources, and ranged from 0.6 to 20 gallons per minute per foot of drawdown (gpm/ft). Eleven estimates of transmissivity for alluvium in the Green River Basin were available from all sources, and ranged from about 40 to 2,680 square feet per day (ft^2/d). One estimate of hydraulic conductivity was available for alluvium in the Green River Basin, and was 27 feet per day (ft/d).

Welder and McGreevy (1966) speculated that alluvial aquifers in many stream valleys in the Great Divide and Washakie basins likely yield small quantities of water to wells. Five measurements of yield from pumped wells were available from the USGS NWIS database, and ranged from 2 to 9 gpm with a median yield of 8 gpm (**Plate 4**). Data from the Black Butte Coal Company cited by Collentine et al. (1981, p. 48) indicated that alluvial aquifers along Bitter Creek could yield 5 to 30 gpm, but that water quality was poor. Two measurements of discharge from springs were available from the USGS NWIS database, and were 1 and 15 gpm. Spring-discharge and well-yield values from other sources ranged from 0.3 to 25 gpm. One estimate of specific capacity was available for alluvium in the Great Divide/Washakie/Sand Wash basins from another source, and was 2 gpm/ft.

In the Fossil Basin, six measurements of yield from pumped wells were available from the USGS NWIS database, and ranged from 6 to 12 gpm with a median yield of 8 gpm (**Plate 4**). No other well-yield and spring-discharge measurements or other hydraulic information was available for alluvium in the Fossil Basin.

Landslide deposits. Numerous landslide deposits have been mapped in the GGRB (Case et al., 1998). The deposits do not typically yield water to wells, but small springs commonly occur at the base of the deposits. Some of these deposits are saturated and may produce enough water locally for stock or domestic use.

Spring-discharge measurements from landslide deposits for the GGRB were only available from the USGS NWIS database (**Plate 4**). Four measured discharges from springs in the Green River Basin ranged from 2 to 200 gpm with a median discharge of 19 gpm. Five measured discharges from springs in the Great Divide/Washakie/Sand Wash basins ranged from 2 to 20 gpm with a median discharge of 5 gpm.

Dune sand (eolian) deposits. Dune sand deposits (also known as sand dunes) are present in the GGRB, although they are rarely used as a source of water, and few wells are completed in the deposits. Dune sand deposits in the Green River Basin are reportedly too thin to contain much water, but they do help to recharge underlying aquifers (Welder, 1968, sheet 2). Similarly, Welder and McGreevy (1966, sheet 3) described dune sand deposits in the Great Divide and Washakie basins as areas of recharge for underlying aquifers. The investigators noted that some areally extensive dune sand deposits in the Great Divide and Washakie basins have a sufficient saturated thickness to yield water to wells and springs.

Spring-discharge and well-yield measurements from the USGS NWIS database and other sources were reviewed for the GGRB (**Plate 4**). Two measured discharges of springs in the Great Divide/Washakie/Sand Wash basins were available from the USGS NWIS database, and were 1 and 20 gpm. Two measurements of yield from pumped wells in the Great Divide/Washakie/Sand Wash basins were available from the USGS NWIS database, and were 2 and 3 gpm. Spring-discharge and well-yield values in the Great Divide/Washakie/Sand Wash basins from other sources were 5 and 200 gpm.

Playa lake and other lacustrine deposits. Playa lake and other lacustrine deposits in the GGRB are found mainly in the Great Divide and Washakie basins, but some deposits occur in the north-central Green River Basin (Love and Christiansen,

1985) and north of the Rawlins Uplift in the Lost Soldier-Separation Flats area (**Plate 2**) (Gaylord, 1982; Case et al., 1998). Welder and McGreevy (1966, sheet 3) described the lacustrine deposits in the Great Divide Basin as clay, silt, and sand deposits less than about 25 feet thick and unlikely to yield usable groundwater in most areas. Because of limited area and thickness, and lack of hydrogeologic data, the playa lake and other lacustrine deposits in the GGRB were not assessed as a part of this study.

Glacial deposits. Although limited in area in the GGRB study area, glacial deposits are present in the Sierra Madre, southwestern corner of the Green River Basin, Overthrust Belt, Wind River Range, and Gros Ventre Range (**Plate 2**). These deposits generally are composed of poorly sorted, unconsolidated deposits of silt, sand, gravel, and boulders (Love and Christiansen, 1985). Spring-discharge and well-yield measurements from the USGS NWIS database and other reports were reviewed for the GGRB (**Plate 4**). There were no measured flows for springs discharging from glacial deposits in the GGRB in the USGS NWIS database, but spring-discharge and well-yield values from other sources ranged from 15 to 25 gpm with a median yield of 25 gpm. Three estimates of specific capacity for glacial deposits in the Green River Basin from other sources ranged from about 1 to 5 gpm/feet. Five estimates of transmissivity for glacial deposits in the Green River Basin from other sources ranged from about 121 to 4,020 ft^2/day.

Terrace deposits. Terrace deposits, consisting primarily of gravel, are limited in areal extent and are located primarily along upland areas adjacent to principal streams of the Green River Basin (**Plate 2**). In the Green River Basin, five measured discharges of springs were available from the USGS NWIS database, and ranged from 7 to 225 gpm with a median discharge of 35 gpm (**Plate 4**). One measurement of yield for a pumped well was available from the USGS NWIS database, and was 8 gpm.

In the Fossil Basin, two measured discharges of springs were available from the USGS NWIS database, and were 4 and 8 gpm. One measurement of yield each for one pumped well and one flowing well was available from the USGS NWIS database, and the yields were 270 gpm and 20 gpm, respectively.

Alkalic extrusive and intrusive igneous rocks. Alkalic extrusive and intrusive igneous rocks (igneous rocks) are limited in area in the GGRB, and are primarily present on the northern Rock Springs Uplift (**Plate 2**). These igneous rocks likely yield very little water to wells, and development potential is likely very poor (Welder and McGreevy, 1966, sheet 3; Welder, 1968, sheet 2). Spring-discharge and well-yield measurements from the USGS NWIS database and other reports were reviewed for the GGRB, and little information was found. One measurement of discharge from a spring on the Rock Springs Uplift was available from the USGS NWIS database, and was 5 gpm (**Plate 4**).

Tertiary hydrogeologic units

Tertiary hydrogeologic units composed of sedimentary rock contain the most abundant and widely used shallow aquifers in the GGRB. Aquifers in Tertiary hydrogeologic units are widely used because they are areally extensive and relatively thick throughout the GGRB (**Figure 5-6**), and yield enough water with sufficient quality for many different uses. These aquifers are present in a relatively large number of different saturated Tertiary geologic formations, members, and tongues (geologic units) in the GGRB, and the hydrologic characteristics of the geologic units have been used to name and define them in relation to their hydrogeologic function (aquifers or confining units) (**Figures 5-1** and **5-2**). The nomenclature used to characterize and define these hydrogeologic units (**Figures 5-1** and **5-2**) differs among investigators and has changed over time. The last column in both **Figure 5-1** and **Figure 5-2** is the hydrogeologic nomenclature preferred and used in this memorandum.

Upper Tertiary hydrogeologic units

In this report, upper Tertiary hydrogeologic units are composed of aquifers in geologic units of Miocene and Pliocene age (**Figures 5-1** and **5-2**). Upper Tertiary hydrogeologic units discussed include undifferentiated Miocene rocks, the Miocene

Split Rock Formation, and the Browns Park aquifer (**Figures 5-1** and **5-2**). Whitehead (1996, p. 111) reported that aquifers in upper Tertiary hydrogeologic units (Miocene and Pliocene) in Wyoming typically are less extensive than aquifers in lower Tertiary hydrogeologic units (Oligocene, Eocene, and Paleocene), but commonly have greater permeability and are important sources of water.

Miocene rocks (undifferentiated). The hydrogeologic characteristics of undifferentiated Miocene rocks in the Rawlins Uplift area are generally unknown, but Berry (1960, p. 25–26) reported that these rocks "yield adequate water for domestic and stock use" and were "sufficiently permeable to allow free movement of water, and, because the water table generally lies at a relatively shallow depth, moderate to large amounts of water can be obtained from the thick saturated sections of the formation." Little additional information is available describing hydrogeologic characteristics of these rocks, but five measurements of well yields for pumped wells in the Rawlins Uplift area were available from the USGS NWIS database, and ranged from 4 to 15 gpm with a median yield of 6 gpm. Undifferentiated Miocene rocks also are present in the southwestern part of the Rock Springs Uplift (**Plate 2**), but no information could be found describing the hydrogeologic characteristics of these rocks.

Split Rock Formation. Miocene rocks in the north-central part of the Great Divide Basin were defined by Love (1961) as the Split Rock Formation. Subsequently, Love and Christiansen (1985) mapped the same rocks as Miocene rocks. Little information could be found describing the hydrogeologic characteristics of these rocks.

Browns Park aquifer. The Browns Park Formation is one of the most important and widely used upper Tertiary aquifers in southwestern Wyoming (Browns Park aquifer; **Figures 5-1** and **5-2**); however, most withdrawals from the aquifer are in areas outside of the GGRB study area, such as the Saratoga Valley and south of the city of Rawlins where the aquifer is exposed at land surface. In addition, the aquifer appears to be much more "productive" in these areas (especially Saratoga Valley area) than in areas where the aquifer is present in the GGRB (primarily in the southern Washakie Basin) (**Plate 2**).

Spring-discharge and well-yield measurements from the USGS NWIS database and other sources were reviewed for the GGRB (**Plate 4**). Little information was available for the Browns Park aquifer in the Green River Basin.

More information was available for the Browns Park aquifer in the Great Divide/Washakie/Sand Wash basins (**Plate 4**) than in the Green River Basin. Thirteen measured discharges of springs were available from the USGS NWIS database, and ranged from 0 to 250 gpm with a median discharge of 1 gpm. Three measurements of yields for pumped wells were available from the USGS NWIS database, and ranged from 4 to 7 gpm with a median yield of 6 gpm. Eleven spring-discharge and well-yield values were available from other sources, and ranged from 2 to 25 gpm with a median yield of 15 gpm. Thirteen estimates of specific capacity for the Browns Park aquifer in the Great Divide/Washakie/Sand Wash basins from all sources ranged from 0.03 to 6.25 gpm/ft. Eleven estimates of transmissivity for the Browns Park aquifer in the Great Divide/Washakie/Sand Wash basins from all sources ranged from about 13 to 1,340 ft^2/d.

Basalt flows and intrusive igneous rocks. Basalt flows and intrusive igneous rocks are very limited in areal extent in the GGRB. No hydrogeologic information is available for these rocks.

Lower Tertiary hydrogeologic units

Aquifers in lower Tertiary hydrogeologic units are the most widely used in the GGRB. Rocks containing these aquifers occur at or near the surface throughout the GGRB. Lower Tertiary units include the Oligocene Bishop Conglomerate and White River Formation; the Eocene Ice Point Conglomerate, Crooks Gap Conglomerate, and Washakie, Bridger, Green River, Battle Spring, and Wasatch Formations; and the Paleocene Fort Union Formation. In the Fossil Basin, lower Tertiary hydrogeologic units include various members of the Green River and Wasatch Formations. Lower Tertiary units are discussed as grouped into two broad categories based on area and local or regional hydrogeologic function. Hydrogeologic units with limited geographic extent are considered and discussed as "Local lower Tertiary hydrogeologic units," whereas regionally extensive hydrogeologic units present throughout the Green River, Great Divide, and Washakie basins are considered and discussed as parts of two large regional lower Tertiary aquifer systems: the Green River Basin lower Tertiary aquifer system and the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system.

Local lower Tertiary hydrogeologic units

Geologic units of limited areal extent are discussed and evaluated in relation to their hydrogeologic characteristics in this section of the report. The hydrogeologic characteristics of the Bishop Conglomerate, White River Formation, Ice Point Conglomerate, Crooks Gap Conglomerate, and Washakie Formation are described and assessed. Local lower Tertiary aquifers in the Fossil Basin occupy older formations, and are discussed following the *Great Divide/Washakie/Sand Wash basins lower Tertiary Aquifer System* section below.

Bishop Conglomerate. Little information is available describing and assessing the hydrogeologic characteristics of the Oligocene Bishop Conglomerate. Welder (1968, sheet 2) and Welder and McGreevy (1966, sheet 3) reported that the potential for groundwater development in the Bishop Conglomerate is not known, but is likely poor to fair. Welder (1968, sheet 2) indicated that the deposits are generally topographically high and, consequently, probably well drained in most areas.

Well-yield and spring-discharge measurements and other hydraulic properties for the Bishop Conglomerate in the Green River Basin were reviewed and summarized from the USGS NWIS database, and many other sources (**Plate 4**). Five measurements of discharge for springs were available from the USGS NWIS database, and ranged from 5 to 200 gpm with a median discharge of 15 gpm. One measurement of yield for one pumped well was available from the USGS NWIS database, and was 42 gpm.

White River aquifer. Little information is available describing the hydrogeologic characteristics of the Oligocene White River Formation within the Great Divide Basin. In the GGRB study area, the formation is exposed at land surface in a small area in the Sweetwater Uplift north of the Great Divide Basin (**Plate 2**). The saturated thickness of the White River Formation in the Great Divide/Washakie/Sand Wash basins is unknown. The formation is an aquifer in the Wind River Basin and is likely an aquifer in the study area, and is defined as such in **Figure 5-2** and **Plate 1b**. Whitcomb and Lowry (1968, sheet 3) reported that the White River Formation in the Wind River Basin yielded small supplies of generally good quality groundwater to many stock and domestic wells, and that large supplies could be obtained where saturated thicknesses were great or where the permeability had been increased by fractures.

Ice Point Conglomerate. In the GGRB study area, the Eocene Ice Point Conglomerate is exposed at land surface in a very small area on the Sweetwater Uplift north of the Great Divide Basin (**Plate 2**). On the basis of the description of the distribution and thickness of the conglomerate by Love (1970, p. C59), the formation in the GGRB likely consists of little more than thin lag deposits that are likely unsaturated.

Crooks Gap Conglomerate. In the GGRB study area, the Eocene Crooks Gap Conglomerate is exposed at land surface in a very small area in the Sweetwater Uplift north of the Great Divide Basin (**Plate 2**). No information was available describing the hydrogeologic characteristics of this formation, and the water-supply potential for these rocks is likely small, so they were not assessed as a part of this study.

Washakie Formation. The Eocene Washakie Formation is present in the central Washakie Basin. Welder and McGreevy (1966, sheet 3) used the names Uinta and Bridger Formations instead of Washakie Formation in their report, and they reported that the potential for groundwater development in these rocks was not known but probably poor. Collentine et al. (1981) and Glover et al. (1998) later defined the formation as an aquifer, and that convention is followed herein (**Figure 5-2**).

Well-yield and spring-discharge measurements and other hydraulic properties for the Washakie Formation in the Washakie Basin were reviewed and summarized from the USGS NWIS database, and many other sources (**Plate 4**). Six measurements of discharge for springs were available from the USGS NWIS database, and ranged from 0.3 to 650 gpm with a median discharge of 6 gpm. Two measurements of yield for flowing wells were available from the USGS NWIS database, and were 2 and 17 gpm.

Green River Basin lower Tertiary aquifer system

Lower Tertiary hydrogeologic units composing the Green River Basin Lower Tertiary aquifer system (Martin, 1996; Naftz, 1996; Glover et al., 1998) are discussed in this section of the report. This large, areally extensive aquifer system coincides with the boundaries of the Green River Basin and is thousands of feet in thickness. Most wells in the Green River Basin are completed in this aquifer system. Characteristics of individual hydrogeologic units composing the aquifer system are discussed, and the relation among the various hydrogeologic units functioning as part of the areally extensive Green River Basin lower Tertiary aquifer system is described.

Bridger aquifer. The Eocene Bridger Formation, located in the southern part of the Green River Basin, is composed of fractured sandstone, tuff, and shale and is classified as an aquifer (**Figure 5-1**). The aquifer overlies the Laney Member of the Green River Formation, also classified as an aquifer. The area and thickness of the Bridger aquifer are shown in **Figure 5-7**.

A potentiometric surface map of the Bridger aquifer constructed by Martin (1996) indicates the direction of groundwater flow for the entire aquifer (**Figure 5-8**). The investigator noted that hydraulic-head data in the Bridger aquifer were highly variable, suggesting that local recharge and discharge occur and that vertical hydraulic gradients exist within the aquifer, even though groundwater flow was primarily horizontal. He reported large amounts of vertical leakage from the Bridger aquifer into deeper aquifers along the front of the Uinta Mountains where the underlying Green River Formation is composed of conglomerate. He also noted that local groundwater flow systems in discontinuous overlying Quaternary unconsolidated aquifers likely affect water levels in the Bridger aquifer (presumably through groundwater recharge). Groundwater in the Bridger aquifer flows from recharge areas along the Uinta Mountains to the north and northeast, and discharge from the aquifer is primarily to the Smiths Fork, Blacks Fork, and the Green River (Martin, 1996; Naftz, 1996; Glover et al., 1998).

Well-yield and spring-discharge measurements and other hydraulic properties for the Bridger Formation in the Green River Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Twelve measurements of discharge for springs were available from the USGS NWIS database, and ranged from 0.5 to 150 gpm with a median discharge of 4 gpm. Eight measurements of yields for pumped wells were available from the USGS NWIS database, and ranged from 6 to 32 gpm with a median yield of 11 gpm. Two measurements of yield for flowing wells were available from the USGS NWIS database, and were 30 and 44 gpm. Spring-discharge and well-yield values from other sources ranged from 2 to 100 gpm, with a median yield of 20 gpm. Twenty-eight measurements of specific capacity for the Bridger Formation in the Green River Basin from all sources ranged from 0.1 to 5 gpm/ft. Thirty-three estimates of transmissivity from all sources ranged from about 4 to 5,223 ft^2/d. One estimate of storage was available, and was 4×10^{-5}.

Twenty-eight estimates of hydraulic conductivity were available from all sources and ranged from 0.03 to 423 ft/d. Hydraulic conductivity of the Bridger aquifer in the Green River Basin is reportedly small in unfractured areas and large in fractured areas (Martin, 1996; Glover et al., 1998).

Green River Formation. The Eocene Green River Formation has been divided into numerous members and tongues in the GGRB. The Green River Formation interbeds and intertongues in a very complicated manner with the Wasatch Formation across the GGRB (**Figure 5-9**). The hydrogeologic role (aquifer or confining unit) of the Green River Formation, and the various members and tongues composing it, varies with location primarily as a result of variations in lithology or secondary permeability (fractures and solution channels). However, even those parts of the formation considered to be confining units may yield enough water locally in some areas to supply water to springs and wells.

Well-yield and spring-discharge measurements and other hydraulic properties for the undifferentiated Green River Formation in the Green River Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Two measurements of yields for pumped wells were available from the USGS NWIS database, and were 12 and 25 gpm. One measurement of yield for a flowing well was available from the USGS NWIS database, and was 12 gpm. Spring-discharge and well-yield values from other sources ranged from 2 to 45 gpm, with a median yield of 28 gpm. Three measurements of specific capacity from all sources ranged from 1 to 2 gpm/ft. Five estimates of transmissivity from all sources ranged from 20 to 161 ft^2/d. Two estimates of hydraulic conductivity were available from all sources, and were 0.1 to 0.5 ft/d.

Laney aquifer. The Laney aquifer in the Green River Basin is composed of the Laney Member of the Green River Formation (**Figure 5-1**). The areal extent and thickness of the Laney aquifer in the Green River Basin is shown in **Figure 5-10**. The Laney aquifer intertongues with the Wasatch zone of the Wasatch-Fort Union aquifer (composed of the Wasatch Formation) in the northern Green River Basin (**Figure 5-1**). Martin (1996) indicates that these aquifers are in direct hydraulic connection in this area, indicating that groundwater flowing south in the Wasatch zone moves directly into the Laney aquifer across the contact between the two aquifers. Most groundwater recharge to the Laney aquifer is upward leakage from the Farson Sandstone-Alkali Creek aquifer in the central Green River Basin and from irrigation recharge in the Farson-Eden area. Near the Big Sandy River, the Laney Member is highly productive because of fractures and solution channels. Bedded trona deposits within the Wilkins Peak confining unit prevent upward movement of water to the Laney aquifer in some areas. Discharge from the aquifer is primarily to the Big Sandy River and to the Green River between the Fontenelle and Flaming Gorge reservoirs. A potentiometric surface map of the Laney aquifer by Martin (1996) shows the direction of groundwater flow for the entire aquifer (**Figure 5-11**).

Well-yield and spring-discharge measurements and other hydraulic properties for the Laney Member of the Green River Formation in the Green River Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Seven measurements of discharge from springs were available from the USGS NWIS database, and ranged from 2 to 2,700 gpm with a median discharge of 10 gpm. Twenty-three measurements of yields for pumped wells were available from the USGS NWIS database, and ranged from 2 to 2,250 gpm with a median yield of 17 gpm. Five measurements of yield for flowing wells were available from the USGS NWIS database, and ranged from 1 to 5 gpm with a median yield of 2 gpm.

Spring-discharge and well-yield values from other sources ranged from 1 to 300 gpm, with a median yield of 25 gpm. Well yields are reportedly highest in areas near the Big Sandy River (Martin, 1996, Table 1). Six measurements of specific capacity for the Laney Member of the Green River Formation in the Green River Basin from all sources ranged from 0.1 to 150 gpm/ft. Fifteen estimates of transmissivity from all sources ranged from about 5 to 47,900 ft^2/d. One estimate of porosity was available, and was about 34 percent. Three estimates of storage were available, and ranged from 5×10^{-4} to 8×10^{-3}.

Eighteen estimates of hydraulic conductivity were available from all sources, and ranged from 0.2 to 1,450 ft/day. Martin (1996) indicated that the hydraulic conductivity of the Laney Member was greater in the northern Green River Basin than in the southern basin. In fact, he stated that low hydraulic conductivity of the Laney Member in the southern basin where buried by the Bridger aquifer indicates that the Laney is a confining unit in this area.

Wilkins Peak confining unit. The Wilkins Peak confining unit is composed of the Wilkins Peak Member and the southern part of the Laney Member of the Green River Formation (with low hydraulic conductivity—as noted above in the "Laney aquifer" description). The areal extent and thickness of the Wilkins Peak confining unit is shown in **Figure 5-12**. Martin (1996) also mapped the Wilkins Peak confining unit with the Tipton confining unit near the east and south margins of the basin (as shown in **Figure 5-1**). The Wilkins Peak confining unit is absent in the northern Green River Basin, but separates the Laney aquifer from the underlying Farson Sandstone-Alkali Creek aquifer in the central basin. Martin (1996) noted that bedded trona and halite deposits prevent vertical groundwater flow in a large part of the Wilkins Peak confining unit. Similarly, Ahern et al. (1981, p. 68) had reported earlier that "in the south-central basin the Wilkins Peak deposits are completely impermeable, as evidenced by unsaturated trona deposits located directly below the Green River."

Well-yield and spring-discharge measurements and other hydraulic properties for the Wilkins Peak Member of the Green River Formation in the Green River Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Ten measurements of discharge from springs were available from the USGS NWIS database and ranged from 0.8 to 75 gpm, with a median discharge of 4 gpm. Yield for one flowing well was available from the USGS NWIS database, and was 2 gpm. Spring-discharge and well-yield values from other sources ranged from 1 to 5 gpm, with a median yield of 2 gpm.

Farson Sandstone-Alkali Creek aquifer. The Farson Sandstone-Alkali Creek aquifer is composed of arkosic sandstone within the Farson Sandstone Member of the Green River Formation and Alkali Creek Tongue of the Wasatch Formation. This aquifer was named the "New Fork aquifer" by Martin (1996) on the basis of earlier stratigraphic nomenclature identifying these rocks as the "New Fork and Alkali Creek Tongues of the Wasatch Formation," and as used by Welder (1968, sheet 2). The historic stratigraphic nomenclature of the rocks composing this aquifer is confusing.

The Farson Sandstone Member of the Green River Formation composing the aquifer has been assigned different names by different investigators. Donavan (1950) and Lawrence (1963) assigned the rocks composing the Farson Sandstone Member to the Fontenelle Tongue of the Green River Formation. Oriel (1961) assigned the rocks to the New Fork Tongue of the Wasatch Formation, whereas Sullivan (1980) assigned the rocks to the Tipton Shale Member of the Green River Formation. Roehler (1991a) proposed assigning these rocks with these former names to the newly proposed Alkali Creek Tongue of the Wasatch Formation and Farson Sandstone Member of the Green River Formation, and abandoning the New Fork Tongue and Fontenelle Tongue names. This convention is used herein, so the rocks composing this aquifer are referred to as the *Farson Sandstone-Alkali Creek aquifer* (**Figure 5-1**).

The Farson Sandstone-Alkali Creek aquifer is located in the northern Green River Basin between the Wilkins Peak and Tipton Shale Members of the Green River Formation. The altitude of the top of the Farson Sandstone-Alkali Creek aquifer is shown in **Figure 5-13**. The area and thickness of the aquifer is shown in **Figure 5-14**. Recharge to the aquifer is from areas adjacent to the Wind River Range and from upward leakage through the Tipton confining unit from the underlying Wasatch zone of the Wasatch-Fort Union aquifer. Discharge from the aquifer is generally by upward leakage to the Laney aquifer (Martin, 1996).

Well-yield and spring-discharge measurements and other hydraulic properties for the Farson Sandstone-Alkali Creek aquifer in the Green River Basin were reviewed (**Plate 4**). Measured discharge for one spring was available from the USGS NWIS database, and was 15 gpm. Seventeen measurements of yields from pumped wells were available from the USGS NWIS database, and ranged from 7 to 30 gpm with a median yield of 15 gpm. Two measurements of yield for flowing wells were available from the USGS NWIS database, and were 1 and 6 gpm. Spring-discharge and well-yield values from other sources ranged from 18 to 26 gpm, with a median yield of 25 gpm. Two measurements of specific capacity were available from all sources, and were 0.8 and 1 gpm/ft. Six estimates of transmissivity available from all sources ranged from about 26 to 707 ft^2/d. Seven estimates of hydraulic conductivity were available from all sources, and ranged from 0.2 to 46 ft/d. One estimate of storage was available, and was 1×10^{-9}.

Tipton Confining Unit. The Tipton confining unit is composed of shales and marlstones of the Tipton Shale Member of the Green River Formation, as well as the Luman Tongue of the Green River Formation and the Niland Tongue of the Wasatch Formation in the southern Green River Basin (**Figure 5-1**). In the central Green River Basin, the Tipton confining unit separates the Farson Sandstone-Alkali Creek aquifer from the Wasatch zone of the Wasatch-Fort Union aquifer (**Figure 5-1**). In the southern Green River Basin where the Farson Sandstone-Alkali Creek aquifer is not present, the Tipton confining unit underlies and is mapped with the Wilkins Peak confining unit (**Figure 5-1**). The area and thickness of the Tipton confining unit in the Green River Basin are shown in **Figure 5-15**.

Well-yield and spring-discharge measurements and other hydraulic properties for the Tipton Shale Member of the Green River Formation in the Green River Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Three measurements of discharge from springs were available from the USGS NWIS database, and ranged from 1 to 9 gpm with a median discharge of 6 gpm. Four measurements of yield from flowing wells were available from the USGS NWIS database, and ranged from 5 to 26 gpm with a median yield of 18 gpm. Four spring-discharge and well-yield values from other sources ranged from 20 to 170 gpm, with a median yield of 24 gpm. One estimate of transmissivity was available, and was 40 ft^2/d. One estimate of porosity was available, and was about 24 percent. Estimates of hydraulic conductivity, available from all sources, ranged from 0.05 to 11 ft/d. One estimate of storage was available, and was 3×10^{-5}.

Wasatch-Fort Union aquifer. The Wasatch-Fort Union aquifer is composed of two zones represented by the Wasatch and Fort Union Formations and related formations (**Figure 5-1**). The aquifer forms the base of the Green River Basin Lower Tertiary aquifer system in the Green River Basin, and is in direct contact with underlying upper Cretaceous rocks at the top of the Mesaverde aquifer (**Figure 5-3**). No regional confining unit separates the Green River Basin Lower Tertiary aquifer system from the underlying Mesaverde aquifer. The Wasatch-Fort Union aquifer is the thickest Cenozoic hydrogeologic unit in the Green River Basin, as much as 11,000 feet thick. The altitude and configuration of the base of the Green River Basin Lower Tertiary aquifer system, represented by the base of the Fort Union zone of the Wasatch-Fort Union aquifer, is shown in **Figure 5-16**.

(Wasatch zone) The Wasatch zone of the Wasatch-Fort Union aquifer is composed of the Wasatch Formation (main body), undifferentiated Green River and Wasatch Formations along the western edge of the Green River Basin, the Pass Peak Formation in the northwestern basin, various Eocene (and possibly younger) rocks in the northeastern basin, as well as numerous small tongues and members including the Farson Sandstone Member of the Green River Formation and the Alkali Creek Member of the Wasatch Formation between the New Fork River and the southernmost exposure of the Laney aquifer in the north and central basin; the Niland Tongue of the Wasatch Formation in the southeast; the "La Barge Member"; the Chappo Member of the Wasatch Formation; and the Luman Tongue of the Green River Formation in the southeast (Martin, 1996) (**Figure 5-1**). The "La Barge Member" of the Wasatch Formation refers to rocks in the Wasatch Formation that directly overlie the Chappo Member of the Wasatch Formation in the Green River Basin, as named by Love and Christiansen (1985). Love et al. (1993) subsequently reassigned the "La Barge Member" to the main body of the Wasatch Formation and discontinued use of the name. In this report, hydrogeologic characteristics of these rocks are described separately from those of the main body of the Wasatch Formation for characterization purposes, and the use of the name is informally retained because of its widespread use in older reports.

Sandstone beds, interbedded with various fine-grained sedimentary rocks in these various units composing the Wasatch zone, generally provide most of the water to wells completed in the aquifer. The thickness and amount of sandstone at a given location generally depends on the distance from the sediment source area. Throughout the northern Green River Basin, many investigators have noted thick, permeable, areally extensive sandstones at or near land surface. In fact, Welder (1968, sheet 2) noted that "aggregate thickness of water-bearing sandstone probably ranges from one-third to two-thirds of total formation thickness; consequently, a large amount of water is in storage and the water is under pressure where deeply buried." In the southern Green River Basin, the Wasatch zone is overlain by the Green River Formation, and the number and thickness of sandstone beds in the aquifer vary greatly both areally and vertically. Large well yields in thick sandstone have been reported along basin margins.

The elevation of the top of the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin is shown in **Figure 5-17**. The area and thickness of the Wasatch zone are shown in **Figure 5-18**.

A potentiometric surface map of the Wasatch zone of the Wasatch-Fort Union aquifer constructed by Martin (1996) shows the direction of groundwater flow for the entire aquifer (**Figure 5-19**). Groundwater generally flows from basin margins (assumed to represent recharge areas) toward the center of the basin and to the south (assumed to represent discharge areas). Martin noted that water-table conditions predominate in the northern Green River Basin, whereas artesian (confined) conditions predominate elsewhere.

Well-yield and spring-discharge measurements and other hydraulic properties for the Wasatch Formation (main body and undifferentiated) within the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin aquifer system were reviewed and summarized (**Plate 4**). Twenty-one measurements of discharge from springs were available from the USGS NWIS database, and ranged from 0.2 to 200 gpm with a median discharge of 2 gpm. One hundred sixteen measurements of yields from pumped wells were available from the USGS NWIS database, and ranged from 2 to 302 gpm with a median yield of 20 gpm. Thirty-one measurements of yield from flowing wells were available from the USGS NWIS database, and ranged from 1 to 440 gpm with a median yield of 20 gpm. Spring-discharge and well-yield values from other sources ranged from 1 to 688 gpm, with a median yield of 25 gpm. Fifty-two measurements of specific capacity were available from all sources, and ranged from 0.2 to 31 gpm/ft. One hundred fifty-eight estimates of transmissivity were available from all sources, and ranged from about 0.09 to 40,836 ft^2/d. Four measurements of porosity were available from all sources, and ranged from 20 to 25 percent. Two hundred seventy estimates of hydraulic conductivity were available from all sources, and ranged from 0 to 2,106 ft/d. Eight estimates of storage were available, and ranged from 1×10^{-9} to 1×10^{-3}.

Well-yield and spring-discharge measurements and other hydraulic properties for the Cathedral Bluffs Tongue of the Wasatch Formation within the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin were reviewed and summarized (**Plate 4**). Six measurements of yield from flowing wells were available from the USGS NWIS database, and ranged from 20 to 30 gpm with a median yield of 25 gpm. Spring-discharge and well-yield values from other sources ranged from 18 to 27 gpm. One measurement of specific capacity was available from other sources, and was 0.2 gpm/ft. One measurement of transmissivity was available, and was 90 ft^2/d. One estimate of storage was available, and was 2×10^{-9}.

Well-yield and spring-discharge measurements and other hydraulic properties for the "La Barge Member" of the Wasatch Formation within the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin were reviewed and summarized (**Plate 4**).

One measurement of discharge from one spring was available from the USGS NWIS database, and was 5 gpm. Eight measurements of yield from pumped wells were available from the USGS NWIS database, and ranged from 0.5 to 48 gpm with a median yield of 4 gpm. Four measurements of yield from flowing wells were available from the USGS NWIS database, and ranged from 3 to 280 gpm with a median yield of 12 gpm. Spring-discharge and well-yield values from other sources ranged from 30 to 295 gpm, with a median yield of 115 gpm. Ten measurements of specific capacity were available from all sources, and were 0.2 to 6 gpm/ft. Eighteen estimates of transmissivity were available from all sources, and ranged from 46 to 2,680 ft^2/d. Two estimates of hydraulic conductivity were available from all sources, and were 0.6 to 8 ft/d. Nine estimates of storage were available, and ranged from 1×10^{-4} to 1×10^{-3}.

Well-yield and spring-discharge measurements and other hydraulic properties for the Niland Tongue and the Chappo Member of the Wasatch Formation within the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin were reviewed and summarized (**Plate 4**). Six measurements of spring-discharge and (or) well-yield were available for the Niland Tongue, and ranged from 3 to 40 gpm with a median of 30 gpm. One measurement of discharge from one spring discharging from the Chappo Member was available from the USGS NWIS database, and was 0.01 gpm.

Well-yield and spring-discharge measurements and other hydraulic properties for the "Almy Formation" within the Wasatch zone of the Wasatch-Fort Union aquifer in the Green River Basin were reviewed and summarized (**Plate 4**). The "Almy Formation" is the name for a zone within the basal Wasatch Formation in the western Green River Basin used by producers to denote a part of the Wasatch Formation utilized in oil and gas production. No spring-discharge or well-yield values from the sources reviewed were available. Five estimates of transmissivity were available from all sources, and ranged from about 3 to 134 ft^2/d. Nine measurements of porosity were available from all sources, and ranged from 14 to 29 percent. Six estimates of hydraulic conductivity were available from all sources, and ranged from 0.03 to 1 ft/d.

(Fort Union zone) The Fort Union zone of the Wasatch-Fort Union aquifer is composed of the Fort Union Formation and the Hoback Formation (**Figure 5-1**). The Hoback Formation is equivalent to the Fort Union Formation in the northwestern Green River Basin. The Fort Union Formation is lithologically very similar to the Wasatch Formation; it is also composed of fluvial sandstones and fine-grained sedimentary rocks. In the subsurface, it is often difficult to differentiate the two formations. Although the Fort Union zone is present throughout the Green River Basin, in the "northwestern part of the structural basin where the Hoback Formation is exposed at the surface, the Fort Union zone is not included as part of the aquifer system because it is north of a groundwater divide outside of the hydrologic basin" (Martin, 1996, p. 21).

The elevation of the top of the Fort Union zone of the Wasatch-Fort Union aquifer in the Green River Basin is shown in **Figure 5-20**. The area and thickness of the Fort Union zone of the Wasatch-Fort Union aquifer in the Green River Basin are shown in **Figure 5-21**. The potentiometric surface of the Fort Union zone is shown in **Figure 5-22**.

Well-yield and spring-discharge measurements and other hydraulic properties for the Fort Union Formation within the Fort Union zone of the Wasatch-Fort Union aquifer in the Green River Basin aquifer system were reviewed and summarized (**Plate 4**). One measurement of discharge from one spring was available from the USGS NWIS database, and was 100 gpm. One measurement of yield for one flowing well was available from the USGS NWIS database, and was 5 gpm. Thirteen estimates of transmissivity were available from all sources, and ranged from 0.01 to 24 ft^2/d. Ten estimates of porosity were available from all sources, and ranged from 9 to 23 percent. Sixty-six estimates of hydraulic conductivity were available from all sources, and ranged from 4×10^{-5} to 1,134 ft/d. (Such a range – eight orders of magnitude – is not exceptional in a set of samples from an extensive, heterogeneous aquifer).

Regional recharge, discharge, groundwater budget, and groundwater flow

Recharge to Tertiary aquifers in the Green River Basin occurs by infiltration of precipitation on outcrop areas, infiltration of snowmelt runoff from the mountains, and leakage of streamflow (Welder and McGreevy, 1966, p. 2; Welder, 1968 p. 2; Ahern et al., 1981; Martin, 1996, p. 25; Naftz, 1996; Glover et al., 1998). Infiltration of surface water used for irrigation is likely another source of recharge to Tertiary aquifers in parts of the Green River Basin (Welder, 1968, p. 3). Ahern et al. (1981) and Martin (1996) concluded that recharge from irrigation water in the Farson-Eden area occurs by downward movement of water through alluvial deposits into the underlying Laney aquifer. Calibration of a numerical groundwater flow model of the Green River Basin lower Tertiary aquifer system constructed by Martin (1996) indicated that recharge to Tertiary hydrogeologic units in the Farson-Eden area as a result of irrigation was likely about 18 cubic feet per second (ft^3/s) (**Table 5-1**).

Martin (1996, p. 25) reported that analysis of streamflow-gaging records indicated that all the major streams in the Green River Basin are gaining streams, except the Blacks Fork, Smiths Fork, and Hams Fork, which are losing streams and provide recharge to underlying Tertiary hydrogeologic units or are losing water because of evapotranspiration.

Martin (1996, p. 27) estimated the total recharge to Tertiary hydrogeologic units in the Green River structural basin using methods developed by Eakin et al. (1951) and modified by Hood et al. (1968). These methods, adjusted to account for separate recharge from precipitation, snowmelt, streams, and canals, were used to estimate recharge as a percentage of average annual precipitation. Using these methods, total recharge to Tertiary hydrogeologic units composing the Green River Basin lower Tertiary aquifer system was estimated to be about 165 ft^3/s, distributed among the various water-budget components shown in **Table 5-1**. The areal distribution of groundwater recharge is shown in **Figure 5-23**. Identified recharge areas shown in **Figure 5-23** generally correspond well to areas of recharge indicated by highs in the potentiometric-surface maps for Tertiary hydrogeologic units (see figures at end of this chapter).

Geochemical methods also have been used to identify areas of recharge and discharge. Naftz (1996) examined major-ion geochemistry to identify areas of recharge, discharge, and interaquifer leakage in the Bridger aquifer, Laney aquifer, and the Wasatch zone of the Wasatch-Fort Union aquifer. He noted that recharge areas are characterized by small dissolved-solids concentrations, positive log $(([Ca]+[Mg])/[Na])^2$ values, and small sodium and fluoride concentrations. According to Glover et al. (1998), these positive log $(([Ca]+[Mg])/[Na])^2$ values indicate that recharge areas to the Bridger aquifer and the Wasatch zone of the Wasatch-Fort Union aquifer are very similar to those delineated by hydraulic-gradient data from potentiometric-surface maps. The trends in positive log $(([Ca]+[Mg])/[Na])^2$ values indicate that recharge to the Bridger aquifer occurs in the southern Green River Basin adjacent to the Uinta Mountains Uplift, and that possible localized recharge to the Bridger aquifer occurs east of Evanston and in the vicinity of the Blacks Fork. The trends in positive log $(([Ca]+[Mg])/[Na])^2$ values in water from the Wasatch zone of the Wasatch-Fort Union aquifer indicate recharge in the northern, eastern, and western Green River Basin. These trends in positive log $(([Ca]+[Mg])/[Na])^2$ values correspond to the hydraulic gradient and indicate that groundwater moves toward the central and southern basin. Sulfate concentrations generally increase along projected groundwater flowpaths, and water with dissolved-solids concentrations greater than 1,500 mg/l is high in sodium and chloride (Naftz, 1996). Examining calcium-to-chloride ratios, Naftz concluded that ratios that exceed the local precipitation ratio indicate recharge areas, and ratios less than the local precipitation ratio indicate discharge areas.

Most groundwater discharge from Tertiary hydrogeologic units occurs as seepage to Flaming Gorge Reservoir, the Green River and its major tributaries, and alluvial deposits associated with the streams (Martin, 1996; Glover et al., 1998). Discharge to the Flaming Gorge Reservoir area also can be seen on the potentiometric-surface map of the Wasatch

Table 5-1. Estimated steady-state groundwater budget for Tertiary hydrogeologic units composing the Green River Basin lower Tertiary aquifer system (from Martin, 1996)

Recharge components	*Inflow to the groundwater system (cfs)*
Infiltration of precipitation, snowmelt runoff, and streamflow	138
Excess irrigation water in the Farson-Eden area, Wyoming	18
Streamflow leakage along the Blacks Fork, Smiths Fork, and Henrys Fork	9
Total	**165**
Discharge components	*Outflow from the groundwater system (cfs)*
Green and New Fork rivers upstream from Fontenelle Reservoir	94
Green River between Fontenelle Reservoir and the town of Green River, Wyoming	23
Green River downstream from the town of Green River, Wyoming, including Flaming Gorge Reservoir	13
Big Sandy River	17
Henrys Fork	16
Total	**163**

zone of the Wasatch-Fort Union aquifer (**Figure 5-19**). Smaller streams in the northern Green River Basin likely receive discharge from local groundwater flow systems. Small amounts of discharge occur at springs discharging from the Bridger aquifer in the southern Green River Basin and from the Laney aquifer in the Farson-Eden area (Ahern et al., 1981; Martin, 1996). Total groundwater discharge from Tertiary hydrogeologic units composing the Green River Basin lower Tertiary aquifer system was estimated by Martin (1996) to be about 163 ft^3/s, distributed among the various water-budget components (streams and stream reaches) listed in **Table 5-1**.

Discharge from pumping wells and evapotranspiration in the Green River Basin was reported as negligible by Martin (1996). It is unclear if this is still the case in the northern Green River Basin, where numerous wells in the Wasatch zone of the Wasatch-Fort Union aquifer are currently (2008) being used to supply water to drill and construct gas wells in the Jonah Field and Pinedale anticline production areas.

Improved understanding of regional groundwater flow through modeling

Martin (1996) created a groundwater flow model to simulate steady-state groundwater flow in hydrogeologic units composing the Green River Basin lower Tertiary aquifer system. Hydrogeologic characteristics of the aquifers at basin scale are described by the calibrated steady-state groundwater flow model. The three-dimensional finite-difference model was constructed using an early version of the groundwater flow model currently known as MODFLOW (McDonald and Harbaugh, 1988). The major aquifers and confining units in the aquifer system were divided into model layers representing (in descending order) the Bridger aquifer, Laney aquifer, Farson Sandstone-Alkali Creek aquifer (referred to as the "New Fork" aquifer by Martin), the Wilkins Peak and Tipton confining units (represented by one layer), the Wasatch zone of the Wasatch-Fort Union aquifer, and the Fort Union zone of the Wasatch-Fort Union aquifer (**Figure 5-24**).

The groundwater flow model was calibrated through a trial-and-error process by adjusting aquifer property parameters to minimize differences between estimated and simulated stream-aquifer leakage (primarily groundwater leakage to streams) and to minimize the differences between measured and simulated hydraulic heads in the five layers of the model. Groundwater flow within and among the layers of the model representing hydrogeologic units composing the Green River Basin lower Ter-

Table 5-2. Estimated and simulated stream-aquifer leakage in the Green River Basin lower Tertiary aquifer system (from Martin, 1996)
[+ indicates groundwater leakage (streamflow gain); - indicates streamflow leakage to aquifer (streamflow loss); – indicates not simulated]

Stream reach	*Stream-aquifer leakage (cfs)*	
	Estimated from streamflow-gaging data	Simulated by flow-model analysis
Green and New Fork rivers upstream from Fontenelle Reservoir	+94	[1]+98
Green River between Fontenelle Reservoir and the town of Green River, Wyoming	+23	+23
Green River downstream from the town of Green River, Wyoming, including Flaming Gorge Reservoir	+13	+14
Big Sandy River	+17	+12
Blacks Fork, Smiths Fork, and Hams Fork	-9	[2]+9
Henrys Fork	+16	–

[1]*New Fork River was not simulated*
[2]*Blacks Fork and Smiths Fork simulated as one stream*

tiary aquifer system was successfully simulated, the conceptual understanding of groundwater flow and recharge was refined, and effective basin values of hydraulic conductivity were determined.

Groundwater discharge to streams simulated by the groundwater flow model compared well with estimates from streamflow-gaging data except for three streams (Blacks Fork, Smiths Fork, and Hams Fork) (**Table 5-2**). Martin (1996) noted that the potentiometric surface of the Bridger aquifer suggests that groundwater discharges into the Blacks Fork and Smiths Fork, but, in contrast, streamflow gaging data indicate that the Blacks Fork and Smiths Fork are losing streams. Martin (1996, p. 34) speculated that "evapotranspiration due to vegetation along the stream banks causes the streams to be losing streams, whereas groundwater also is lost to evapotranspiration along same reaches."

Groundwater flow generally has a vertical component. An improved understanding of vertical hydraulic groundwater flow among the various hydrogeologic units composing the Green River Basin lower Tertiary aquifer system also was obtained through simulation. **Figure 5-25** shows the direction of vertical groundwater flow between the aquifers as simulated in the model.

Large differences were noted between published estimates of horizontal hydraulic conductivity obtained from aquifer tests and effective basin values of adjusted hydraulic conductivity obtained from groundwater flow-model calibration. With the exception of the Farson Sandstone-Alkali Creek aquifer, simulated basin values of hydraulic conductivity were generally much lower than point estimate values of hydraulic conductivity obtained from aquifer tests (**Table 5-3**). Martin (1996) attributed this to local variations in sandstone content or fracture density that results in point estimates of hydraulic conductivity that are much different from values obtained by basin flow-model simulation.

Martin (1996) summarized all of his work (including results from the calibrated groundwater flow model) showing the relative rates and direction of groundwater movement among aquifers composing the Green River Basin lower Tertiary aquifer system in a diagrammatic cross-section (**Figure 5-26**). In **Figure 5-26**, arrows show the direction of groundwater flow within and between hydrogeologic units. The relative length of the arrows indicates the length of groundwater flowpaths: short arrows indicate local groundwater flow, medium arrows indicate intermediate groundwater flow, and long

Table 5-3. Summary of hydraulic conductivity estimates from the Green River Basin lower Tertiary aquifer system groundwater flow model (from Martin, 1996)
[– indicates no data]

Hydrogeologic unit	Range of hydraulic conductivity (feet per day)		
	Simulated		*Measured*
	Vertical	Horizontal	Horizontal
Bridger aquifer	0.00001	0.09–0.9	0.03–420
Laney aquifer	0.00001–17.3	0.04–17.3	2–1,400
Wilkins Peak and Tipton confining units[1]	0.00001	0.00009	–
Farson Sandstone-Alkali Creek aquifer	0.1	6.5	0.2–2.0
Wasatch zone of the Wasatch-Fort Union aquifer	0.001–4	0.04–6.5	0.03–2,100
Fort Union zone of the Wasatch-Fort Union aquifer	0.00001–0.01	0.00001–0.3	0.02–1,100

[1] These values were used in the part of the confining bed modeled as a layer.

arrows indicate regional (basin) groundwater flow. **Figure 5-26** shows that groundwater flow in aquifers composing the Green River Basin lower Tertiary aquifer system generally is from recharge areas along the margins of the basin toward the center of the basin and to the south. Local and intermediate groundwater flow occurs in many of the shallower aquifers, but regional groundwater flow generally occurs in deep parts of the Wasatch and Fort Union zones of the Wasatch-Fort Union aquifer where overlain by the Tipton confining unit. Recharge occurs along basin boundaries, and discharge occurs to streams and associated alluvial aquifers.

Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system

Lower Tertiary hydrogeologic units composing the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system (Naftz, 1996; Glover et al., 1998) are discussed in this section of the report. Lower Tertiary hydrogeologic units within these three structural basins were shown to be in hydraulic connection by Glover et al. (1998) using hydraulic head and water-quality data; together, the lower Tertiary hydrogeologic units compose a large, areally extensive interbasin aquifer system thousands of feet thick that coincides with the boundaries of the Great Divide, Washakie, and Sand Wash structural basins (**Figure 5-2**). The Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system consists of one regional confining unit (Green River confining unit) and one interbasin regional aquifer (Wasatch-Fort Union aquifer) (**Figure 5-2**). Many of the wells in the Great Divide, Washakie, and Sand Wash basins are completed in this aquifer system. Characteristics of individual hydrogeologic units composing the aquifer system are discussed, and the relation among the various hydrogeologic units functioning as part of the areally extensive Great Divide/Washakie/Sands Wash basins lower Tertiary aquifer system is described.

Green River confining unit. The Green River confining unit is composed of the Green River Formation (and various tongues and members) and part of the Wasatch Formation (Welder and McGreevy, 1966; Glover et al., 1998) (**Figure 5-2**). The confining unit is present in the Washakie Basin in southern Sweetwater County (Wyoming) and western parts of the Great Divide and Sand Wash basins in northern Sweetwater County (Wyoming) and in Moffat County (Colorado), and overlies Tertiary rocks (**Figure 5-27**). Shale and marlstones in the Green River Formation, and shale and fine-grained sandstone in tongues of the Wasatch Formation, compose the confining unit. Where buried by the overlying Washakie Formation in the Washakie and Sand Wash basins, the confining unit typically ranges from 1,000 to 5,000 feet in thickness (**Figure 5-27**). The confining unit is thinner in the Great Divide Basin, and thickness is typically less than 2,000 feet there.

Well-yield and spring-discharge measurements and other hydraulic properties for the undifferentiated Green River Formation within the Green River confining unit in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). One measurement of yield for a pumped well was available from the USGS NWIS database, and was 16 gpm. Spring-discharge and well-yield values from other sources ranged from 15 to 250 gpm, with a median yield of 134 gpm. One estimate of transmissivity was available from all sources, and was 130 ft^2/d.

Well-yield and spring-discharge measurements and other hydraulic properties for the Laney Member of the Green River Formation within the Green River confining unit in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). Eleven measurements of discharges from springs were available from the USGS NWIS database, and ranged from 0.5 to 500 gpm with a median discharge of 4 gpm. Three measurements of yields for pumped wells were available from the USGS NWIS database, and ranged from 5 to 40 gpm with a median discharge of 9 gpm. One measurement of yield from one flowing well was available from the USGS NWIS database, and was 1 gpm. Spring-discharge and well-yield values from other sources were 10 and 100 gpm. One transmissivity estimate was available from all sources, and was 953 ft^2/d. One hydraulic conductivity estimate was available from all sources, and was 5 ft/d.

Well-yield and spring-discharge measurements and other hydraulic properties for the Wilkins Peak Member of the Green River Formation within the Green River confining unit in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). Five measurements of discharge from springs were available from the USGS NWIS database, and ranged from 0.5 to 50 gpm with a median discharge of 3 gpm.

Well-yield and spring-discharge measurements and other hydraulic properties for the Tipton Shale Member of the Green River Formation within the Green River confining unit in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). Four measurements of discharge from springs were available from the USGS NWIS database, and ranged from 2 to 15 gpm with a median discharge of 4 gpm. One measurement of yield for one flowing well was available from the USGS NWIS database, and was 12 gpm.

Wasatch-Fort Union aquifer. The Wasatch-Fort Union aquifer is composed of two zones: the Wasatch zone, represented by the Wasatch and Battle Spring Formations, and the Fort Union zone, represented by the Fort Union Formation (**Figure 5-2**; Glover et al., 1998, Figure 4). The aquifer, overlain by the Green River confining unit in places, forms the base of the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system in the Great Divide, Washakie, and Sand Wash basins, and is in direct contact with underlying upper Cretaceous rocks composing the Mesaverde aquifer. No regional confining unit separates the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system from the underlying Mesaverde aquifer. The Wasatch-Fort Union aquifer is the thickest Cenozoic hydrogeologic unit in the Great Divide, Washakie, and Sand Wash basins. Glover et al. (1998) noted that Tertiary rocks composing the aquifer system are continuous with Tertiary aquifers in small areas north and south of the Rock Springs Uplift and across the Axial Basin Arch, which is located in northwestern Colorado (**Figure 2-2**).

(Wasatch zone) The Wasatch zone of the Wasatch-Fort Union aquifer is composed of the Wasatch Formation (and associated members and tongues) and the Battle Spring Formation (Glover et al., 1998). The Wasatch Formation is a thick sequence of fine-grained sedimentary rocks (sandy shale and siltstone) and varying amounts of channel sandstones and coal. The Battle Spring Formation is a fluvial sheet of arkosic sandstone present throughout much of the Great Divide Basin. The Wasatch zone occurs at land surface throughout the Great Divide, Washakie, and Sand Wash basins except where overlain by the Green River confining unit (**Figure 5-28**). The area and thickness of the Wasatch zone of the Wasatch-Fort Union aquifer are shown in **Figure 5-29**. The thickness of the zone throughout the basins typically ranges from 1,000 to 4,000 feet.

A potentiometric surface map of the Wasatch zone of the Wasatch-Fort Union aquifer, constructed by Glover et al. (1998) using water-level measurements in wells that generally penetrated less than 300 feet below land surface, shows the direction of groundwater flow for the entire aquifer (**Figure 5-30**). Groundwater generally flows from basin margins (assumed to represent recharge areas) toward the centers of the Great Divide and Washakie basins (assumed to represent discharge areas, and shown by hachured contours), where the Wasatch zone is exposed at land surface in the basin.

Welder and McGreevy (1966) and Collentine et al. (1981) described the hydrogeologic characteristics of the Battle Spring Formation in the Great Divide Basin. Welder and McGreevy (1966, sheet 3) reported good groundwater development possibilities in the northern Great Divide Basin and noted "maximum yields of wells penetrating the entire formation might exceed 1,000 gpm." Collentine et al. (1981, p. 52) reported that the aquifer is "capable of yielding at least 150 gpm to water wells, though most yields generally range from 30 to 40 gpm."

Well-yield and spring-discharge measurements and other hydraulic properties for the Wasatch Formation (main body and undifferentiated) within the Wasatch zone of the Wasatch-Fort Union aquifer in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). Eight measurements of discharge from springs were available from the USGS NWIS database, and ranged from 0.1 to 15 gpm with a median discharge of 3 gpm. Twenty-one measurements of yields for pumped wells were available from the USGS NWIS database, and ranged from 4 to 55 gpm with a median yield of 15 gpm. Six measurements of yield for flowing wells were available from the USGS NWIS database, and ranged from 2 to 50 gpm with a median yield of 7 gpm. Spring-discharge and well-yield values from other sources ranged from 3 to 325 gpm, with a median yield of 30 gpm. Nine measurements of specific capacity were available from all sources, and ranged from 0.2 to 10 gpm/ft. Thirty-two estimates of transmissivity were available from all sources, and ranged from 11 to 1,340 ft^2/d. Thirteen measurements of porosity were available from all sources, and ranged from 7 to 29 percent. Sixteen estimates of hydraulic conductivity were available from all sources, and ranged from 0.004 to 9.1 ft/d.

Well-yield and spring-discharge measurements and other hydraulic properties for the Cathedral Bluffs Tongue of the Wasatch Formation within the Wasatch zone of the Wasatch-Fort Union aquifer in the Great Divide/Washakie/Sand Wash basins aquifer system were reviewed and summarized (**Plate 4**). Fifteen measurements of discharge from springs were available from the USGS NWIS database, and ranged from 0.2 to 200 gpm, with a median discharge of 6 gpm. One measurement of yield from one pumped well was available from the USGS NWIS database, and was 15 gpm. Spring-discharge and well-yield values from other sources ranged from 15 to 125 gpm, with a median yield of 52 gpm. Four measurements of specific capacity were available from all sources, and ranged from 0.2 to 50 gpm/ft. Four estimates of transmissivity were available from all sources, and ranged from 80 to 13,400 ft^2/d.

Well-yield and spring-discharge measurements and other hydraulic properties for the Battle Spring Formation within the Wasatch zone of the Wasatch-Fort Union aquifer in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). One measurement of discharge from a spring was available from the USGS NWIS database, and was 3 gpm. Three measurements of yield for pumped wells were available from the USGS NWIS database, and ranged from 10 to 20 gpm with a median yield of 10 gpm. Two measurements of yield from flowing wells were available from the USGS NWIS database, and were 1 and 400 gpm. Spring-discharge and well-yield values from other sources ranged from 5 to 300 gpm, with a median yield of 55 gpm. Thirteen measurements of specific capacity were available from all sources, and ranged from 0.1 to 1 gpm/ft. Twelve estimates of transmissivity were available from all sources, and ranged from 20 to 880 ft^2/d. One measurement of porosity was available from all sources, and was 17 percent. Six estimates of hydraulic conductivity were available from all sources, and ranged from 0.0007 to 10 ft/d. One estimate of storage was available, and was 0.03.

(Fort Union zone) The Fort Union zone of the Wasatch-Fort Union aquifer is composed of the Fort Union Formation (Glover et al., 1998). The Fort Union Formation is a thick interbedded sequence of fine grained sedimentary rocks (sandy shale and siltstone) and varying amounts of channel sandstones, lignite, and coal. The Fort Union zone is buried throughout most of the Great Divide, Washakie, and Sand Wash basins, except for small exposures near the east, west, and southern basin boundaries (**Figure 5-31**). The area and thickness of the Fort Union zone of the Wasatch-Fort Union aquifer are shown in **Figure 5-32**; thickness of the zone typically ranges from 1,000 to 7,000 feet.

A potentiometric surface map of the Fort Union zone of the Wasatch-Fort Union aquifer, constructed by Glover et al. (1998) using water-level measurements in outcrop areas and drill-stem tests in deeply buried parts of the aquifer, shows the direction of groundwater flow for the entire aquifer (**Figure 5-33**). Groundwater generally flows from basin margins (assumed to represent recharge areas) toward the center of the Great Divide Basin in the north and the Washakie Basin in the south (assumed to represent discharge areas and noted by hachured contours). Regional (basin), rather than local, groundwater flow likely predominates in the Fort Union zone.

Welder and McGreevy (1966, Sheet 3) reported that the Fort Union aquifer within the Great Divide and Washakie basins is “a relatively good source of water in the area” and that “a well penetrating the entire formation where the sandstones are thickest might yield as much as 500 [gpm].”

Collentine et al. (1981, p. 54) reported that well yields from the Fort Union aquifer generally are less than 100 gpm, but yields greater than 300 gpm are possible. Collentine et al. (1981, p. 54) noted that many of the individual discontinuous sandstone beds or lenses are hydraulically isolated, although the investigators noted that sandstone and conglomerate beds in the lower part of the formation in some locations may be hydraulically connected by fractures.

Well-yield and spring-discharge measurements and other hydraulic properties for the Fort Union Formation within the Fort Union zone of the Wasatch-Fort Union aquifer in the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system were reviewed and summarized (**Plate 4**). One measurement of discharge from one spring was available from the USGS NWIS database, and was 1 gpm. Eight measurements of yield for pumped wells were available from the USGS NWIS database, and ranged from 3 to 90 gpm with a median yield of 37 gpm. One measurement of yield for one flowing well was available from the USGS NWIS database, and was 20 gpm. Spring-discharge and well-yield values from other sources ranged from 0.02 to 220 gpm. Seven measurements of specific capacity were available from all sources, and ranged from 0.001 to 75 gpm/ft. Thirty estimates of transmissivity were available from all sources, and ranged from 0.2 to 20,100 ft^2/d. Eleven estimates of hydraulic conductivity were available from all sources, and ranged from 0.001 to 938 ft/d. Nine estimates of storage were available, and ranged from 2×10^{-8} to 3×10^{-4}.

Recharge and discharge

Areas of recharge to the Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system can generally be identified on the potentiometric-surface map for the Wasatch zone of the Wasatch-Fort Union aquifer (**Figure 5-30**). These areas are primarily located on highlands along the northern, western, and southeastern boundaries of the aquifer system where increased precipitation and snowpack, in combination with permeable material at land surface, allow infiltration of water and recharge to the aquifers. Positive $(([Ca]+[Mg])/[Na])^2$ values also suggest recharge in the northern and western Great Divide Basin, in the western Washakie Basin, and localized recharge in the southern Washakie Basin (Naftz, 1996; Glover et al., 1998). Welder and McGreevy (1966, p. 2) reported that most streams in the Great Divide and Washakie basins are losing streams; these streamflow losses likely indicate groundwater recharge to underlying hydrogeologic units.

Fisk (1967, p. 65–67) identified major recharge areas to aquifers in the Great Divide Basin as the high area in the northeastern basin (Tps.26–27N., Rs.90–94W.), the southwestern basin where rocks are upturned on the Rock Springs Uplift, the Rawlins Uplift, and the high area around Creston Junction (T.20N., R.92W.) in Sweetwater County. Potentiometric surfaces in hydrogeologic units are higher in these areas than in other parts of the basin, perhaps because the higher altitude of these features results in slightly higher annual precipitation.

Fisk (1967, p. 66–68) identified major recharge areas to aquifers in the Washakie Basin as the upturned outcrops flanking the Rock Springs Uplift, the outcrop area southwest of Rawlins (Atlantic Rim area in Carbon County), and the high area around Creston Junction in Sweetwater County. Again, these high areas probably receive more annual precipitation than the lower parts of the basin. Fisk (1967, p. 66–68) also identified Muddy Creek where it crosses the permeable Late Cretaceous Fox Hills Sandstone and Lance Formation and the Tertiary Fort Union Formation (T.17N., R.91W.) in Carbon County north of Baggs as a recharge area for the basin.

Discharge from the Wasatch-Fort Union aquifer occurs at numerous seeps and springs located throughout all three basins and along Bitter Creek, Separation Creek, and the Little Snake River (Glover et al., 1998). Fisk (1967, p. 69-70) noted groundwater discharge to Bitter Creek, Muddy Creek, Vermillion Creek, and other tributaries to the Little Snake River. Numerous low-flow springs and seeps (discharge generally less than 2 gpm), and the potentiometric surface of the Wasatch zone of the Wasatch-Fort Union aquifer (**Figure 5-30**), suggest potential discharge at lowlands in the center of the Great Divide Basin. Discharge to areas in the Great Divide Basin also may be due to changes in aquifer lithology, and discharges may "correspond to a probable decrease in hydraulic conductivity as water flows from the arkosic sandstone of the Battle Spring Formation towards less permeable mixture of sandstone and shale in the Wasatch Formation" (Glover et al., 1998, p. 91). Glover et al. (1998) also note that attempts to estimate groundwater discharge to Bitter Creek, Separation Creek, and the Little Snake River using streamflow gain/loss studies were unsuccessful because the rates of groundwater discharge along the streams were less than streamflow measurement capability.

Local lower Tertiary aquifers in the Fossil Basin

Characteristics of various local lower Tertiary aquifers in the Fossil Basin are discussed in this report section. Members of the Green River Formation (Fossil Butte and Angelo Members), the Wasatch Formation (undifferentiated and the Bullpen and Tunp Members), and the Evanston Formation are briefly discussed.

Green River Formation. Well-yield and spring-discharge measurements and other hydraulic properties for the Fossil Butte and Angelo Members of the Green River Formation in the Fossil Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Six measurements of discharges from springs in the Fossil Butte Member of the Green River Formation were available from the USGS NWIS database, and ranged from 1 to 80 gpm with a median discharge of 25 gpm. One measurement of discharge from one spring in the Angelo Member of the Green River Formation was available from Ahern et al. (1981) and was 2 gpm.

Wasatch Formation. Well-yield and spring-discharge measurements and other hydraulic properties for the Wasatch Formation in the Fossil Basin were reviewed and summarized from the USGS NWIS database and other sources (**Plate 4**). Nineteen measurements of discharges from springs were available from the USGS NWIS database, and ranged from 0.1 to 80 gpm with a median discharge of 10 gpm. Spring-discharge and well-yield values available from other sources ranged from 3 to 15 gpm with a median yield of 5 gpm.

Bullpen and Tunp Members of the Wasatch Formation. Well-yield and spring-discharge measurements and other hydraulic properties for the Bullpen and Tunp Members of the Wasatch Formation in the Fossil Basin were reviewed and summarized from the USGS NWIS database and other sources (**Plate 4**). One measurement of discharge from one spring in the Bullpen Member of the Wasatch Formation was available from the USGS NWIS database, and was 22 gpm. One measurement of spring-discharge for the Bullpen Member of the Wasatch Formation in the Fossil Basin was available from Ahern et al. (1981), and was 5 gpm. One measurement of discharge from one spring in the Tunp Member of the Wasatch Formation in the Fossil Basin was available from the USGS NWIS database, and was 40 gpm.

Evanston Formation. Well-yield and spring-discharge measurements and other hydraulic properties for the Evanston Formation in the Fossil Basin were reviewed and summarized from the USGS NWIS database and many other sources (**Plate 4**). Two measurements of discharge from springs were available from the USGS NWIS database, and both were 1,000 gpm.

MESOZOIC HYDROGEOLOGIC UNITS

Freethey and Cordy (1991) divided Mesozoic rocks in the Upper Colorado River Basin, including the GGRB, into 10 hydrogeologic units: 5 regional aquifers and 5 regional confining units. Their general classification is used with modification in this report to define and describe the hydrogeologic units in Mesozoic rocks of the GGRB (**Figure 5-3**). Many of the hydrogeologic unit names provided in Freethey and Cordy (1991) have been changed or modified from the original naming convention to reflect Wyoming stratigraphic nomenclature.

Mesozoic rocks are deeply buried throughout most of the GGRB. The total thickness of rock overlying the Mesaverde aquifer (uppermost Mesozoic hydrogeologic unit) ranges from less than 2,000 to more than 12,000 feet (**Figure 5-34**). Mesozoic rocks are very thick in the GGRB and the thickness of the entire Mesozoic sequence ranges from less than 2,500 to more than 15,000 feet (**Figure 5-35**). The percentage of this thickness that is composed of aquifers ranges from 25 to 50 percent (**Figure 5-35**).

Upper Cretaceous hydrogeologic units

Mesaverde aquifer system

The Mesaverde aquifer system in the GGRB is contained in Upper Cretaceous rocks of the **Lance-Fox Hills aquifer** (Lance Formation and Fox Hills Sandstone), the **Lewis confining unit** (Lewis Shale), and the **Mesaverde aquifer** (Mesaverde Formation or Group – Almond Formation, Ericson Sandstone, Rock Springs Formation, Blair Formation, Pine Ridge Sandstone, Allen Ridge Formation, Haystack Mountains Formation – and Adaville Formation) (**Figure 5-3**). The Mesaverde aquifer system is present throughout the GGRB (**Figure 5-36**). Rocks composing the aquifer system crop out in a narrow band surrounding the Rock Springs Uplift (**Plate 2**), but in most places are deeply buried (generally 2,000 to more than 12,000 feet below land surface) beneath younger rocks (**Figure 5-34**).

Rocks composing the aquifer system represent many different depositional environments associated with Late Cretaceous sea transgressions and regressions (Freethey and Cordy, 1991, p. C48). Fluvial, deltaic, lagoonal, swampy, and shallow marine depositional environments are represented by various lithologies, but sandstone beds in the various formations compose the aquifer. The saturated thickness of the Mesaverde aquifer system is shown in **Figure 5-36**. Shale beds in these various formations are local confining units within the aquifer system, especially the Lewis Shale in the Great Divide and Washakie basins; however, in most places, the Mesaverde aquifer system and the overlying Wasatch-Fort Union aquifer are hydraulically connected. The generalized potentiometric surface of the Mesaverde aquifer, areas of recharge and discharge, and inferred directions of groundwater flow are shown in **Figure 5-37**. Well-yield and spring-discharge measurements and other hydraulic properties for the various formations composing the Mesaverde aquifer system are summarized in **Plate 5**.

Baxter-Mowry confining unit. The Baxter-Mowry confining unit is present throughout the GGRB in the subsurface, and consists of the Aspen, Baxter, Mowry, Steele, Cody, Thermopolis, and Hilliard Shales; the Muddy Sandstone; and the Frontier, Niobrara, and Blind Bull Formations (Freethey and Cordy, 1991; **Figure 5-3**). In the Green River Basin, Freethey and Cordy (1991, p. C44 and Plate 2E) reported that the confining unit ranges from about 5,000 feet thick at the margins to more than 12,000 feet thick in the east-central basin. These investigators reported that the confining unit ranges from 6,000 to more than 11,000 feet thick in the Washakie Basin east of the Rock Springs Uplift, and as much as 14,000 feet thick in the central Great Divide Basin. This thick confining unit is composed mostly of shale that hydraulically separates the overlying Mesaverde aquifer from the underlying Cloverly aquifer. The Frontier Formation and Muddy Sandstone, located in the middle of the confining unit, can contain local aquifers (Frontier and Muddy Sandstone aquifers), but probably contain highly mineralized water in most areas. Well-yield and spring-discharge measurements and other hydraulic properties for the various formations composing the Baxter-Mowry confining unit are summarized on **Plate 5**.

Lower Cretaceous hydrogeologic units

Cloverly aquifer. The Cloverly aquifer is present throughout the GGRB in the subsurface, and consists of the Cloverly and Bear River Formations and the Gannett Group (Smoot Formation, Draney Limestone, Bechler Conglomerate, Peterson Limestone, and Ephraim Conglomerate) (Freethey and Cordy, 1991; **Figure 5-3**). Sandstone beds in the various formations compose the aquifer. The aquifer is confined by the overlying Baxter-Mowry confining unit and the underlying Morrison confining unit. The saturated thickness of the Cloverly aquifer (**Figure 5-38**) generally ranges from 100 to 500 feet for most of the GGRB. Well-yield and spring-discharge measurements and other hydraulic properties for the various formations composing the Cloverly aquifer are summarized in **Plate 5**.

Jurassic hydrogeologic units

Morrison confining unit and aquifer. The Morrison confining unit is present throughout the GGRB, and separates the overlying Cloverly aquifer from the underlying Sundance confining unit (**Figure 5-3**). The confining unit is composed primarily of the undifferentiated Morrison Formation, but locally the Cloverly Formation is included as part of the unit where the basal conglomerate is missing and the formation is undifferentiated from the Morrison Formation (Freethey and Cordy, 1991).

Freethey and Cordy (1991, p. C30) noted that the extent of the Morrison aquifer in the northern and easternmost Upper Colorado River Basin (including the GGRB) is unknown, but the investigators noted that the predominance of "the fine-grained lithology of the Morrison Formation in these areas indicates that the presence of an extensive aquifer is unlikely." However, it is possible that the undifferentiated Morrison Formation can contain sandstones in some areas that locally can act as aquifers, although many investigators have noted that water produced from the formation would likely be highly mineralized. Well-yield and spring-discharge measurements and other hydraulic properties for the Morrison Formation (composing the Morrison confining unit) are summarized in **Plate 5**.

Sundance confining unit and Sundance aquifer. The Sundance confining unit in the GGRB is composed of two members of the Sundance Formation (Pine Butte and Redwater Shale members), one member of the Morrison Formation (Windy Hill Sandstone Member), and the Stump Formation (Freethey and Cordy, 1991; **Figure 5-3**). Rocks composing this confining unit were deposited in predominantly marine and marginal marine environments during repeated transgressions and regressions of Jurassic seas that resulted in a complex interfingering of continental and marine beds (Freethey and Cordy, 1991). The Windy Hill Sandstone Member of the Morrison Formation is not continuous or thick enough to act as a regional aquifer, but locally may produce highly mineralized water.

The Sundance aquifer in the GGRB is composed of various members of the Sundance Formation (Lak, Hulett Sandstone, Stockade Beaver Shale, and Canyon Springs Sandstone Members) and the Preuss Sandstone. Rocks composing these members are interbedded sandstone, siltstone, and shale deposited in marginal marine and continental environments (Freethey and Cordy, 1991). The general lithofacies of the Sundance aquifer is shown in **Figure 5-39**. The aquifer is deeply buried by younger rocks in most areas, and is confined by the overlying Sundance confining unit and the underlying Gypsum Spring confining unit (**Figure 5-3**). The saturated thickness of the aquifer generally is less than 100 feet, but it thickens from 100 to 1,000 feet at the western edge of the GGRB (**Figure 5-40**).

Both Collentine et al. (1981) and Richter (1981) stated that the Sundance aquifer (Sundance Formation) is in hydraulic connection with the underlying Nugget aquifer in the Great Divide and Washakie basins. Consequently, Collentine et al. (1981) combined the Sundance Formation and Nugget Sandstone in the Great Divide and Washakie basins into a single aquifer defined as the "Sundance-Nugget aquifer." In the Great Divide and Washakie basins, Collentine et al. (1981) noted confined (artesian) conditions in wells installed in the Sundance Formation on the Rawlins Uplift. Well-yield and spring-discharge measurements and other hydraulic properties for the Sundance and Stump Formations and Preuss Sandstone composing the Sundance confining unit and aquifer are summarized in **Plate 5**.

Gypsum Spring confining unit. The Gypsum Spring confining unit in the GGRB is composed of the Gypsum Spring Formation and Twin Creek Limestone (Freethey and Cordy, 1991) (**Figure 5-3**). Rocks composing this confining unit were deposited in predominantly marginal marine environments during repeated transgressions and regressions of Jurassic seas (Freethey and Cordy, 1991). Freethey and Cordy (1991, plate 2E) indicate that the Gypsum Spring confining unit is as much as 1,500 feet thick in western Wyoming. Little hydrogeologic information is available describing the formations comprising the confining unit, but well-yield and spring-discharge measurements and other hydraulic properties for the Gypsum Spring Formation and Twin Creek Limestone composing the Sundance confining unit and aquifer are summarized in **Plate 5**.

Nugget aquifer. The Nugget aquifer is composed of the Nugget Sandstone (Freethey and Cordy, 1991) (**Figure 5-3**). The sandstone of this formation was deposited in predominantly eolian and fluvial environments. The aquifer is deeply buried by 2,000 to more than 12,000 feet of younger rocks in much of the GGRB (Freethey and Cordy, 1991, Figure 10). The Nugget aquifer is confined by the overlying Gypsum Spring confining unit and the underlying Chugwater-Dinwoody confining unit (Figure 5-3). In most areas of the GGRB, the saturated thickness of the Nugget aquifer ranges from 100 to 1,000 feet (**Figure 5-41**).

Development of secondary permeability (localized fracture zones) in the Nugget aquifer has been noted in the Miller Hill area south of Rawlins (just east of the GGRB) where the aquifer is used as part of the public water supply to the City of Rawlins (James M. Montgomery Consulting Engineers, 1986). Little hydrogeologic information is available, but well-yield and spring-discharge measurements and other hydraulic properties for the Nugget Sandstone composing the Nugget aquifer are summarized in **Plate 5**.

Triassic hydrogeologic units

Chugwater-Dinwoody confining unit. The Chugwater-Dinwoody confining unit in the GGRB consists of the Ankareh Formation, Chugwater Formation or Group (Popo Agie and Red Peak Formations, Crow Mountain Sandstone, and the Alcova Limestone), Dinwoody Formation, Goose Egg Formation (Triassic section), Thaynes Limestone, and Woodside Shale (Freethey and Cordy, 1991; **Figure 5-3**). The rocks composing these formations and members are interbedded sandstone, limestone, siltstone, and shale deposited in both continental and marine environments (Freethey and Cordy 1991). The thick and deeply buried confining unit is present throughout the subsurface in the GGRB, and hydraulically separates Mesozoic hydrogeologic units from underlying Paleozoic hydrogeologic units (Freethey and Cordy 1991).

Parts of the Chugwater-Dinwoody confining unit may act locally as aquifers, but probably would yield highly mineralized water. Little hydrogeologic information is available describing the formations composing the confining unit, but well-yield and spring-discharge measurements and other hydraulic properties for the various formations composing the Chugwater-Dinwoody confining unit are summarized in **Plate 5**.

Recharge and discharge in Mesozoic hydrogeologic units

Recharge to Mesozoic hydrogeologic units in the GGRB is primarily from direct infiltration of precipitation (rain and snow) on exposed Mesozoic hydrogeologic units; from infiltration of perennial and ephemeral surface streamflow crossing Mesozoic hydrogeologic units; and, less commonly, from horizontal and vertical movement of groundwater from adjacent hydrogeologic units of Cenozoic, Mesozoic, and Paleozoic age (Freethey and Cordy, 1991). Precipitation enters Mesozoic hydrogeologic units by infiltrating the unsaturated zone, or as infiltration from runoff entering ephemeral stream channels overlying Mesozoic hydrogeologic units. Most recharge likely occurs in exposed areas with the most precipitation, especially those areas receiving more than 8 inches of normal winter precipitation (Freethey and Cordy, 1991); these areas of likely recharge are identified in **Figure 5-42**. Areas where exposed Mesozoic hydrogeologic units may be recharged by perennial streamflow were identified by Freethey and Cordy (1991) as areas generally located along the flanks of topographically high areas (**Figure 5-43**).

Mesozoic hydrogeologic units also may receive recharge by vertical movement of water from underlying and overlying hydrogeologic units. Groundwater can move vertically between hydrogeologic units when there is a sufficient difference in the vertical hydraulic gradient. The amount of vertical movement (and by inference, hydraulic connection) between units is determined by the vertical hydraulic gradient, the vertical hydraulic properties of the hydrogeologic units that the water is moving through, and the contact between units through which the water moves. Freethey and Cordy (1991) compared potentiometric-surface maps of upper and lower Mesozoic hydrogeologic units with those of adjacent overlying Cenozoic hydrogeologic units and underlying Paleozoic hydrogeologic units to identify possible areas of vertical movement of groundwater and to quantify the volume. An area of possible upward vertical groundwater flow into Mesozoic hydrogeologic units from underlying Paleozoic hydrogeologic units was identified on the western side of the Rock Springs Uplift (**Figure 5-44**), and the quantity of flow (vertical flow) between these units was estimated to be 150 acre-feet per year. Possible downward vertical groundwater flow from Cenozoic (lower Tertiary) hydrogeologic units into Mesozoic hydrogeologic units was identified in an area near the southern end of the Rock Springs Uplift and an in area of the eastern Washakie Basin (**Figure 5-44**). The vertical flow in these areas was estimated to be 50 and 20 acre-feet per year, respectively.

Discharge from Mesozoic hydrogeologic units in the GGRB occurs primarily to streams and as springs, seeps, evapotranspiration, interbasin flow (underflow) across study area boundaries, and vertical interformational flow to overlying Cenozoic and underlying Paleozoic hydrogeologic units. Areas of largest spring discharge from the uppermost Mesozoic hydrogeologic unit (Mesaverde aquifer) were identified by Freethey and Cordy (1991) in the Rock Springs Uplift area, the Overthrust Belt, and along the eastern Washakie Basin (**Figures 5-5** and **5-45**). Areas of largest spring discharge from the Sundance and Nugget aquifers were identified in the Overthrust Belt (**Figure 5-45**).

The Mesaverde aquifer was identified by Freethey and Cordy (1991) as a Mesozoic aquifer likely providing discharge to some perennial streams in the GGRB. Estimates using hydraulic head and Darcy's groundwater flow equation ("Darcy's law") indicated that the aquifer probably discharges 5,000 acre-feet per year to Bitter Creek on the Rock Springs Uplift, and 6,000 acre-feet per year to the upstream reaches of Muddy Creek in the eastern Washakie Basin (Freethey and Cordy, 1991, Table 4).

Areas of possible upward vertical groundwater flow (discharge) from Mesozoic hydrogeologic units to overlying Cenozoic hydrogeologic units, and from Mesozoic hydrogeologic units to underlying Paleozoic hydrogeologic units were identified, and quantity of flow estimated, by Freethey and Cordy (1991, Table 5) using hydraulic head and Darcy's law. Areas of possible upward vertical groundwater flow from Mesozoic hydrogeologic units to overlying Cenozoic hydrogeologic units were identified in the eastern Great Divide and Washakie basins (1,400 acre-feet per year), in the southern Washakie Basin (90 acre-feet per year), and in the eastern Green River Basin (320 acre-feet per year) (**Figure 5-44**). Areas of possible downward vertical groundwater flow from Mesozoic hydrogeologic units to underlying Paleozoic hydrogeologic units also were identified (**Figure 5-44**) in the Great Divide and Washakie basins, and the quantity of vertical flow between these units was estimated to be 2,500 acre-feet per year.

Development potential of Mesozoic hydrogeologic units (aquifers)

Development of Mesozoic aquifers in the GGRB has been very limited to date, except in areas where aquifers crop out and are directly exposed at land surface or are at shallow depth below younger hydrogeologic units. Most wells in Mesozoic aquifers have been installed for oil and gas production, often at depths thousands of feet below land surface. Hydraulic properties, great depth, minimal precipitation and recharge, and generally poor water quality prevents the widespread groundwater development of aquifers in Mesozoic rocks.

Freethey and Cordy (1991) characterized inferred fracture permeability, saturated thickness and recharge potential, and generalized water quality of Mesozoic rocks in the GGRB to evaluate the potential for groundwater development. Fractured zones tend to yield more water, so areas with greater inferred fracture permeability (**Figure 5-46**) indicate greater potential for groundwater development. Saturated thickness and transmissivity affect the quantity of water an aquifer can yield; potential for groundwater development in relation to these characteristics is shown in **Figures 5-47** and **5-48**. Recharge potential affects the capability of an aquifer to yield water over time, and the potential for groundwater development in relation to this characteristic is also shown in **Figure 5-47**. Finally, the quality of groundwater determines the suitability of the resource for possible uses. **Figure 5-49** shows the generalized areal distribution of dissolved solids concentrations in Mesozoic hydrogeologic units, and can be used as a general indicator of groundwater quality. A detailed discussion of the groundwater quality characteristics of Mesozoic hydrogeologic units is provided in Chapter 6 of this report.

PALEOZOIC HYDROGEOLOGIC UNITS

Groundwater in Paleozoic hydrogeologic units is rarely used in the GGRB except near basin margins, because deep burial and highly mineralized groundwater content make it unsuitable for most uses. Only oil or gas wells are completed in Paleozoic hydrogeologic units where they are deeply buried. Most Paleozoic rocks in the GGRB are buried by about 5,000 feet to more than 25,000 feet of younger rock (**Figure 5-50**). The Paleozoic rocks in the GGRB generally range from 2,000 to 6,000 feet in thickness (**Figure 5-51**).

Geldon (2003a and 2003b) divided Paleozoic rocks in the Upper Colorado River Basin, including the GGRB, into large regional hydrogeologic units, and subdivided these regional hydrogeologic units into several smaller hydrogeologic units or zones. The hydrogeologic nomenclature used by Geldon (2003b) in many cases reflects the names of geologic units and geographic locations that do not occur in Wyoming. For this report, the classifications of Paleozoic hydrogeologic units used by Lindner-Lunsford et al. (1989) and Geldon (2003b) were combined and modified to reflect Wyoming stratigraphic nomenclature rather than the stratigraphic nomenclature of the entire Upper Colorado River Basin (**Figure 5-4**).

Upper Paleozoic aquifers

Upper Paleozoic aquifers occur throughout the GGRB but are deeply buried. Upper Paleozoic aquifers are contained in Permian and Pennsylvanian rocks, and the hydrogeologic units are confined by the overlying Chugwater-Dinwoody confining unit (Triassic age) and underlying upper Paleozoic confining units (**Figure 5-4**). Three aquifer zones compose the upper Paleozoic aquifers—the **upper zone aquifer**, composed of the Permian Phosphoria and Goose Egg (Permian section) Formations; the **middle zone aquifer**, composed of the Pennsylvanian Tensleep Sandstone, Weber Sandstone, and Wells Formation (herein referred to as the **Tensleep-Weber aquifer**); and the **lower zone aquifer** composed of the Ranchester Limestone Member of the Amsden Formation and Morgan Formation (**Figure 5-4**). Rocks composing these aquifers represent many different lithologies and depositional environments, and the various geologic units composing these aquifers are described in **Appendix 1**.

The thickness, predominant lithology, and areal extent of the Tensleep-Weber aquifer are shown in **Figure 5-52**. In most areas of the GGRB, the thickness of the Tensleep-Weber aquifer generally ranges from 200 to 600 feet (**Figure 5-52**).

Permeability in the Tensleep-Weber aquifer has been attributed to both primary (intergranular) and secondary (fracture) porosity in areas located east of the GGRB (Collentine et al., 1981; Richter, 1981; Johnson and Huntoon, 1994, and references therein). The Tensleep-Weber aquifer is composed of individual sandstone beds separated (confined) by low-permeability beds of limestone and dolomite. Fractures in these low-permeability lithologies can provide hydraulic connection between the water-bearing layers. Permeability enhancement in areas of structural deformity has been noted. In the Laramie Basin in Albany County (located east of the GGRB), Huntoon (1976) and Lundy (1978) reported that hydraulic conductivity in areas of enhanced fracture permeability (structurally deformed areas) was much greater (about 100 times greater) than in relatively undeformed areas. In addition, in a study of the same general area, Huntoon and Lundy (1979) reported that all major springs are located on or near faults and folds, which are areas commonly associated with fracture permeability.

The potentiometric surface of the Tensleep-Weber aquifer and the inferred directions of groundwater flow (indicated by arrows) are shown in **Figure 5-53**. The potentiometric-surface map shows that groundwater flow generally is away from the outcrop areas (and source of recharge) along basin margins, and toward the centers of the Green River, Great Divide, and Washakie basins, although the map does show some groundwater flow to the east on the eastern side of the Rawlins Uplift. A 1,000-foot-deep groundwater cone of depression can be seen on the potentiometric-surface map as a result of pumping in the vicinity of the Lost Soldier-Wertz-Mahoney oilfields. Well-yield and spring-discharge measurements and other hydraulic properties for the formations composing the Upper Paleozoic aquifers are summarized in **Plate 6**.

Upper Paleozoic confining units

Upper Paleozoic confining units in the GGRB are divided into upper and lower zones. The **upper zone confining unit** is composed of the Pennsylvanian Moffat Trail Limestone Member of the Amsden Formation and the Round Valley Formation, and the **lower zone confining unit** is composed of the Horseshoe Shale Member of the Amsden Formation (**Figure 5-4**). Rocks composing upper Paleozoic confining units represent many different lithologies and depositional environments, and descriptions of the various geologic units composing these confining units are provided in **Appendix 1**. Geldon (2003b) indicated that the combined thickness of upper Paleozoic confining units in the Green River Basin is as much as 700 feet in the Flaming Gorge area. Well-yield and spring-discharge measurements and other hydraulic properties for the formations composing the upper Paleozoic confining units are summarized in **Plate 6**.

The Amsden Formation in the GGRB has been considered a confining unit by many investigators. In the Rawlins Uplift area, Berry (1960, p. 15) stated that little was known about the water-bearing properties of the formation, and that the formation likely "would yield very little water" because of low-permeability rocks. Welder and McGreevy (1966) wrote, "groundwater possibilities not known, but probably poor" in the Great Divide and Washakie basins. Similarly, Collentine et al. (1981, table V-1, p. 46) defined the Amsden Formation as an "aquitard" between the Tensleep aquifer and underlying Madison aquifer in the Great Divide and Washakie basins, and stated that the "unit probably has poor water-bearing potential due to predominance of fine-grained sediments."

Lower-Middle Paleozoic aquifer system

Madison aquifer. The Madison aquifer occurs throughout the GGRB but is deeply buried except in areas near basin margins. The Madison aquifer is contained in rocks of Mississippian age, and is confined by the overlying upper Paleozoic confining units and underlying Darby confining unit (**Figure 5-4**). The Darby confining unit is not present in the Great Divide and Washakie basins, and the Madison aquifer directly overlies undifferentiated Cambrian rocks in these basins (Love et al., 1993). The aquifer also represents the uppermost member of the Lower-Middle Paleozoic aquifer system (**Figure 5-4**).

The thickness, predominant lithology, and areal extent of the upper zone of the Madison aquifer (Darwin Sandstone Member of the Amsden Formation) is shown in **Figure 5-54**; the **lower zone** (Madison Limestone) is shown in **Figure 5-55**. The Darwin Sandstone Member of the Amsden Formation, which composes the **upper zone** of the Madison aquifer, is generally only present along basin margins (**Figure 5-54**). In most of these marginal areas of the GGRB, the thickness of the upper zone of the Madison aquifer generally ranges from 100 to 200 feet, whereas the thickness of the lower zone of the aquifer is more variable and ranges from 200 to 2,500 feet (**Figures 5-54** and **5-55**, respectively).

Permeability in the Madison aquifer is primarily secondary, and is well-developed in places (Berry, 1960; Collentine et al., 1981; Johnson and Huntoon, 1994, and references therein). Solution cavities and channeling, caverns, and fractures (karstic features) have been noted by these previous investigators. The potentiometric surface of the Madison aquifer and the inferred direction of groundwater flow (indicated by arrows) are shown in **Figure 5-56**. The potentiometric-surface map indicates that groundwater generally flows away from the outcrop areas (and source of recharge) along basin margins, and toward the centers of the Green River, Great Divide and Washakie basins. Well-yield and spring-discharge measurements and other hydraulic properties for the Madison aquifer are summarized in **Plate 6**.

Darby confining unit. The Darby confining unit is composed of the Devonian Darby Formation (**Figure 5-4**). The confining unit is present only in the Rock Springs Uplift, Green River Basin, and Overthrust Belt areas. The lithology of the formation is described in **Appendix 1**. The Darby Formation does not readily yield water to wells, but Lines and Glass (1975) reported springs discharging from the formation near faults in the Overthrust Belt. Little hydrogeologic information is available describing the Darby Formation, but well-yield and spring-discharge measurements and other hydraulic properties for the various formations composing the Darby confining unit are summarized in **Plate 6**.

Bighorn aquifer. The Bighorn aquifer comprises the Ordovician Bighorn Dolomite and Cambrian Gallatin Limestone (**Figure 5-4**). The Bighorn Dolomite is present only in the Green River Basin and Overthrust Belt areas. Water availability from this aquifer may be due primarily to secondary permeability (fractures and solution openings). Lines and Glass (1975) reported large volumes of poorly permeable rock in the Bighorn Dolomite in the Overthrust Belt, but noted that water is discharged from solution-enlarged fractures. The thickness and lithology of the Bighorn aquifer is shown in **Figure 5-57**. Thickness of the aquifer ranges from about 200 to 1,800 feet in the GGRB. Little hydrogeologic information is available describing the formations composing the Bighorn aquifer, but well-yield and spring-discharge measurements and other hydraulic properties for the Bighorn Dolomite are summarized in **Plate 6**.

Gros Ventre confining unit. The Gros Ventre confining unit is composed of the Cambrian Gros Ventre Formation (**Figure 5-4**). The formation consists largely of shale, and has very low permeability. Lines and Glass (1975) noted very low permeability for this unit in the Overthrust Belt. The thickness of the confining unit ranges from about 200 to 1,000 feet in the GGRB (Geldon, 2003b, Figure 28). Little hydrogeologic information is available describing the Gros Ventre Formation, but well-yield and spring-discharge measurements and other hydraulic properties are summarized in **Plate 6**.

Flathead aquifer. The Flathead aquifer consists of the Cambrian Flathead Sandstone (**Figure 5-4**). The aquifer is confined by the overlying Gros Ventre confining unit and underlying Precambrian rocks. The thickness and lithology of the aquifer is shown in **Figure 5-58**. Thickness of the aquifer ranges from about 200 to 800 feet in the GGRB (**Figure 5-58**). As noted by Geldon (2003b, p. B43), the amount of water yielded to wells completed in the aquifer "depends mostly on the amount of cementation by silica and carbonate minerals and the degree of fracturing, which are related to past and present structural settings." Berry (1960) noted that the Flathead Sandstone on the Rawlins Uplift readily yielded water to wells. Little hydrogeologic information is available describing the Flathead Sandstone, but well-yield and spring-discharge measurements and other hydraulic properties were reviewed and are summarized in **Plate 6**.

Recharge and discharge

Recharge to Paleozoic hydrogeologic units in the Upper Colorado River Basin, including the GGRB, is primarily from direct infiltration of precipitation (rain and snow) on exposed Paleozoic hydrogeologic units, infiltration of perennial and ephemeral streamflow crossing Paleozoic hydrogeologic units (streamflow losses), and interbasin flow (Geldon, 2003b).

Geldon (2003b) indicated that the largest potential for recharge to upper Paleozoic hydrogeologic units occurs where head differences between upper Paleozoic aquifers and the Lower-Middle Paleozoic aquifer system are most positive. The areas with the largest positive head differences—and thus indicative of recharge—were identified as the Wind River Range, the Sierra Madre, and the Granite Mountains (Sweetwater Arch) (**Figure 5-59**).

Precipitation is the largest source of recharge to Paleozoic hydrogeologic units through infiltration of the unsaturated zone when precipitation occurs, or through infiltration as runoff enters ephemeral and perennial stream channels overlying Paleozoic hydrogeologic units. Geldon (2003b) noted that recharge to aquifers in Paleozoic rocks is likely to occur in areas with the most precipitation, including those receiving as little as 10 inches of average annual precipitation. Geldon (2003b, p. B121) noted that in most areas in the Upper Colorado River Basin, "including the structural basins, altitudes above 5,900 feet generally receive at least 10 inches of precipitation in most years;" and, "on the basis of climatic studies in the region, it is estimated that evapotranspiration consumes between 45 and 90 percent of precipitation at altitudes between 6,000 and 9,000 feet, less precipitation at higher altitudes, and nearly all precipitation at lower altitudes." Berry (1960) noted that the Rawlins Uplift, with as little as 11 inches average annual precipitation, was a recharge area for both Paleozoic and Mesozoic aquifers. Ephemeral streams crossing outcropping and (or) shallowly buried Paleozoic rocks have been identified as providing recharge to Paleozoic rocks on the Rawlins Uplift by Berry (1960) and the Sierra Madre by Welder and McGreevey (1966).

Interbasin flow may provide groundwater recharge to some Paleozoic hydrogeologic units in the GGRB. Geldon (2003b) noted that potentiometric-surface maps indicate that groundwater flows into the GGRB from the Sierra Madre, the south flank of the Granite Mountains (Sweetwater Arch), the Hoback Basin, and the Overthrust Belt. He quantified the volume of recharge from interbasin flow for these four areas (Geldon, 2003b, Table 19). Annual interbasin flow contributing recharge from the Sierra Madre to the Tensleep-Weber aquifer (middle zone upper Paleozoic aquifer) was estimated to be 50 acre-feet per year. Annual interbasin flow contributing recharge from the Granite Mountains (Sweetwater Arch) was estimated to be 183 acre-feet per year to the Tensleep-Weber aquifer, 44 acre-feet per year to the lower zone of the Upper Paleozoic aquifer, and 23 acre-feet per year to the lower zone of the Madison aquifer. Annual interbasin flow contributing recharge from the Hoback Basin was estimated to be 15 acre-feet per year to the Tensleep-Weber aquifer, 6.6 acre-feet per year to the lower zone upper Paleozoic aquifer, and 29 acre-feet per year to the lower zone of the Madison aquifer. Annual interbasin flow contributing recharge from the Overthrust Belt was estimated to be 129 acre-feet per year to the Tensleep-Weber aquifer, 21 acre-feet per year to the lower zone Upper Paleozoic aquifer, and 1.5 acre-feet per year to the lower zone of the Madison aquifer.

Discharge from Paleozoic hydrogeologic units in the GGRB is primarily to streams and springs, seeps, evapotranspiration, interbasin flow (underflow) across study area boundaries, and vertical interformational flow to overlying Mesozoic and Cenozoic hydrogeologic units. Geldon (2003b) indicated that the largest potential for discharge from Paleozoic hydrogeologic units occurs where head differences between upper Paleozoic aquifers and the Lower-Middle Paleozoic aquifer system are the most negative. The areas with the largest negative head differences—and thus indicative of discharge—were identified as valleys within the Overthrust Belt and the Green River, Great Divide, Washakie, and Sand Wash basins.

Areas of seepage to streams and springs from Paleozoic hydrogeologic units in the GGRB may occur in some areas as a result of geologic structure. As noted by Geldon (2003b) and explained earlier by Huntoon (1983), springs can develop in response to changes in aquifer permeability along homoclinal edges of structural uplift areas such as the Rawlins Uplift. This development is due to a large decrease in hydraulic conductivity as aquifers become less fractured and more cemented farther from uplift axes.

Aquifers along thrust-fault margins of mountain ranges are commonly severed by faulting; consequently, separate groundwater flow systems often develop in the hanging wall and foot wall (Huntoon, 1983). Large springs often develop in the hanging wall where the aquifers are thrust up against formations with low permeability, and groundwater is forced to flow and rise along the fault to the land surface. This type of spring has been noted on the southwestern flank of the Wind River Range and the Gros Ventre Range, and on the east flank of the northern Overthrust Belt (Salt River Range and Wyoming Range). Examples of this type of spring are the Hogsback and Sheep Creek springs in the Overthrust Belt (Lines and Glass, 1975; Geldon 2003b).

Water production from wells completed in Paleozoic hydrogeologic units is relatively small in most areas of the GGRB, but some areas of locally substantial withdrawal are likely in areas associated with oil and gas production (Geldon, 2003b). For example, the potentiometric-surface map of the Tensleep-Weber aquifer presented earlier (**Figure 5-53**) indicates substantial drawdown due to oil and gas production.

Upward movement of water from Paleozoic to Mesozoic and Cenozoic hydrogeologic units also accounts for discharge (Freethey and Cordy, 1991; Geldon, 2003b). Much of this movement occurs in areas around the edges and in the interior of structural basins, especially along faults, joints, and areas of lithologic change (Geldon, 2003b). This upward movement of water likely provides substantial recharge to overlying Mesozoic and Cenozoic hydrogeologic units.

One area of interbasin flow (groundwater underflow/outflow) in the GGRB study area was identified by Geldon (2003b), although the volume is believed to represent only a small quantity of annual groundwater discharge. He indicated that groundwater in the Great Divide Basin between the Rawlins Uplift and Sierra Madre flows northeastward out of the GGRB into the Hanna Basin.

Summarizing his examination of recharge to and discharge from Paleozoic hydrogeologic units, Geldon (2003b) noted that areas of recharge to Paleozoic hydrogeologic units are characterized by predominantly downward groundwater flow, streamflow losses, unsaturated zones, unconfined (water-table) conditions, and fresh groundwater, whereas discharge areas are characterized by predominantly upward groundwater flow, streamflow gain, spring discharge, flowing confined (artesian) wells, and brackish to briny groundwater. Using these characteristics, Geldon (2003b) identified recharge and discharge areas for Paleozoic rocks in the GGRB (**Figure 5-59**).

PRECAMBRIAN HYDROGEOLOGIC UNITS

Undifferentiated rock units of Precambrian age act as a basal confining unit for the Cambrian Flathead aquifer. Little is known about Precambrian rocks at depth in the GGRB; however, wells are completed locally for domestic use in outcrop areas. Wells are completed at relatively shallow depths where the rocks crop out— permeability is attributable to weathered, fractured, or faulted rocks (Berry, 1960; Lowry et al., 1973; Collentine et al., 1981; Richter, 1981). Lowry et al. (1973) noted that the shallow permeable zone typically is less than 100 feet deep. They also noted that fractures decrease in both size and number at greater depths.

SUMMARY OF GROUNDWATER FLOW IN THE GGRB

Groundwater flow in all the aquifers of the GGRB moves from recharge areas generally located along structural basin margins in uplifted areas towards the centers of the structural basins (**Figures 5-60** and **5-61**). Aquifer discharge is by upward leakage into shallower aquifers, and ultimately to major streams in the GGRB. Groundwater flow is relatively simple where geologic structures consist of broad basins and gentle uplifts, but may be complex where aquifers have been folded and faulted, primarily along basin margins.

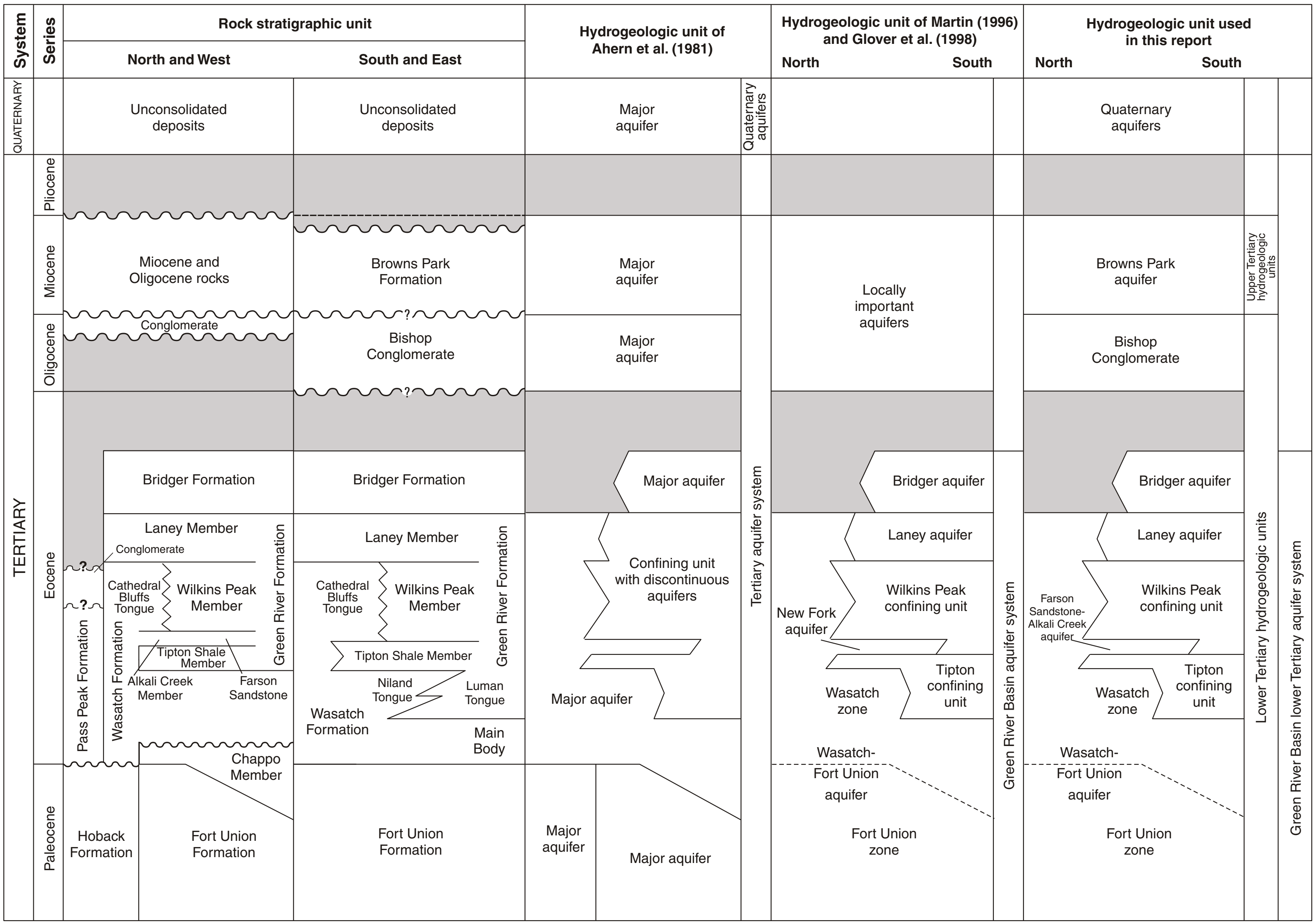


Figure 5-1. Generalized stratigraphic relation of hydrogeologic units in Quaternary and Tertiary rocks of the Green River Basin. *Modified from Ahern et al. (1981), Love et al. (1993), Martin (1996), and Glover et al. (1998).*

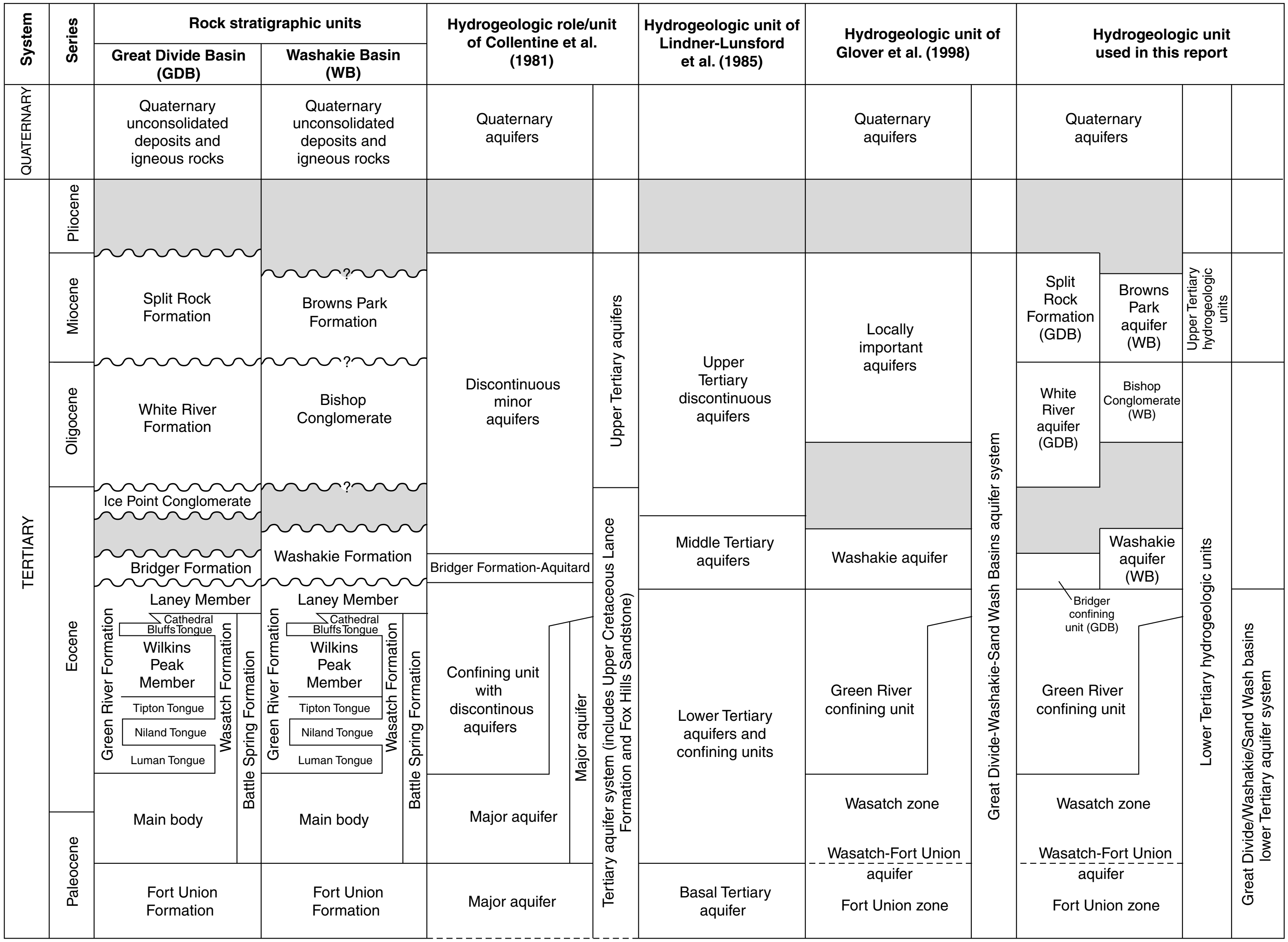


Figure 5-2. Generalized stratigraphic relation of hydrogeologic units in Quaternary and Tertiary rocks of the Great Divide and Washakie basins. *Modified from Collentine et al. (1981), Lindner-Lunsford et al. (1985), Love and Christiansen (1993), and Glover et al. (1998).*

Era	System	Component geologic units in Wyoming	Hydrogeologic role/unit of Ahern et al. (1981) for Green River Basin and Overthrust Belt	Hydrogeologic role/unit of Collentine et al. (1981) for Great Divide and Washakie Basins	Hydrogeologic unit of Taylor et al. (1986)	Hydrogeologic unit of Freethey and Cordy (1991)	Hydrogeologic unit used in this report	
MESOZOIC	Cretaceous	Lance Formation and Fox Hills Sandstone	Minor aquifer (part of Tertiary aquifer system)	Minor aquifer (part of Tertiary aquifer system)	Upper Mesozoic confining layers and aquifers	Mesaverde aquifer	Lance-Fox Hills aquifer	Mesaverde aquifer
		Lewis Shale	Aquitard	Major aquitard			Lewis confining unit	
		Mesaverde Group/ Formation, Lance Formation, Fox Hills Sandstone, and Adaville Formation	Major aquifer-Mesaverde-Adaville aquifer	Major aquifer-Mesaverde aquifer			Mesaverde aquifer	
		Aspen Shale, Baxter Shale, Mowry Shale, Steele Shale, Cody Shale, Thermopolis Shale, Hilliard Shale, Muddy Sandstone, Frontier Formation, Niobrara Formation, and Blind Bull Formation	Baxter and Hilliard Shales-Major aquitard Frontier Formation-Minor aquifer (Frontier aquifer) / Upper Jurassic-Lower Cretaceous aquifers	Baxter Shale and equivalents-Major aquitard Frontier Formation-Minor aquifer (Frontier aquifer)		Mancos confining unit	Baxter-Mowry confining unit	
	Jurassic	Cloverly Formation, Bear River Formation, and Gannett Group	Aspen Shale, Bear River Formation, and Gannett Group-Discontinuous aquifers with local confining beds / Upper Jurassic-Lower Cretaceous aquifers	Minor aquifer (Cloverly aquifer)		Dakota aquifer	Cloverly aquifer	
		Morrison Formation	Not present in area	Aquitard	Middle Mesozoic aquifers	Morrison confining unit and aquifer	Morrison confining unit	
		Sundance Formation and Stump Formation	Stump Formation and Preuss Sandstone-Aquitard	Sundance Formation and Nugget Sandstone-Minor aquifer (Sundance-Nugget aquifer)		Curtis-Stump confining unit	Sundance confining unit	
		Sundance Formation and Preuss Sandstone				Entrada-Preuss aquifer	Sundance aquifer	
		Gypsum Spring Formation and Twin Creek Limestone	Twin Creek Limestone-Minor aquifer			Carmel-Twin Creek confining unit	Gypsum Spring confining unit	
		Nugget Sandstone	Nugget Sandstone-Major aquifer / Nugget aquifer system			Navajo-Nugget aquifer	Nugget aquifer	
	Triassic	Dinwoody Formation, Ankareh Formation, Chugwater Group/ Formation, Goose Egg Formation, Thaynes Limestone, and Woodside Shale	Ankareh Formation-Minor aquifer Thaynes Limestone-Major aquifer / Nugget aquifer system Dinwoody Formation and Woodside Shale-aquitard	Chugwater and Phosphoria Formations-aquitard	Lower Mesozoic confining layers	Chinle-Moenkopi confining unit	Chugwater-Dinwoody confining unit	

Figure 5-3. Hydrogeologic nomenclature for Mesozoic rocks in the Greater Green River Basin, Wyoming.

Era	System	Component geologic units in Wyoming	Hydrogeologic role/unit of Ahern et al. (1981) and Collentine et al. (1981)		Hydrogeologic unit of Taylor et al. (1986)	Hydrogeologic unit of Lindner-Lunsford et al. (1989)	Hydrostratigraphic unit of Geldon (1986, 1989a, b, c, d)		Hydrogeologic unit of Geldon (2003b)			Hydrogeologic unit used in this report		
MESOZOIC	Triassic	Chugwater Formation or Group, Woodside Shale, Dinwoody Formation, and Goose Egg Formation	Chugwater Formation or Group-aquitard Woodside Shale-aquitard Dinwoody Formation-aquitard		Lower Mesozoic confining layers	Lower Mesozoic confining layers	Triassic confining layer		Confining unit consisting of Mesozoic rocks (Chinle-Moenkopi confining unit)			Chugwater-Dinwoody confining unit		
PALEOZOIC	Permian	Phosphoria Formation and Goose Egg Formation	Phosphoria Formation-Minor aquifer (locally confining) in GRB and aquitard in GDW	Paleozoic aquifer system	Upper Paleozoic aquifers and confining layers	Upper Paleozoic aquifers	Permian shale and carbonate rocks hydrostratigraphic unit	Canyonlands aquifer	Park City-State Bridge zone	Canyonlands aquifer		Upper zone aquifer		Upper Paleozoic aquifers
	Pennsylvanian	Tensleep Sandstone, Weber Sandstone, and Wells Formation	Tensleep Sandstone-Major aquifer				Pennsylvanian and Permian sandstone hydrostratigraphic unit		Weber-De Chelly zone			Middle zone aquifer (Tensleep-Weber aquifer)		
		Ranchester Limestone Member of Amsden Formation and Morgan Formation	Amsden Formation-Minor aquifer (locally confining) in GRB and aquitard in GDW				Pennsylvanian and Permian red beds and carbonate rocks hydrostratigraphic unit		Cutler-Maroon zone			Lower zone aquifer		
		Moffat Trail Limestone Member of Amsden Formation and Round Valley Formation				Upper Paleozoic confining layers	Mississippian carbonate and evaporites hydrostratigraphic unit	Four Corners confining unit	Paradox-Eagle Valley zone	Four Corners confining unit		Upper zone confining unit		Upper Paleozoic confining units
		Horseshoe Shale Member of Amsden Formation					Mississippian and Pennsylvanian shale and carbonate rocks hydrostratigraphic unit		Beldon-Molas subunit			Lower zone confining unit		
	Mississippian	Darwin Sandstone Member of Amsden Formation			Middle Paleozoic aquifers	Middle Paleozoic aquifers	Mississippian carbonate and clastic rocks hydrostratigraphic unit	Madison aquifer	Darwin-Humbug zone	Madison aquifer	Four Corners aquifer system	Upper zone	Madison aquifer	Lower-Middle Paleozoic aquifer system
		Madison Limestone	Major aquifer				Devonian and Mississippian carbonate rocks hydrostratigraphic unit		Redwall-Leadville zone			Lower zone		
	Devonian	Darby Formation					Devonian carbonate and clastic rocks hydrostratigraphic unit		Elbert-Parting confining unit			Darby confining unit		
	Ordovician	Bighorn Dolomite			Lower Paleozoic aquifers and confining layers	Lower Paleozoic aquifers and confining layers	Cambrian and Ordovician carbonate rocks hydrostratigraphic unit		Bighorn aquifer			Bighorn aquifer		
	Cambrian	Gallatin Limestone and undifferentiated Cambrian rocks	Minor and major aquifer, respectively											
		Gros Ventre Formation	Aquitard				Cambrian shale hydrostratigraphic unit		Gros Ventre confining unit			Gros Ventre confining unit		
		Flathead Sandstone	Minor aquifer		Basal Paleozoic aquifer	Basal Paleozoic aquifer	Cambrian sandstone hydrostratigraphic unit		Flathead aquifer			Flathead aquifer		

Figure 5-4. Hydrogeologic nomenclature for Paleozoic and selected Mesozoic rocks in the Greater Green River Basin and adjacent areas, Wyoming. [GRB, Green River Basin and Overthrust Belt; GDW, Great Divide and Washakie basins]

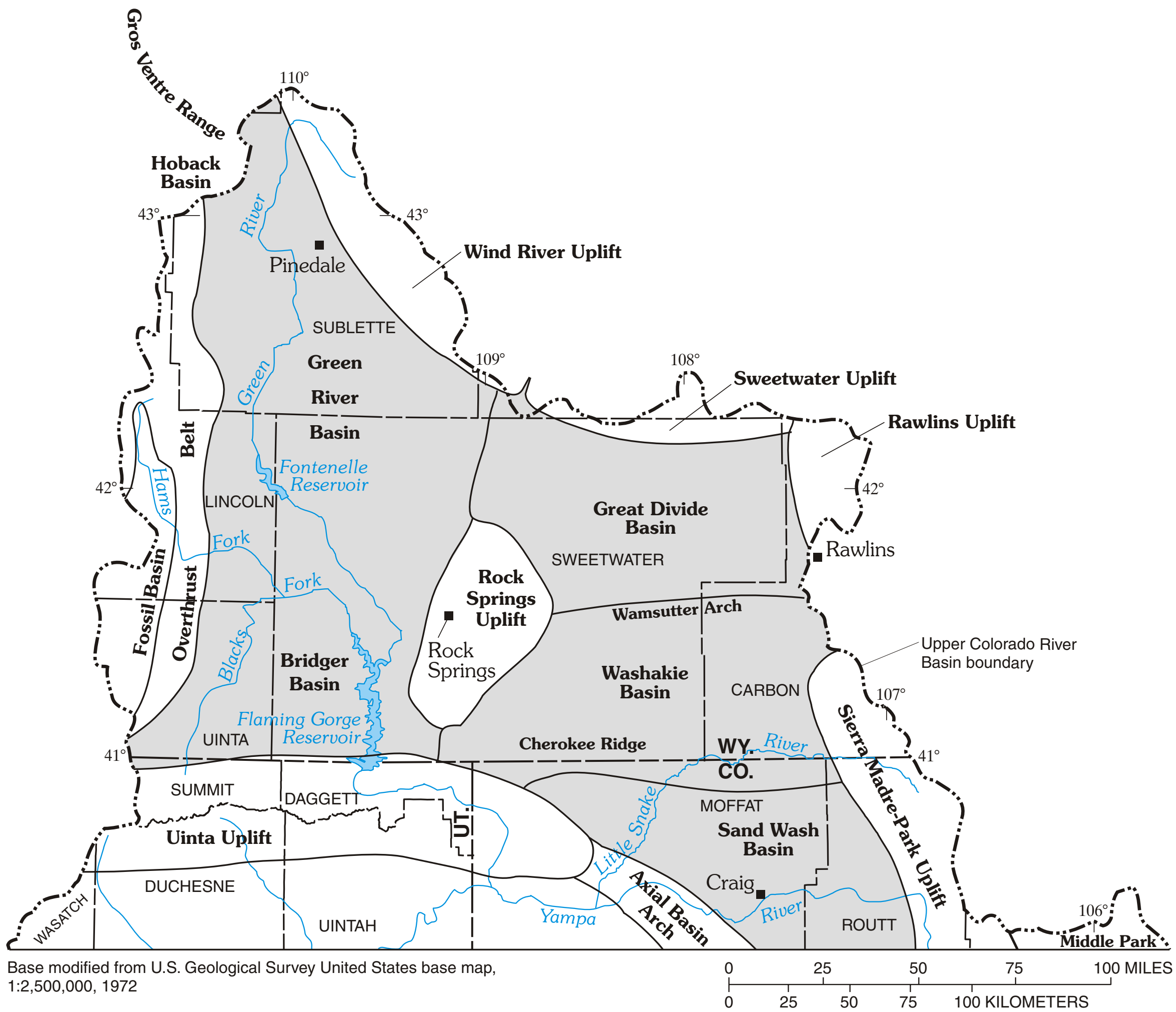


Figure 5-5. Principal tectonic features of the Greater Green River Basin and adjacent areas to the south. *Modified from Taylor et al. (1986) and Geldon (2003a,b).*

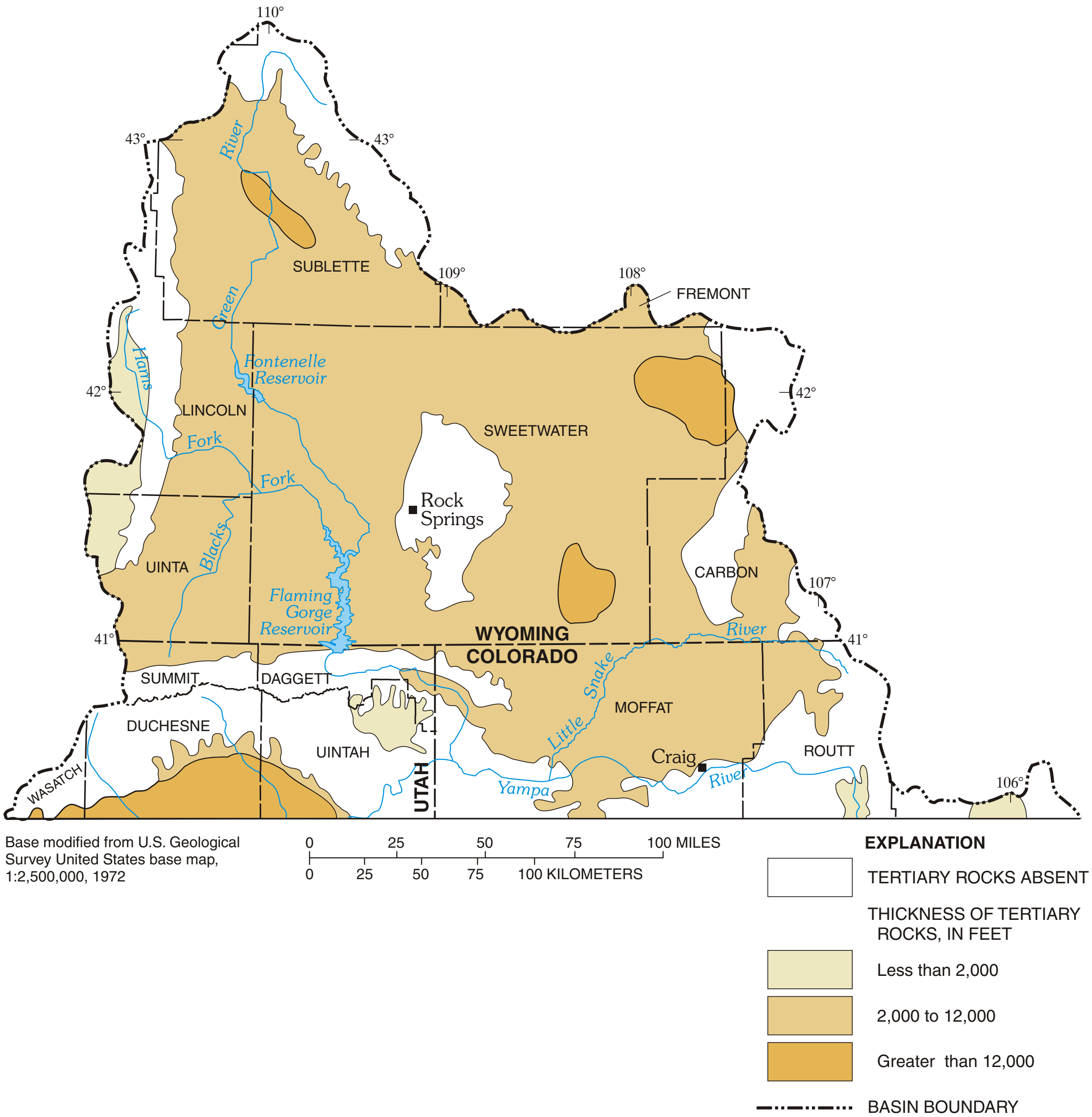


Figure 5-6. Area and thickness of sedimentary rocks of Tertiary age in the Greater Green River Basin and adjacent areas to the south. *Modified from Martin (1996).*

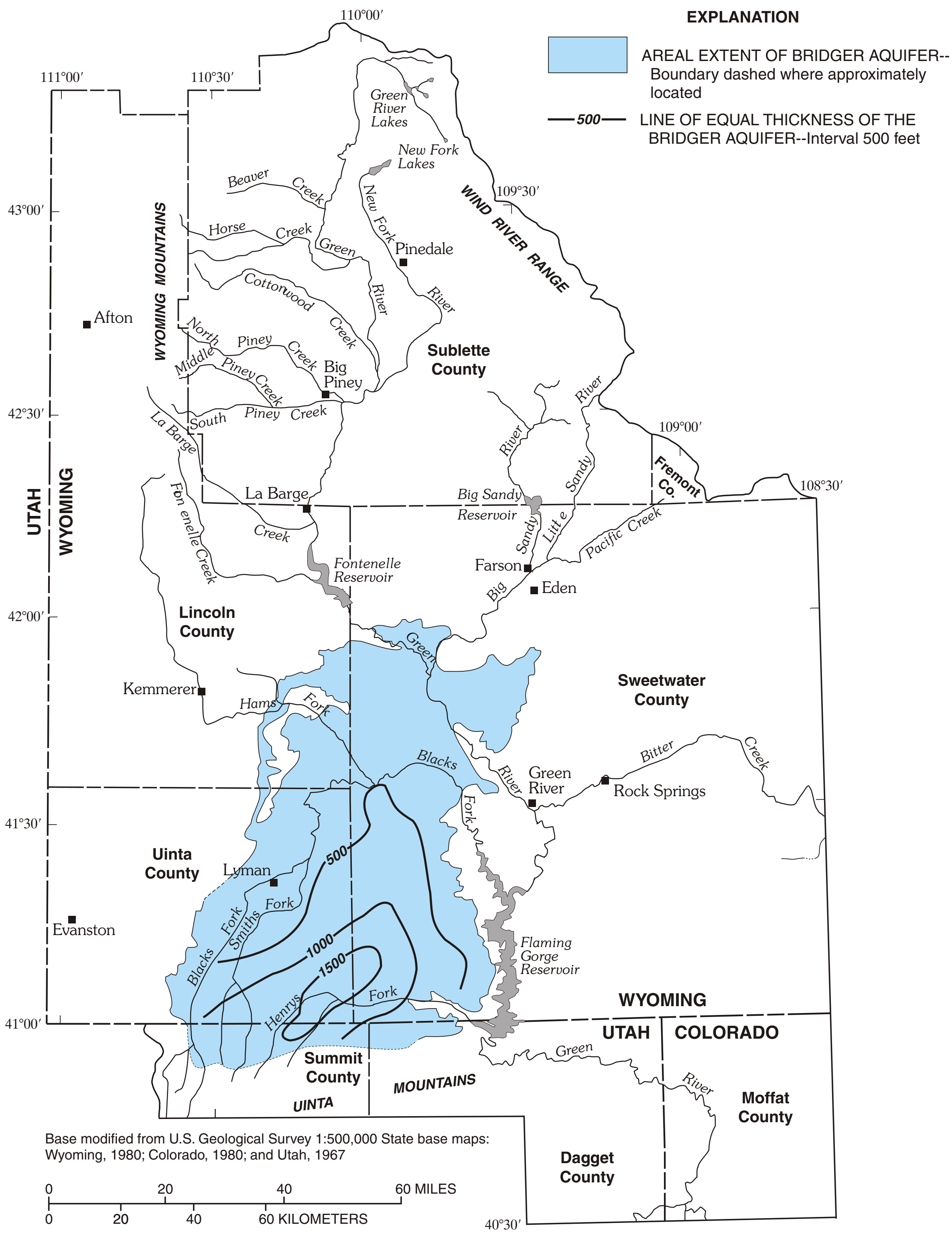


Figure 5-7. Area and thickness of the Bridger aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

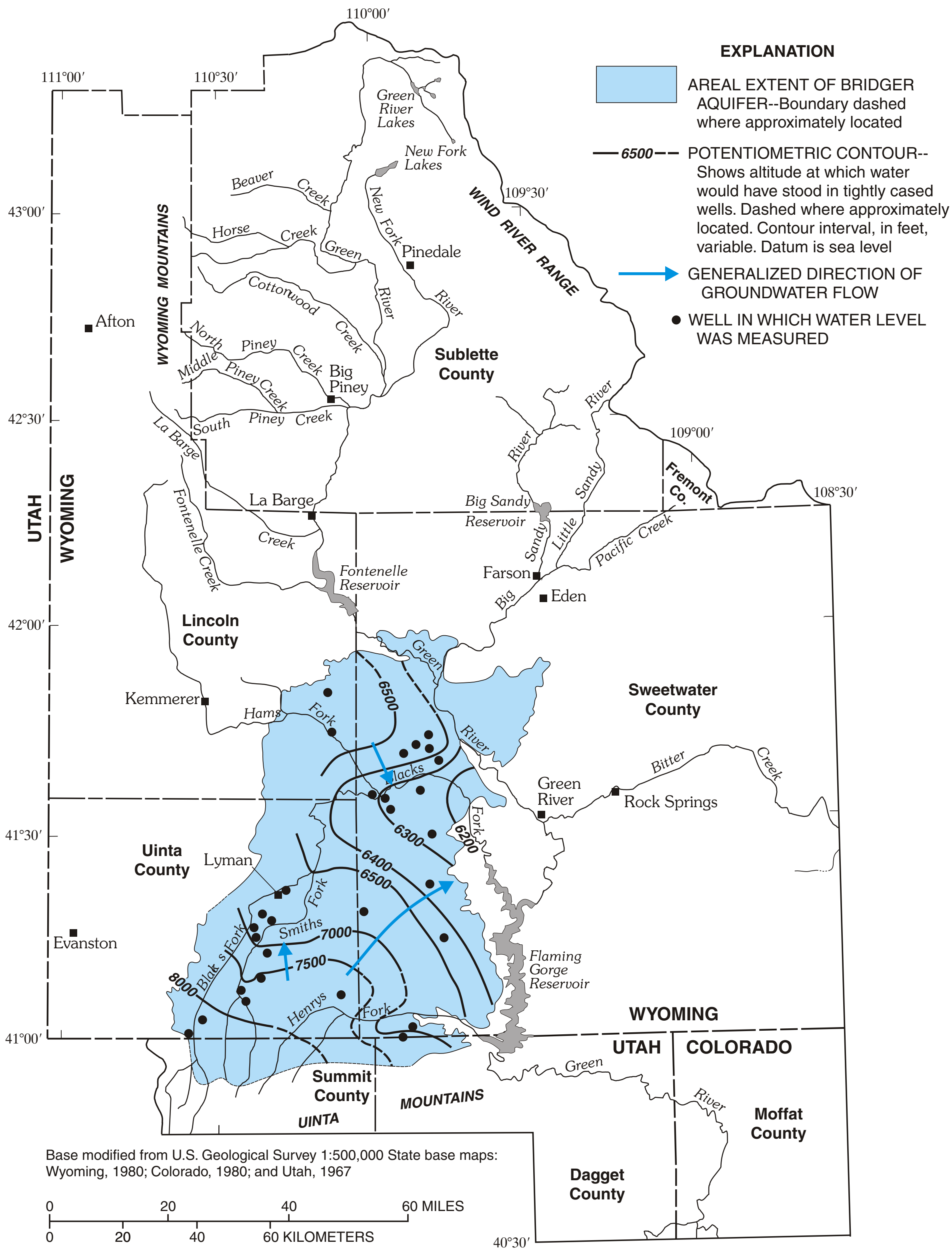


Figure 5-8. Potentiometric surface (1985) of the Bridger aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

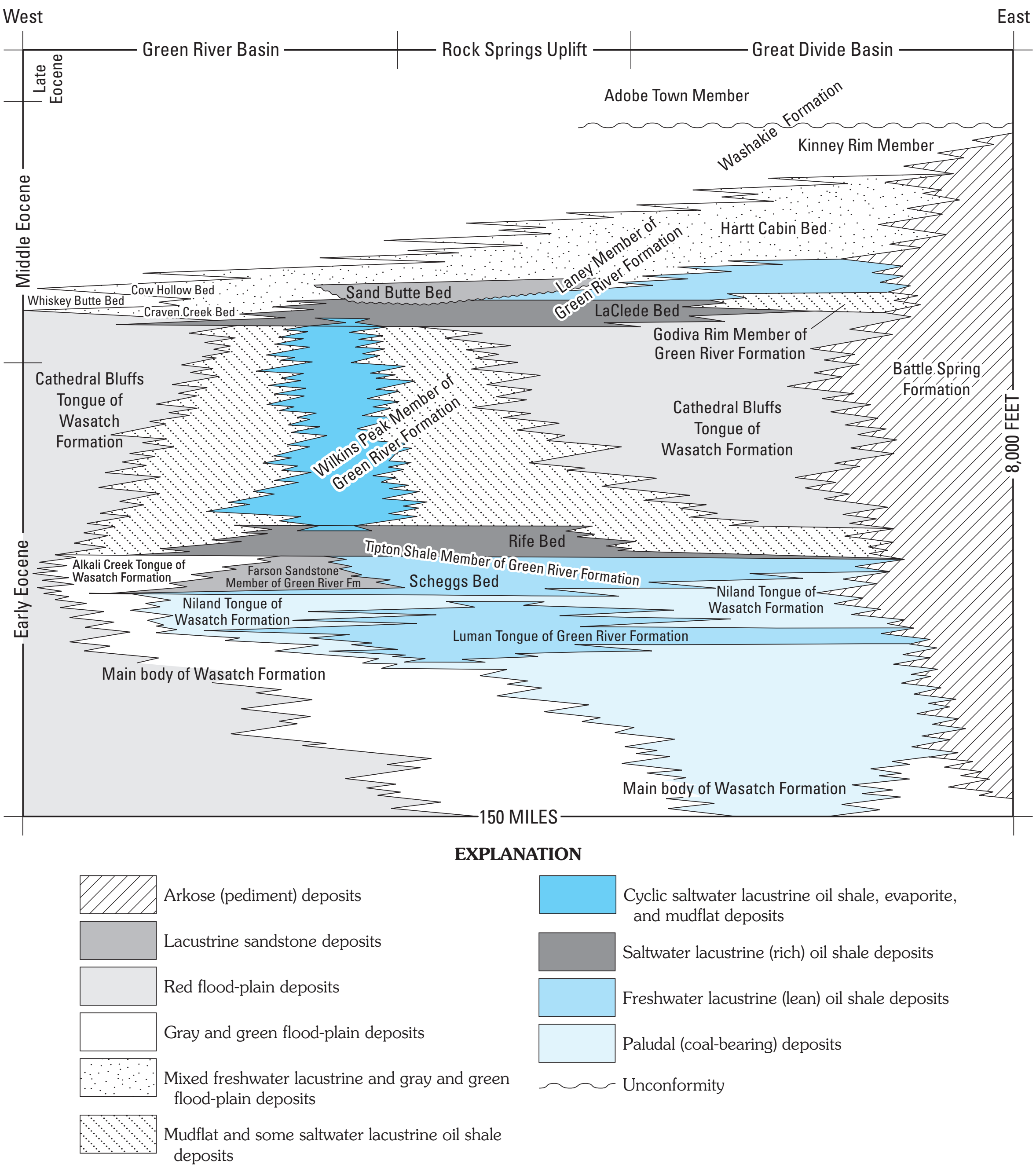


Figure 5-9. West–east stratigraphic correlation of Eocene rocks across the Wyoming Greater Green River Basin. *Modified from Roehler (1991a).*

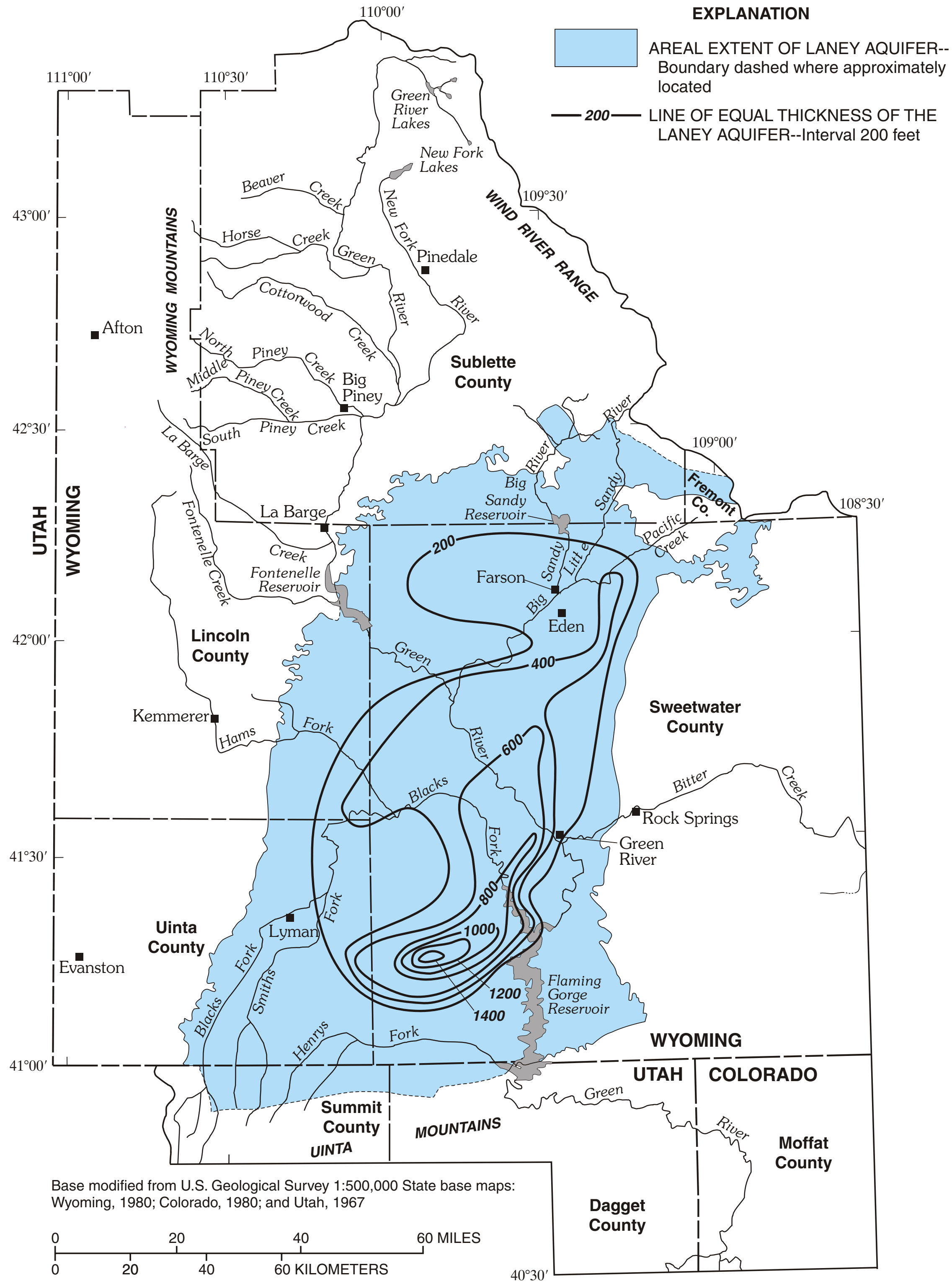


Figure 5-10. Area and thickness of the Laney aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

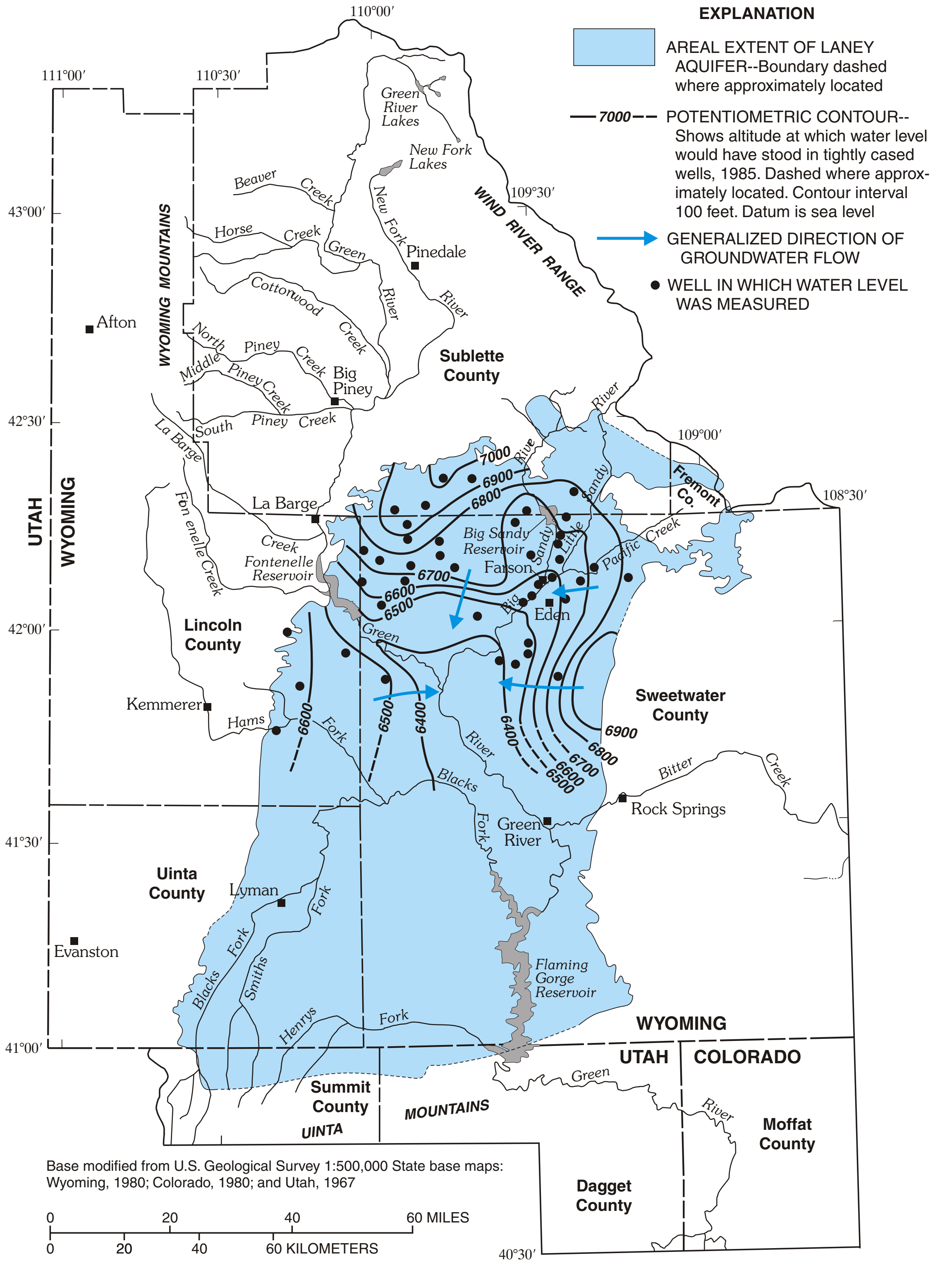


Figure 5-11. Potentiometric surface (1985) of the Laney aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

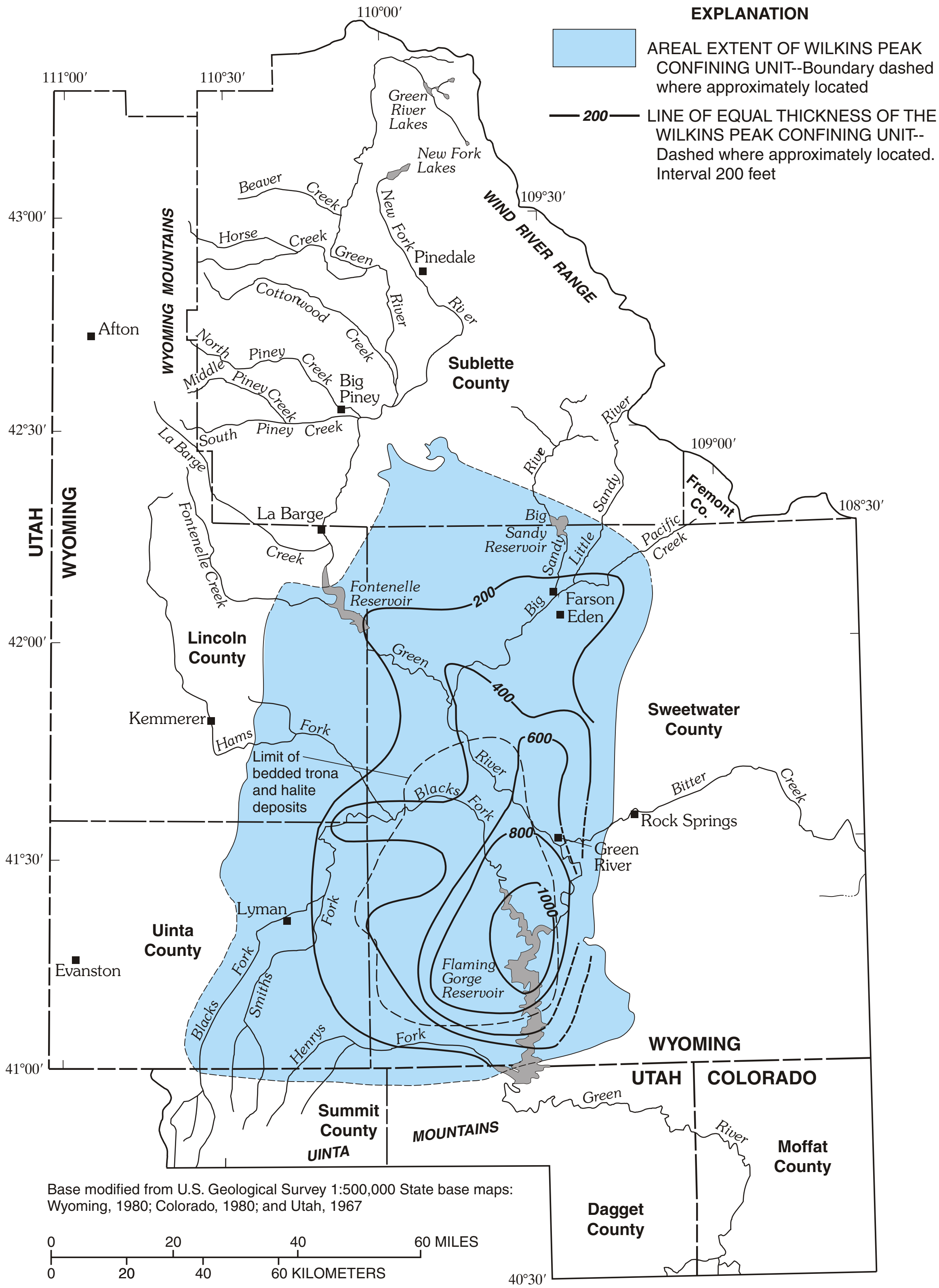


Figure 5-12. Area and thickness of the Wilkins Peak confining unit, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

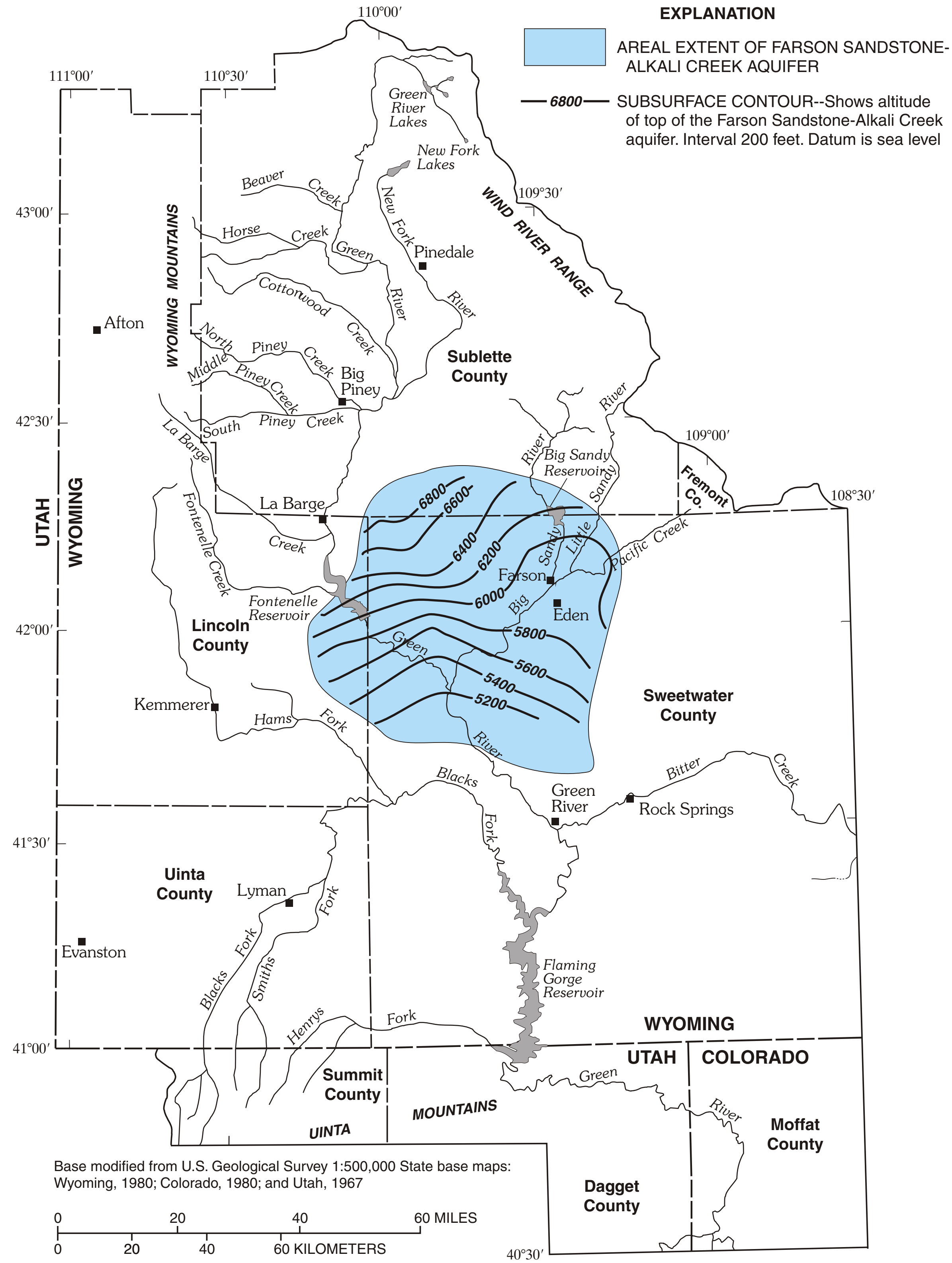


Figure 5-13. Altitude of the top of the Farson Sandstone-Alkali Creek aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Dana and Smith (1973) and Martin (1996).*

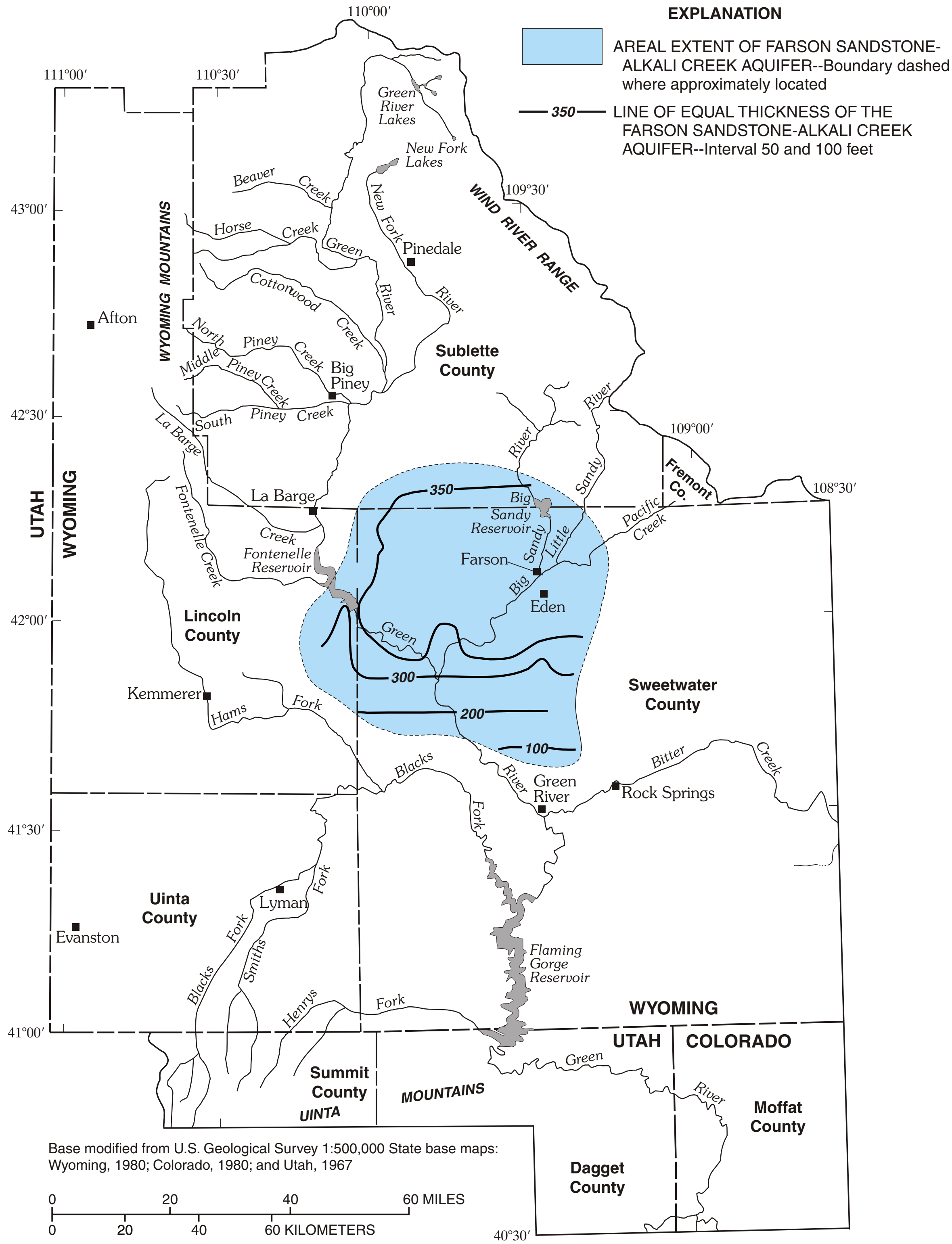


Figure 5-14. Area and thickness of the Farson Sandstone-Alkali Creek aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

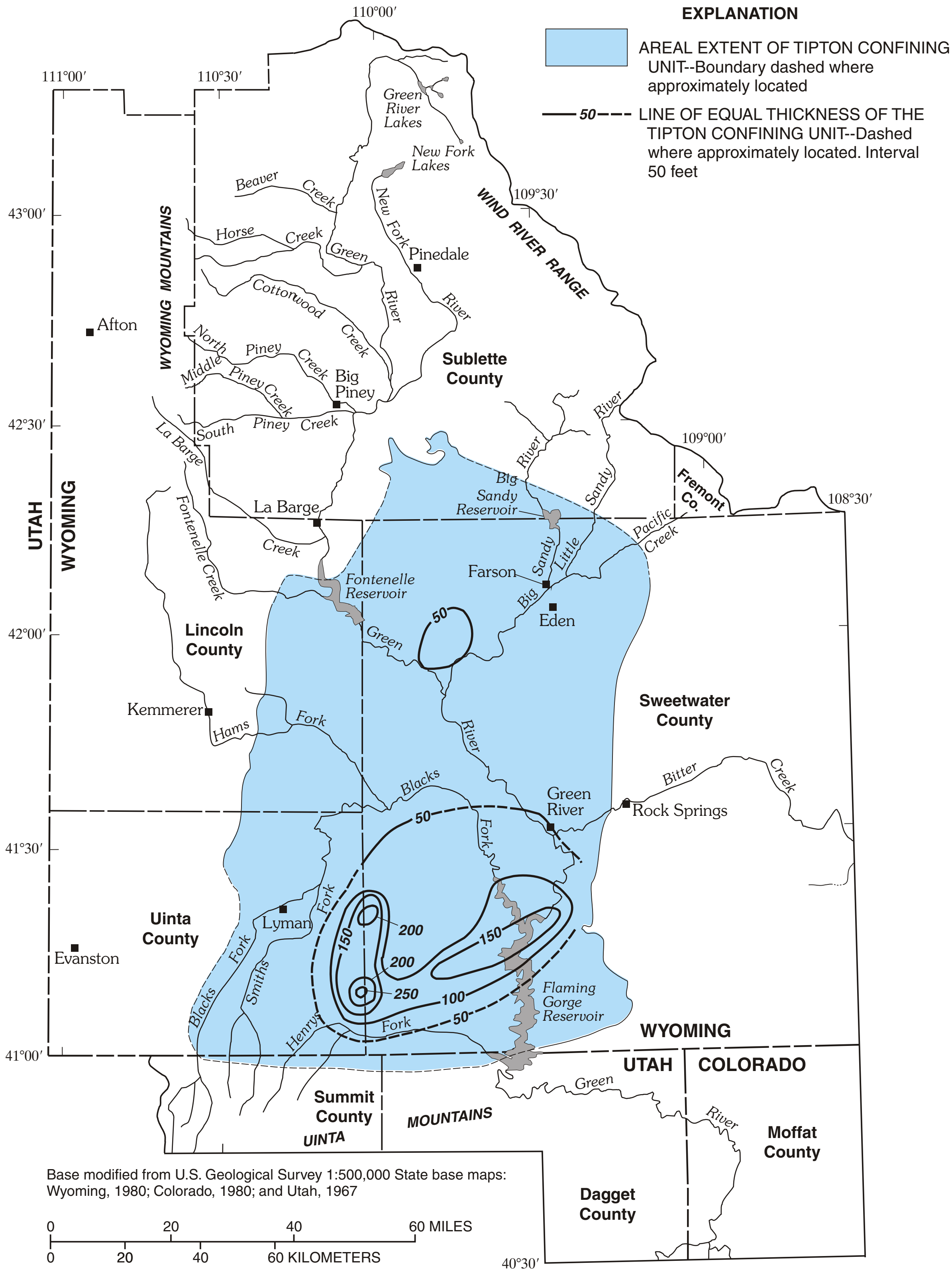


Figure 5-15. Area and thickness of the Tipton confining unit, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

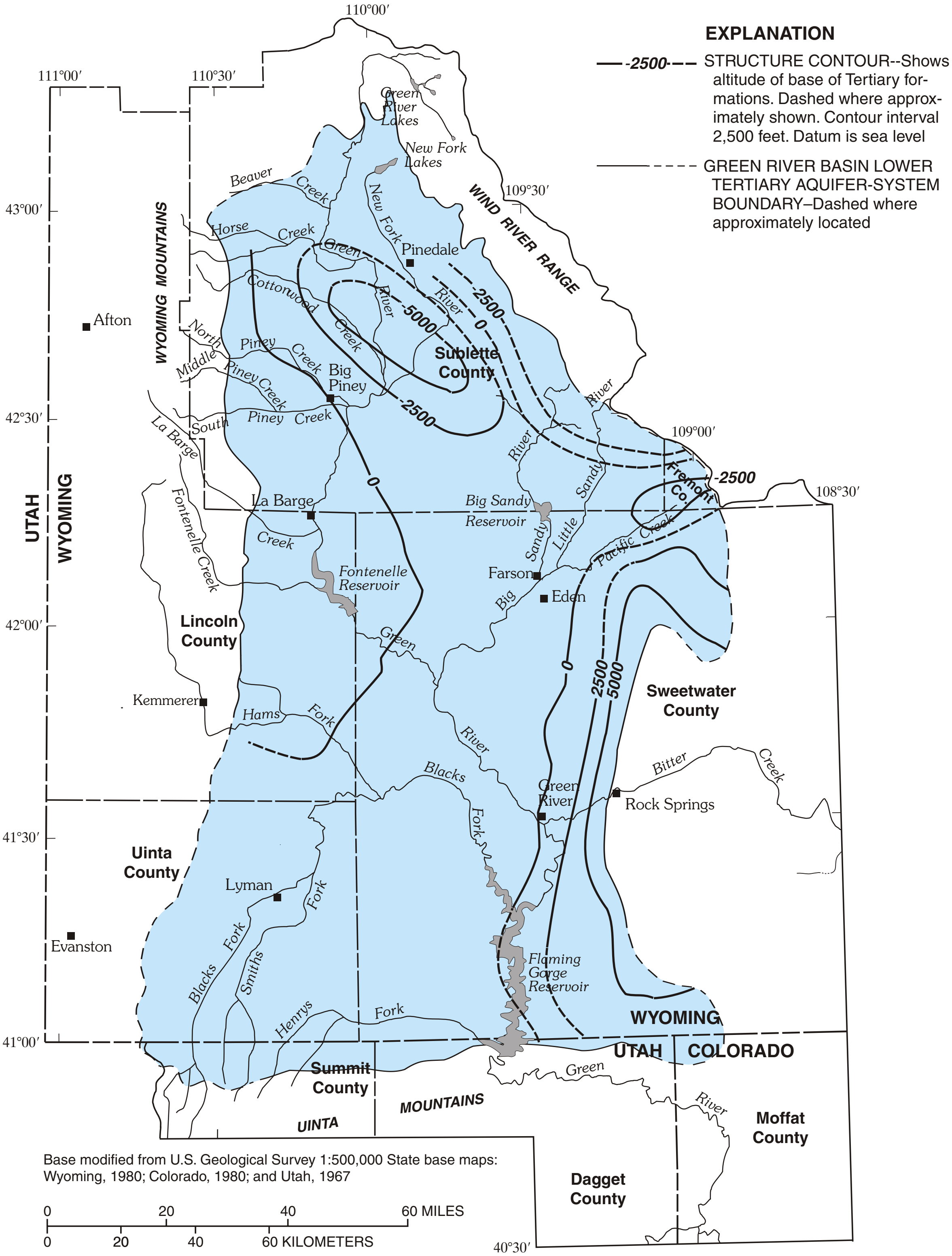


Figure 5-16. Altitude and configuration of the base of the Green River Basin lower Tertiary aquifer system. *Modified from Freethey et al. (1988) and Martin (1996).*

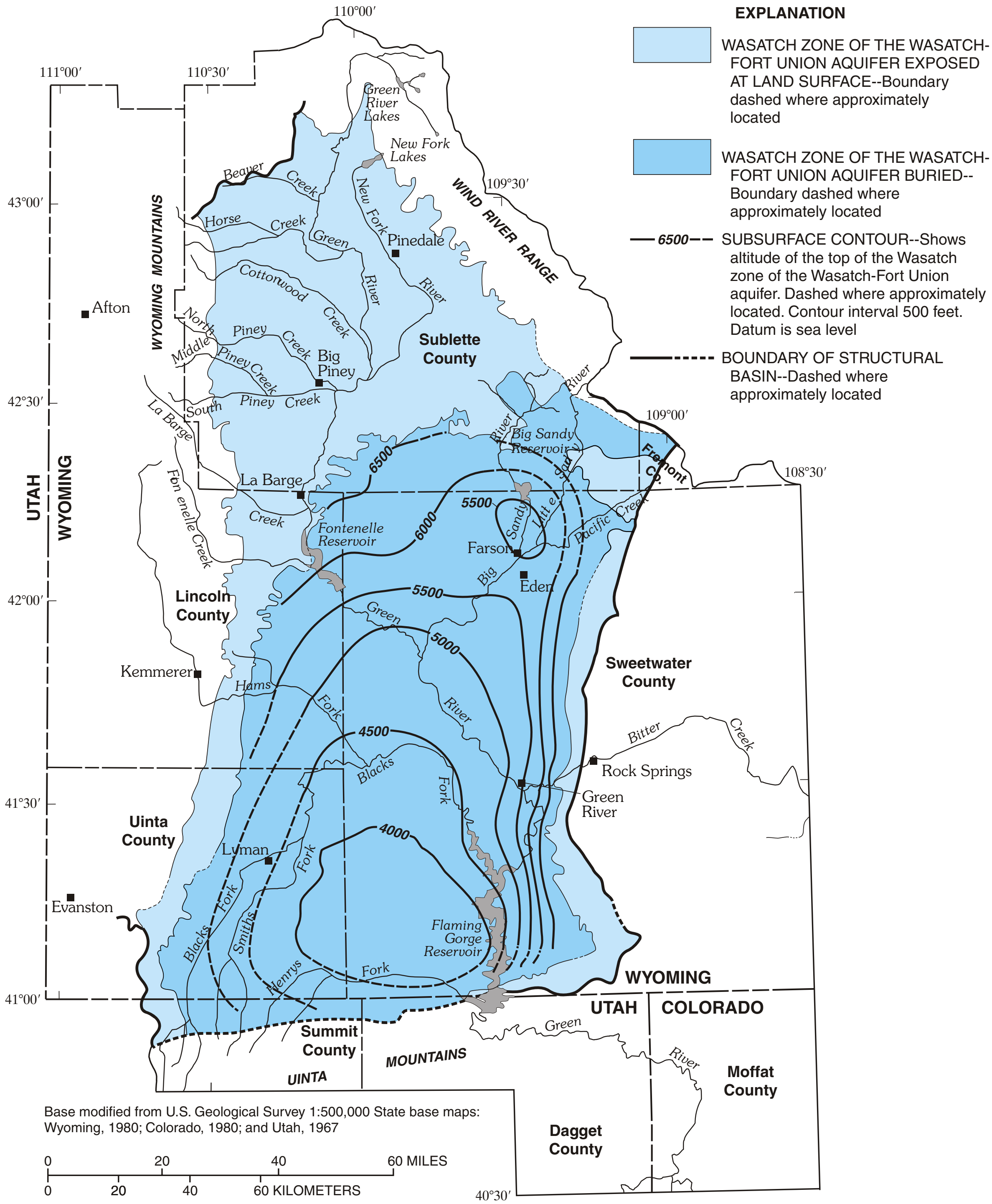


Figure 5-17. Altitude of the top of the Wasatch zone of the Wasatch-Fort Union aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Welder (1968) and Martin (1996).*

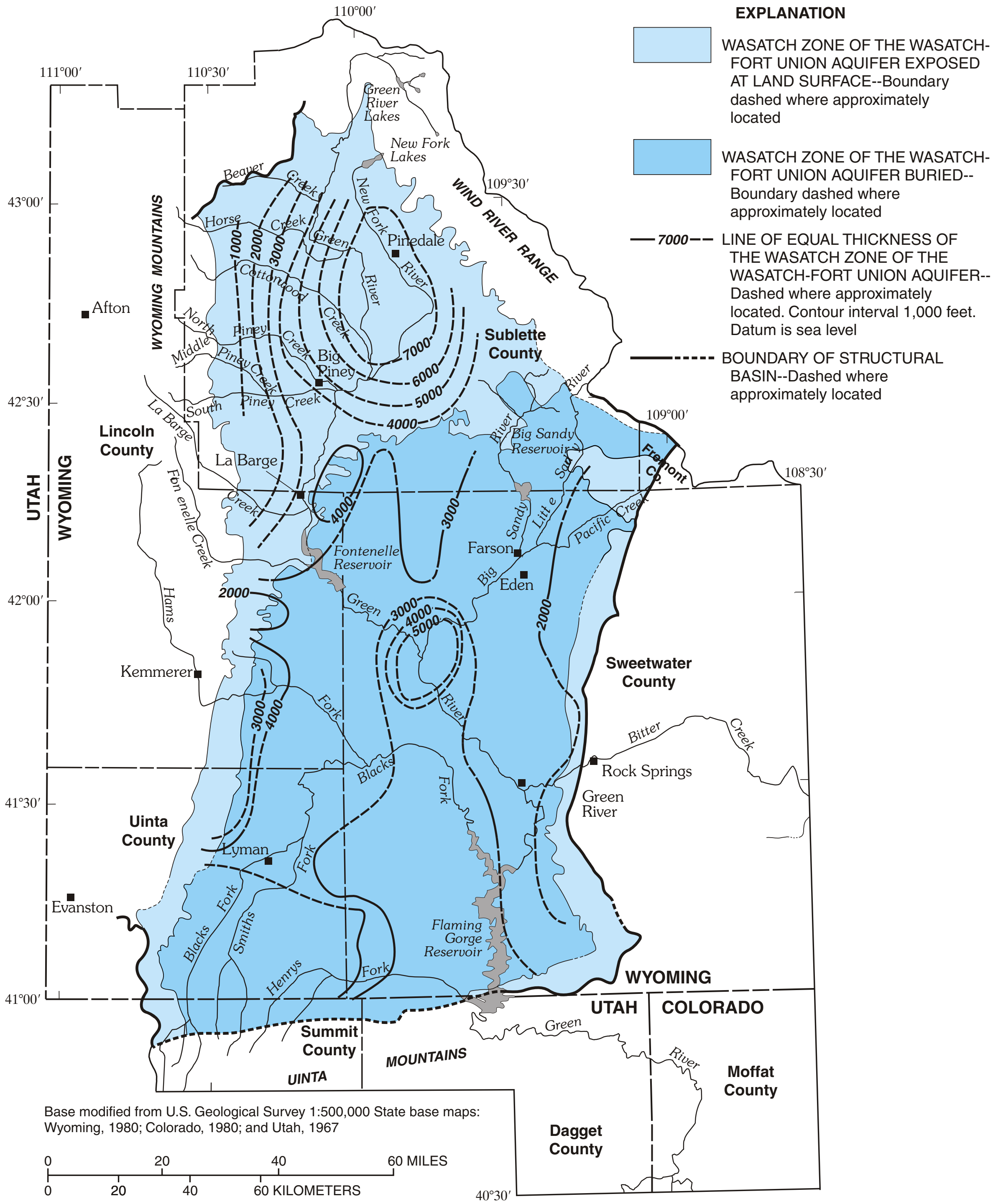


Figure 5-18. Area and thickness of the Wasatch zone of the Wasatch-Fort Union aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

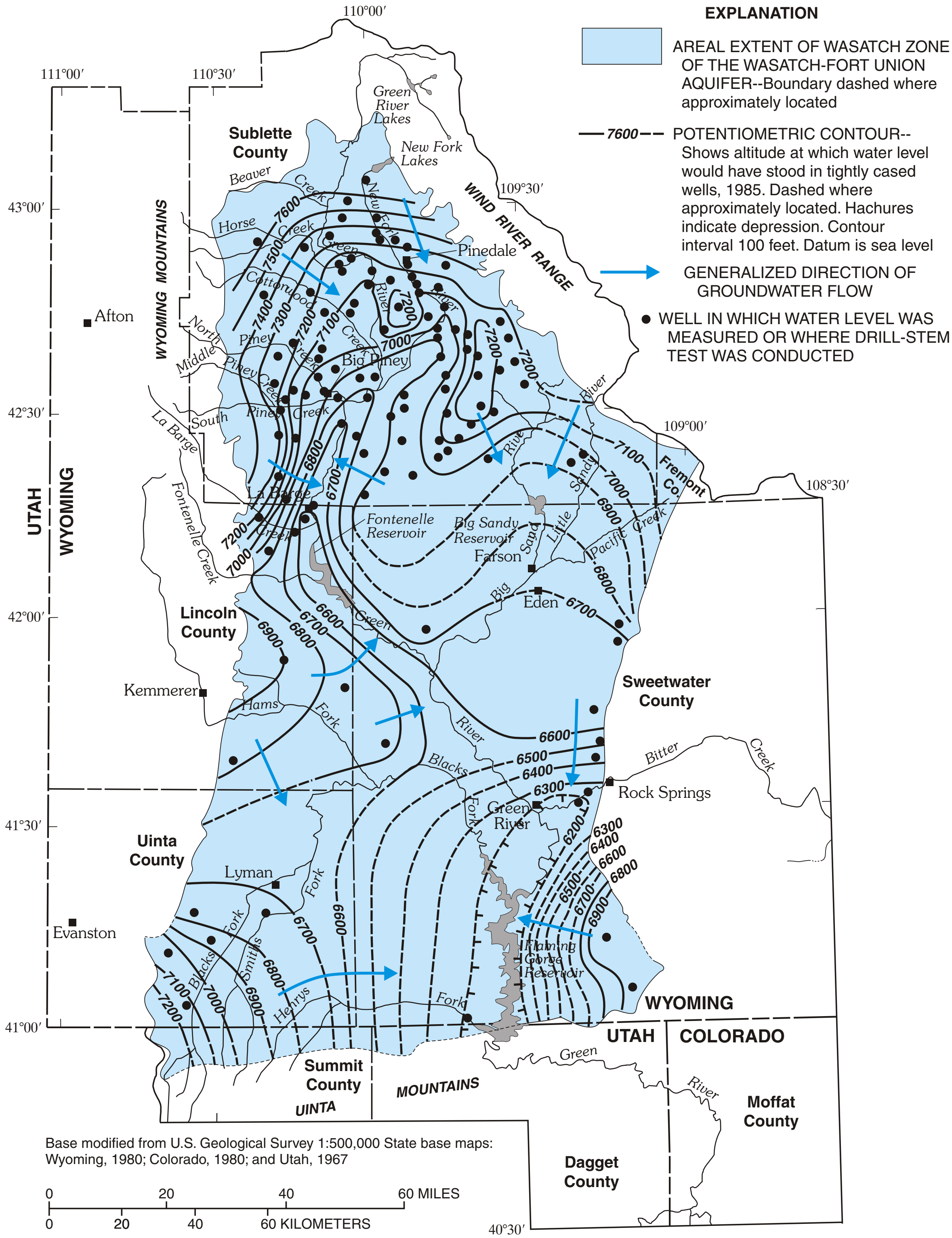


Figure 5-19. Potentiometric surface [1985] of the Wasatch zone of the Wasatch-Fort Union aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

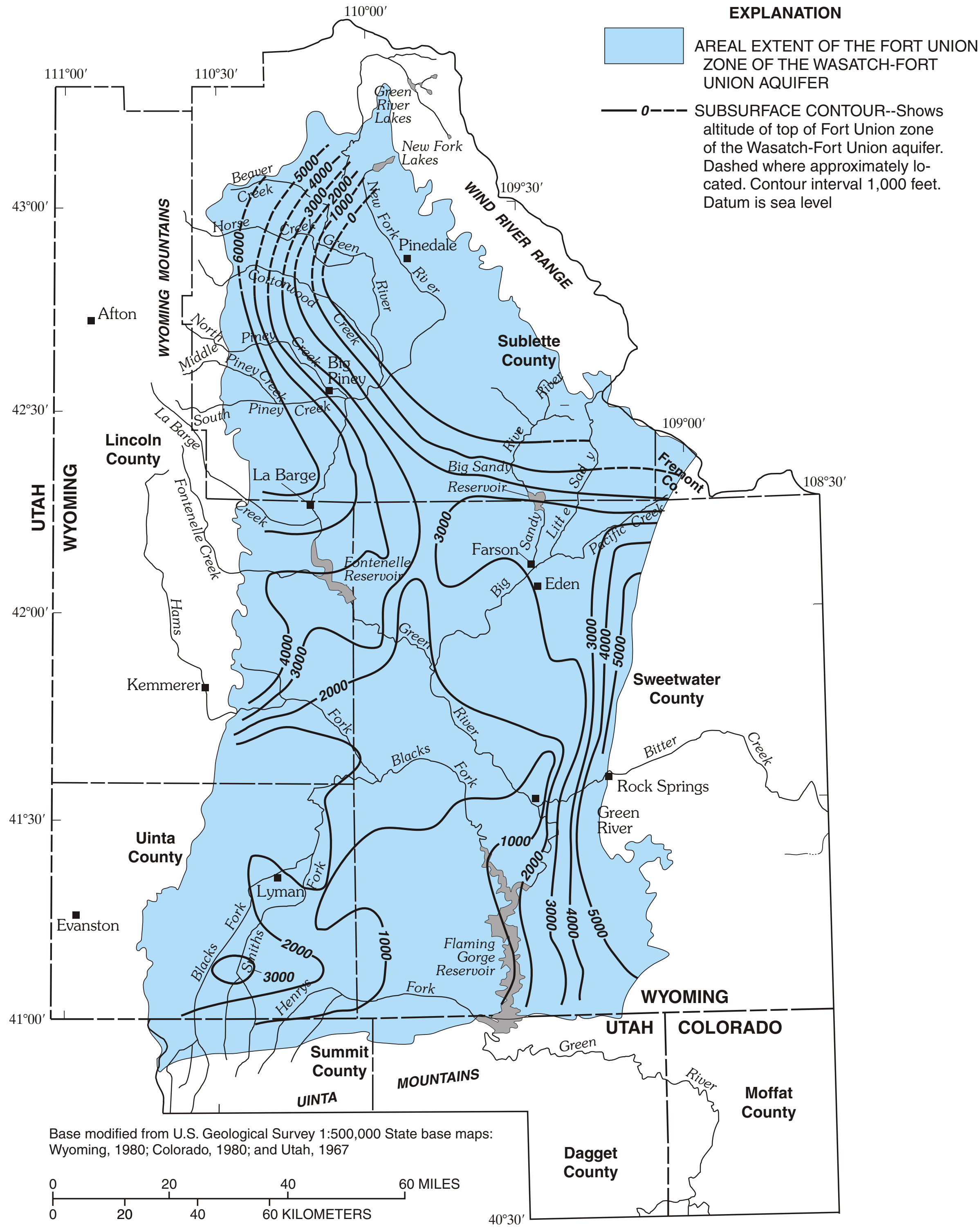


Figure 5-20. Altitude of the top of the Fort Union zone of the Wasatch-Fort Union aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Glover et al. (1998).*

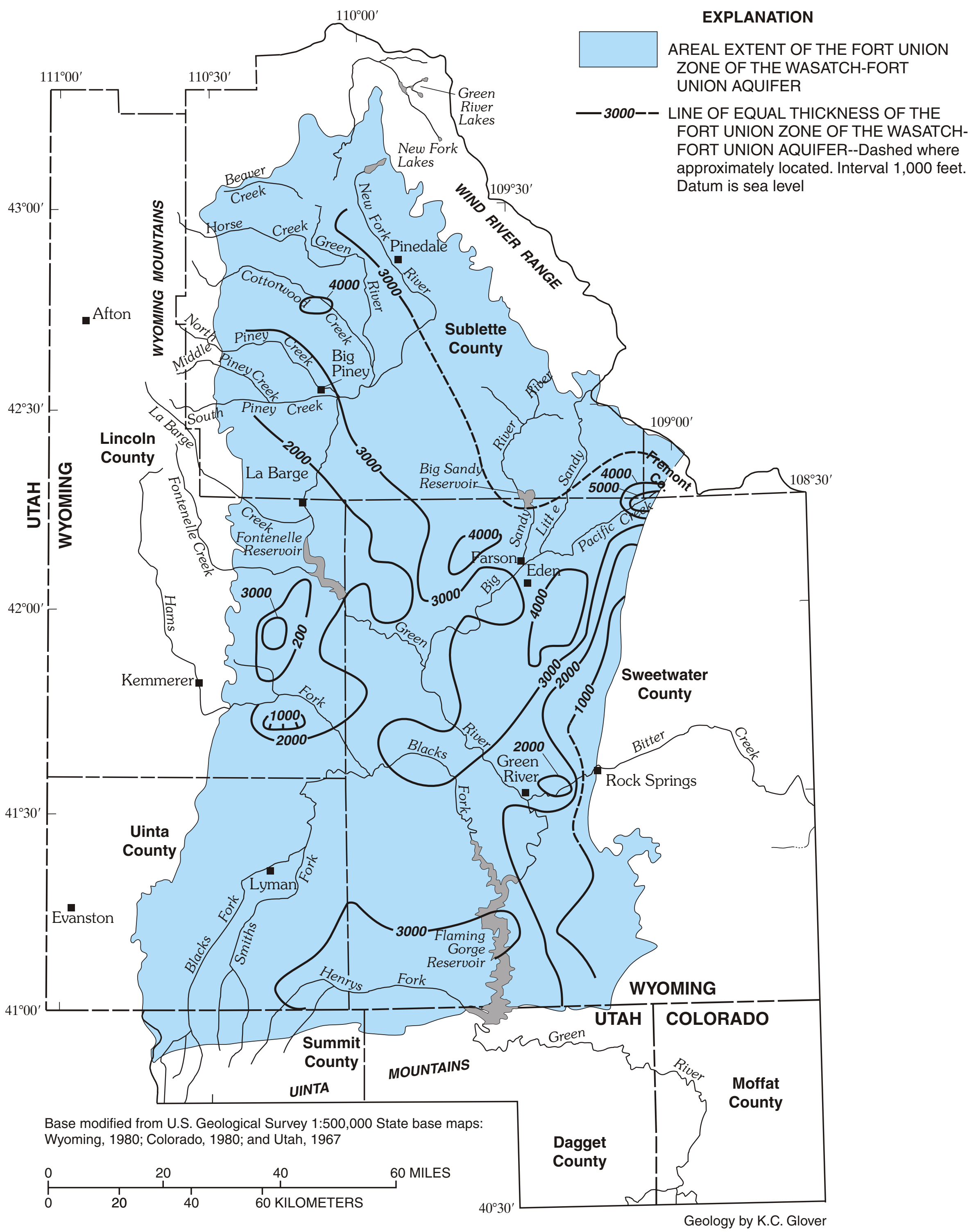


Figure 5-21. Area and thickness of the Fort Union zone of the Wasatch-Fort Union aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

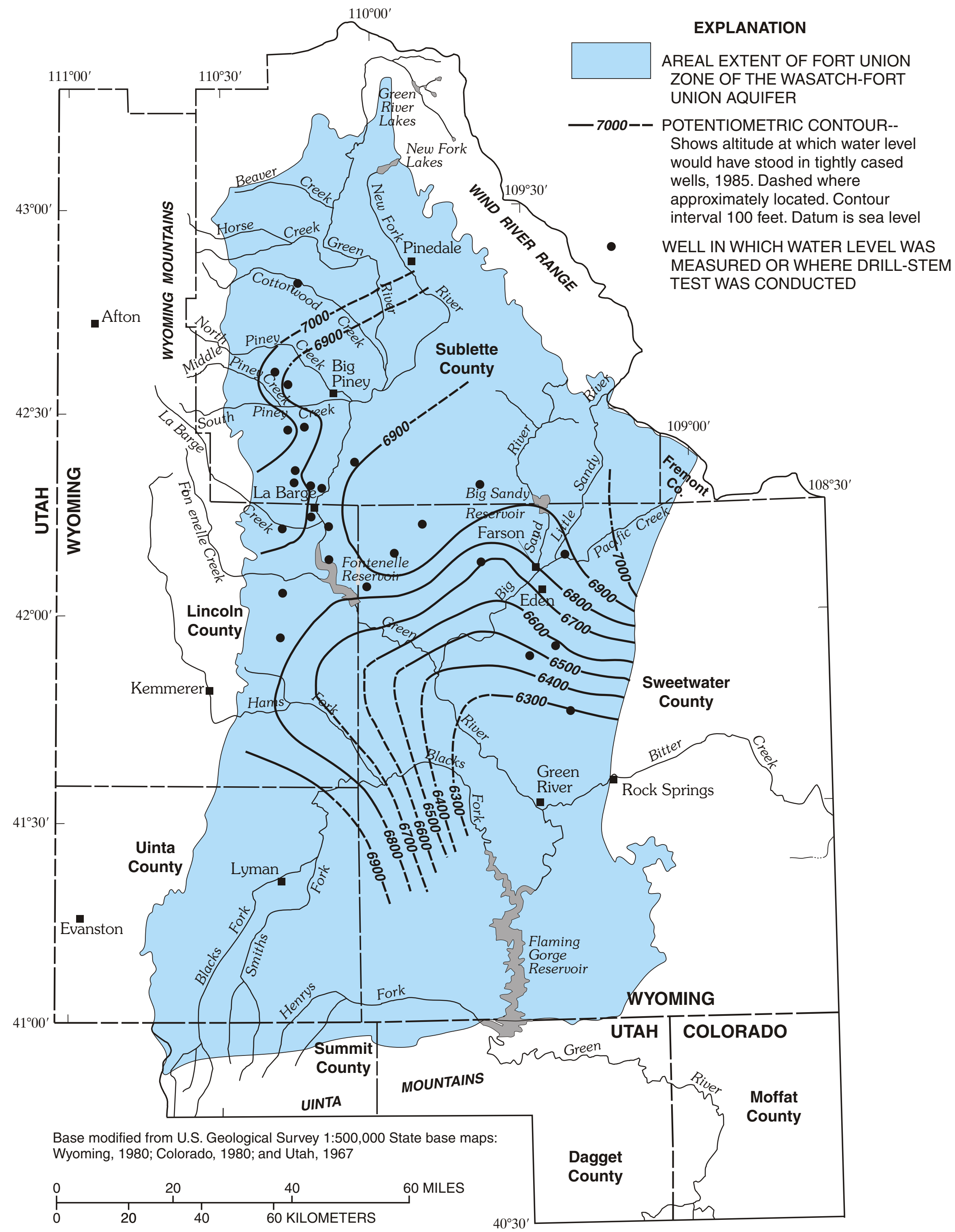


Figure 5-22. Potentiometric surface (1985) of the Fort Union zone of the Wasatch-Fort Union aquifer, Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

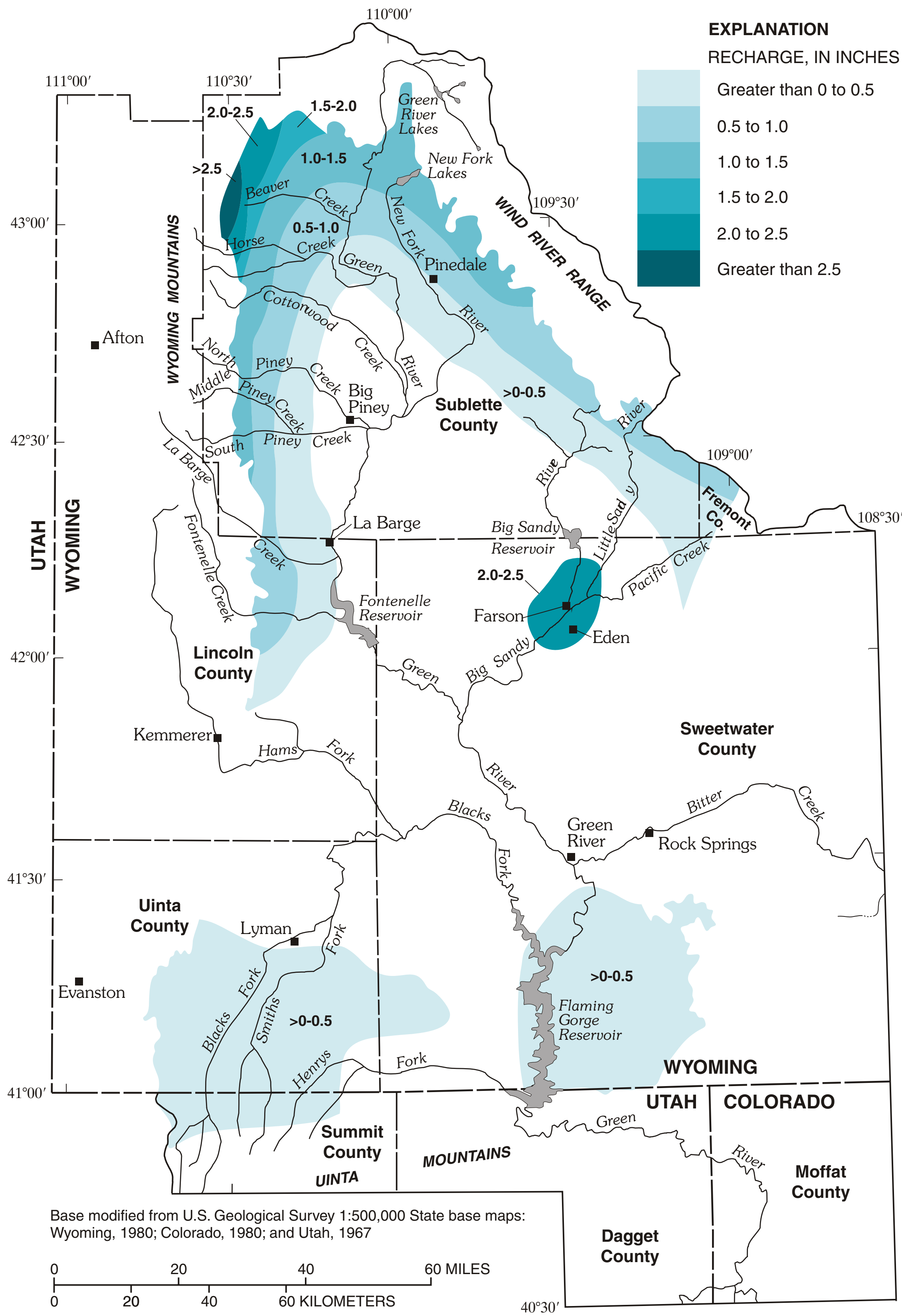


Figure 5-23. Distribution of estimated recharge to the Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

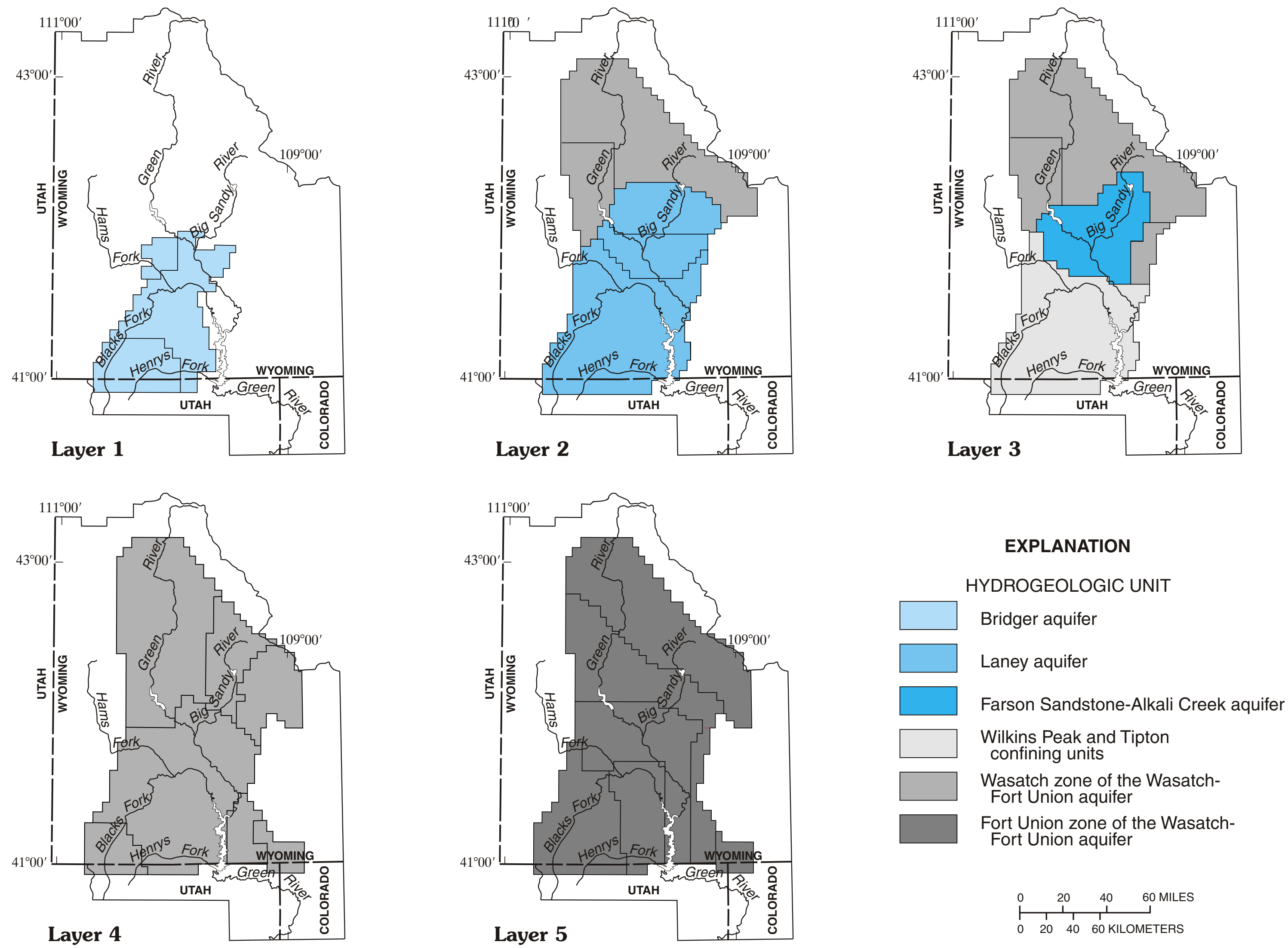


Figure 5-24. Subdivisions of layers in the groundwater model and distribution of hydrogeologic units in the model layers in the Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

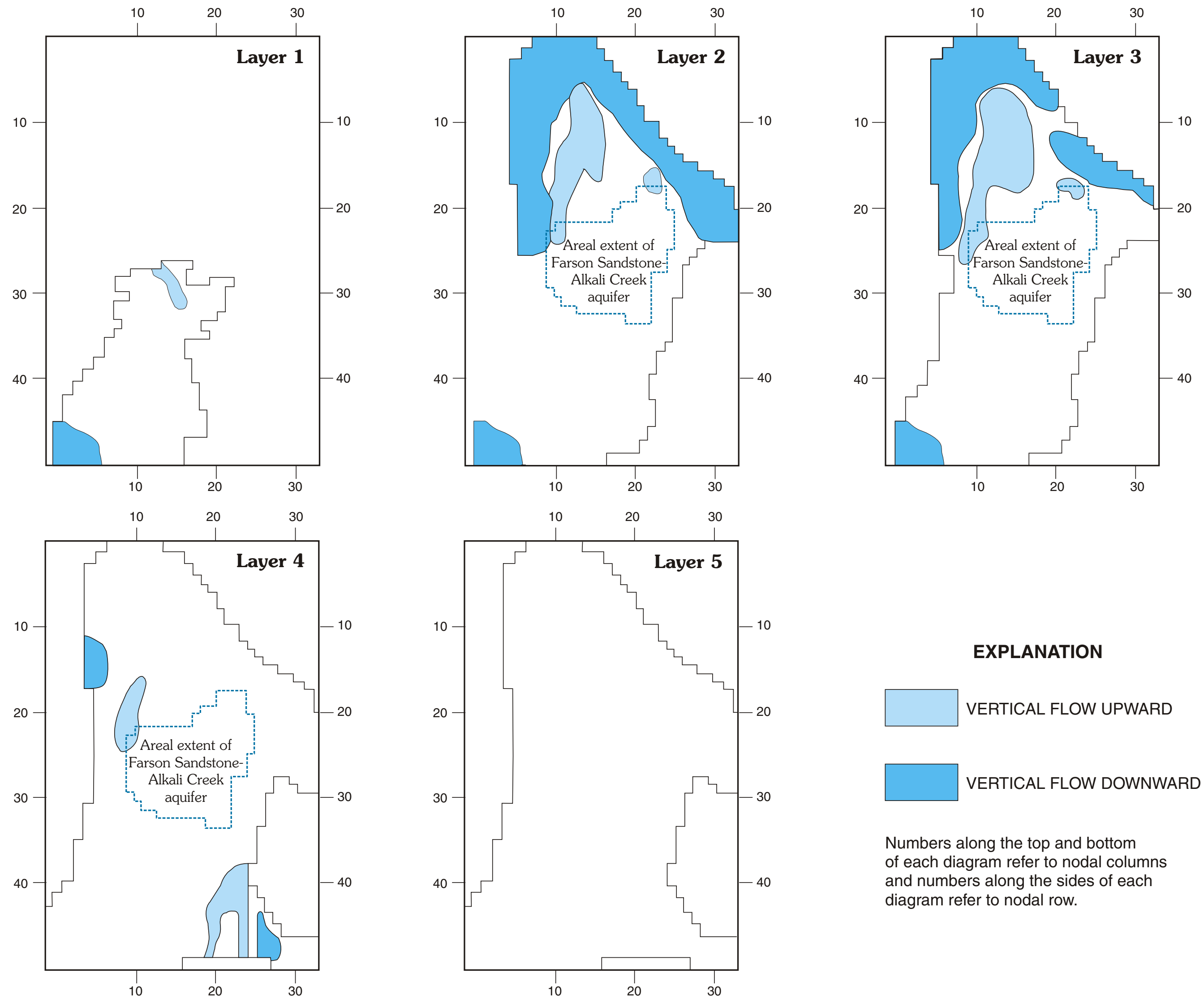


Figure 5-25. Areas of substantial simulated vertical groundwater flow between model layers representing the Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

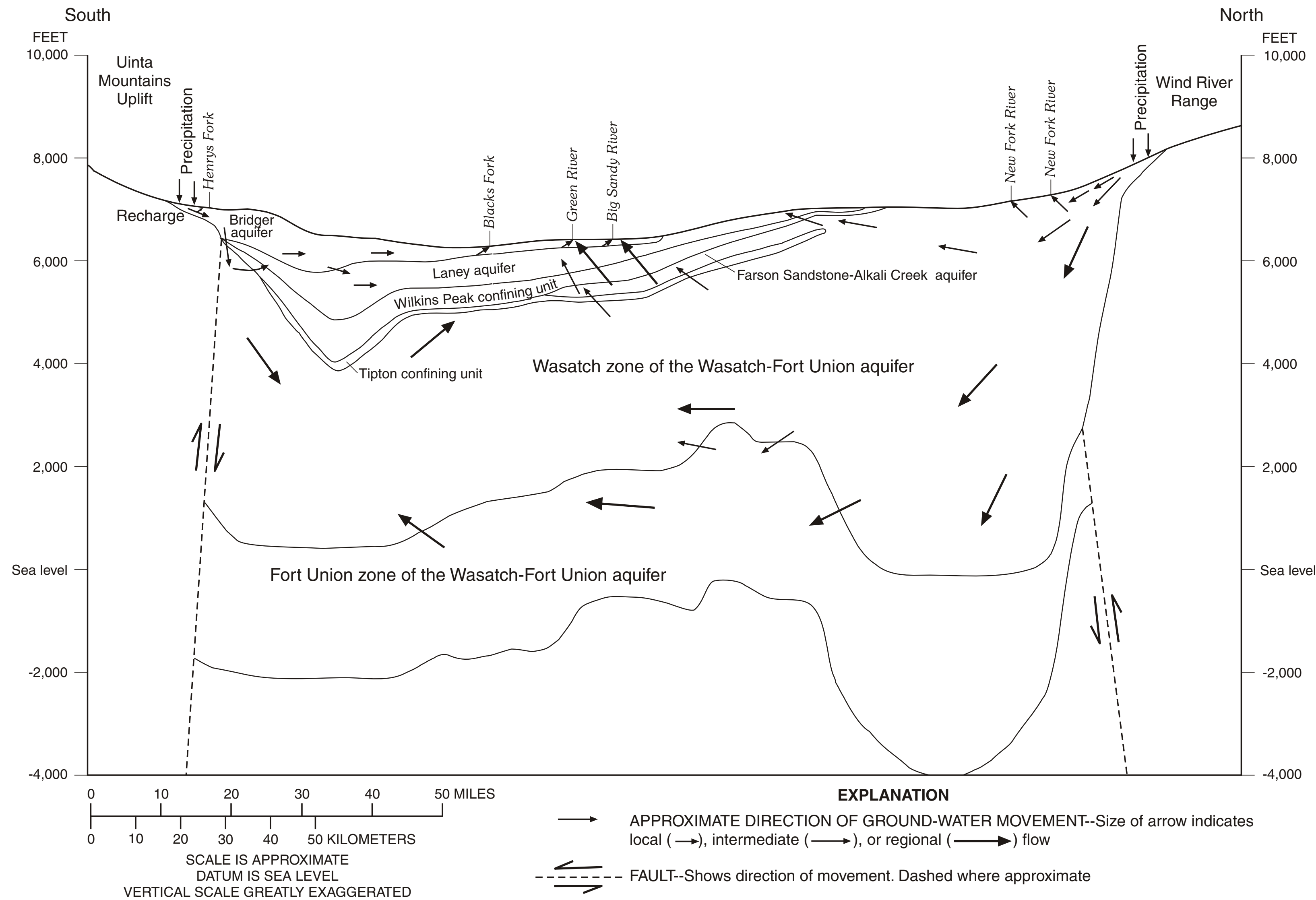


Figure 5-26. South–north diagrammatic cross section summarizing groundwater movement in the Green River Basin lower Tertiary aquifer system. *Modified from Martin (1996).*

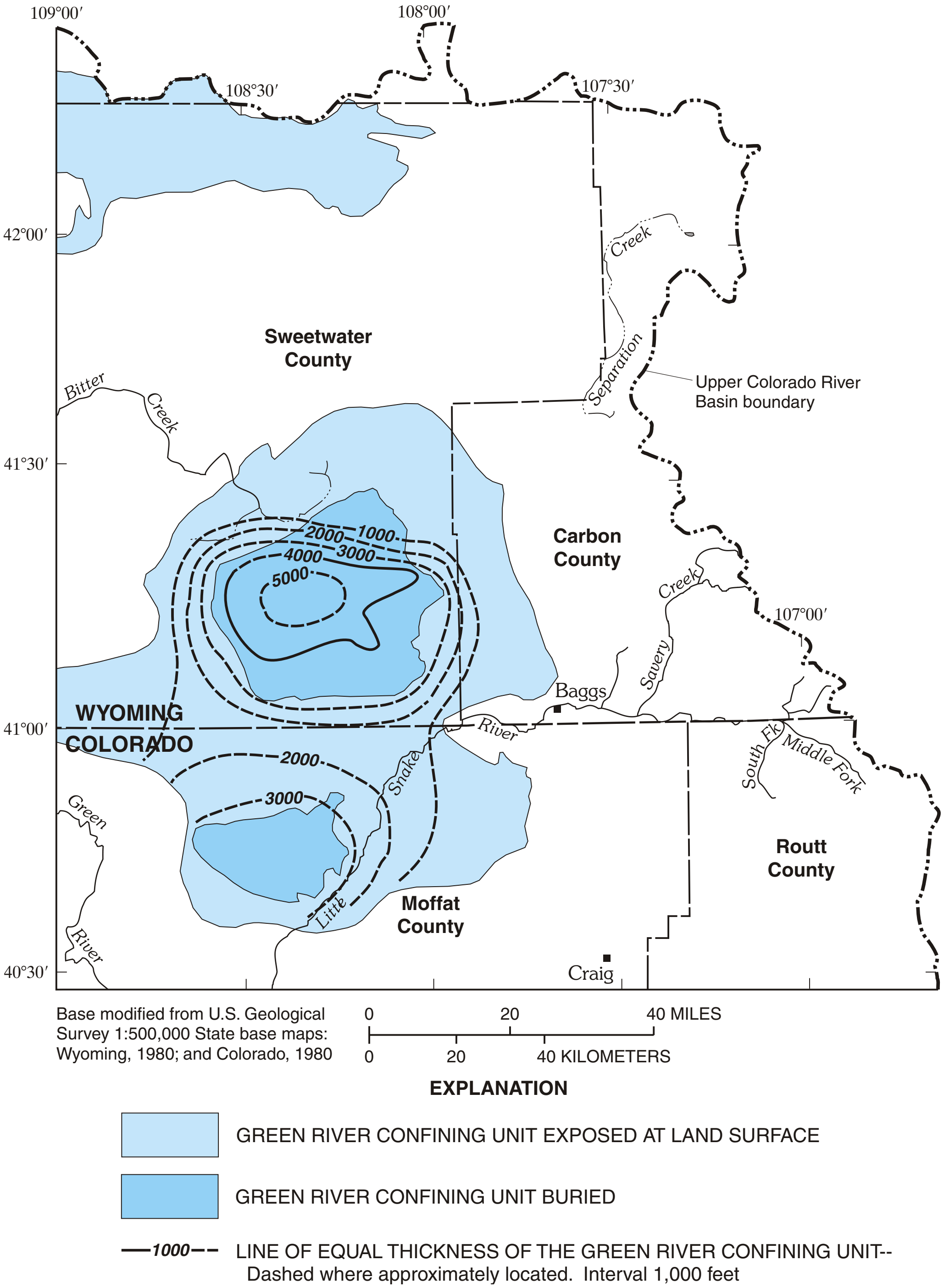


Figure 5-27. Area and thickness of the Green River confining unit, Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Welder and McGreevey (1966) and Glover et al. (1998).*

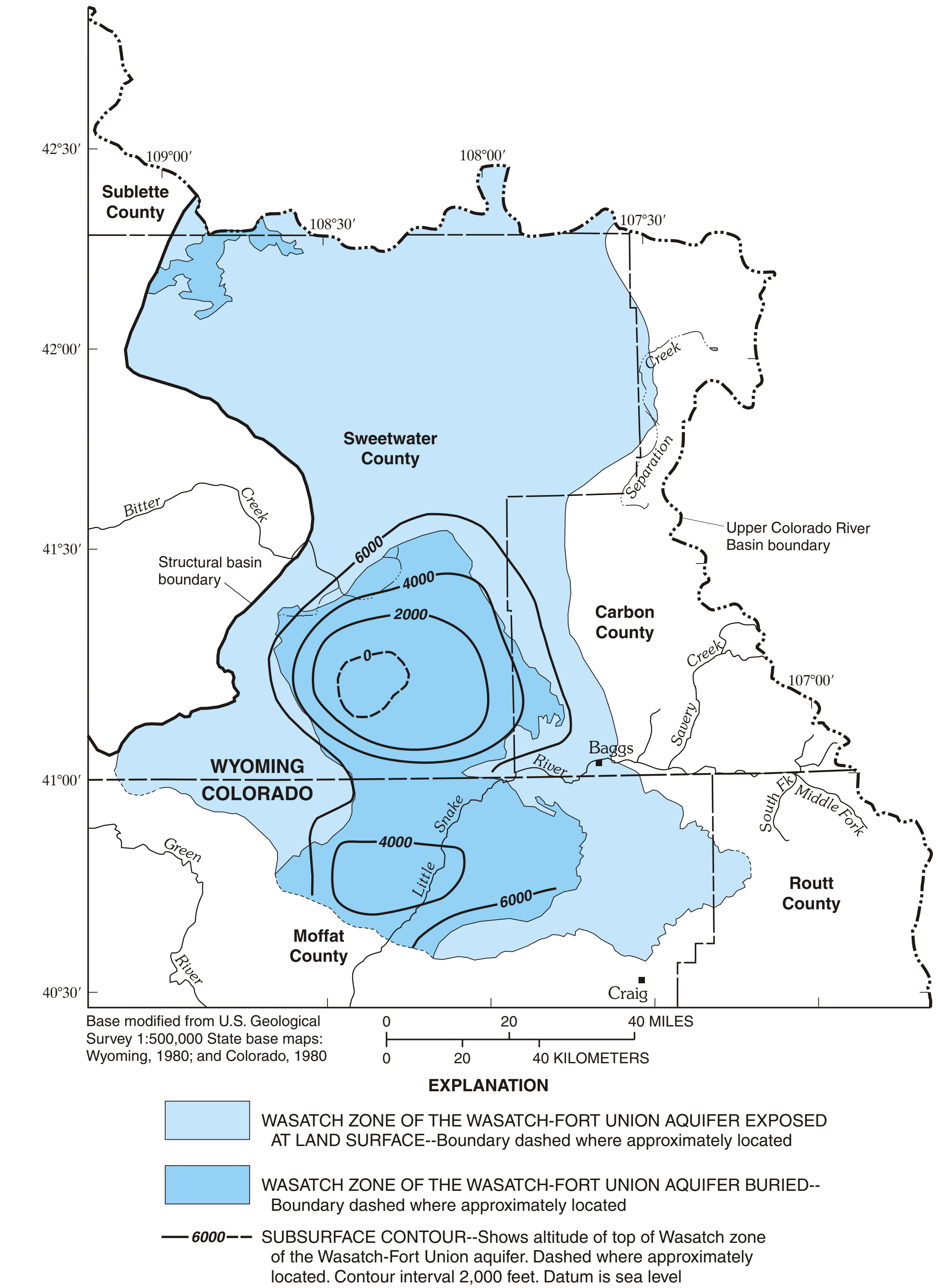


Figure 5-28. Altitude of the top of the Wasatch zone of the Wasatch-Fort Union aquifer, Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Welder and McGreevey (1966) and Glover et al. (1998).*

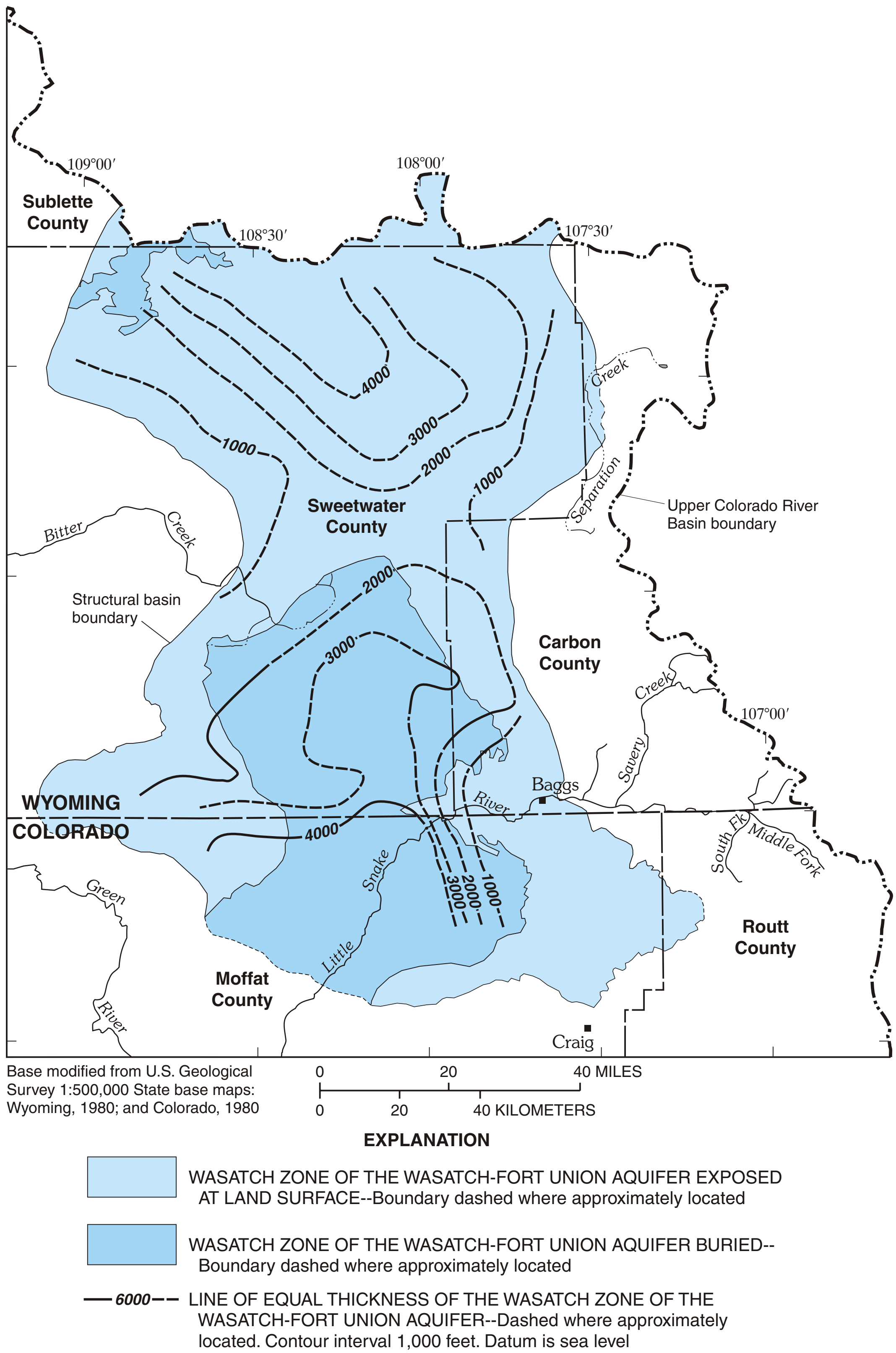


Figure 5-29. Area and thickness of the Wasatch zone of the Wasatch-Fort Union aquifer, Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Glover et al. (1998).*

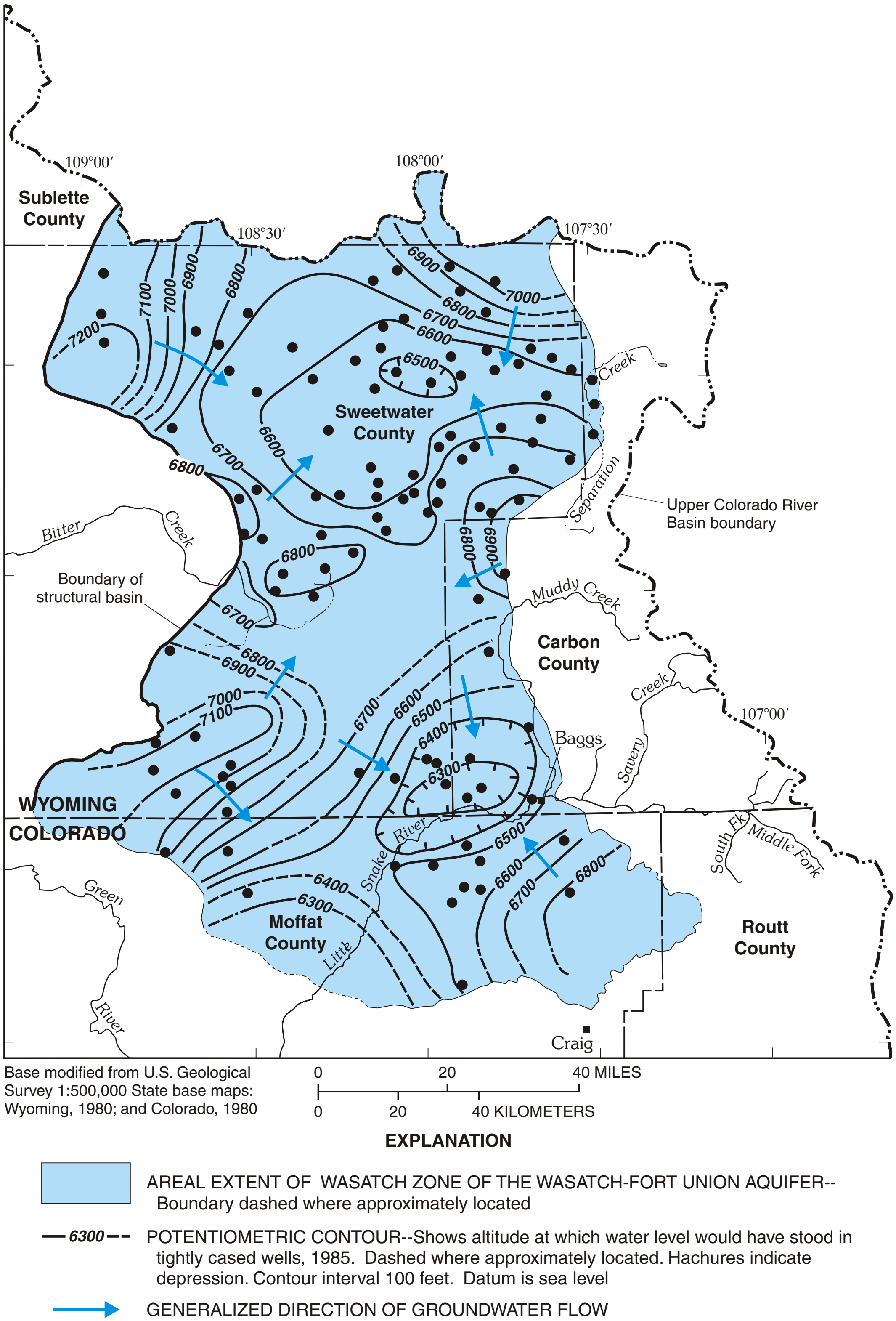
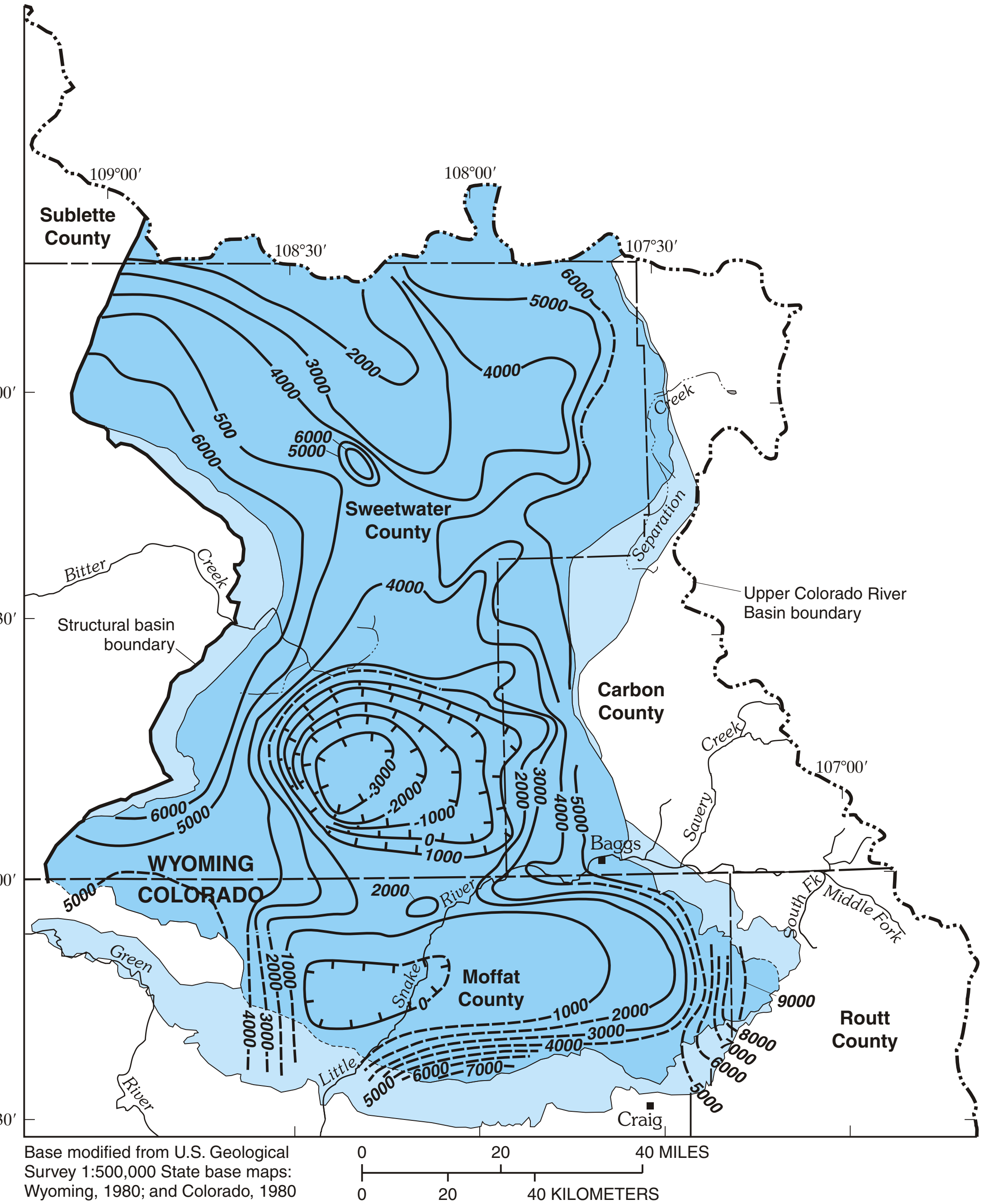


Figure 5-30. Potentiometric surface (1985) of the Wasatch zone of the Wasatch-Fort Union aquifer, Great Divide/ Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Glover et al. (1998).*



EXPLANATION

FORT UNION ZONE OF THE WASATCH-FORT UNION AQUIFER EXPOSED AT LAND SURFACE--Boundary dashed where approximately located

FORT UNION ZONE OF THE WASATCH-FORT UNION AQUIFER BURIED--Boundary dashed where approximately located

5000 STRUCTURE CONTOUR--Shows altitude of top of the Fort Union zone of the Wasatch-Fort Union aquifer. Hachures indicate depression. Dashed where approximately located. Contour interval 1,000 feet. Datum is sea level

Figure 5-31. Altitude of the top of the Fort Union zone of the Wasatch-Fort Union aquifer, Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Glover et al. (1998).*

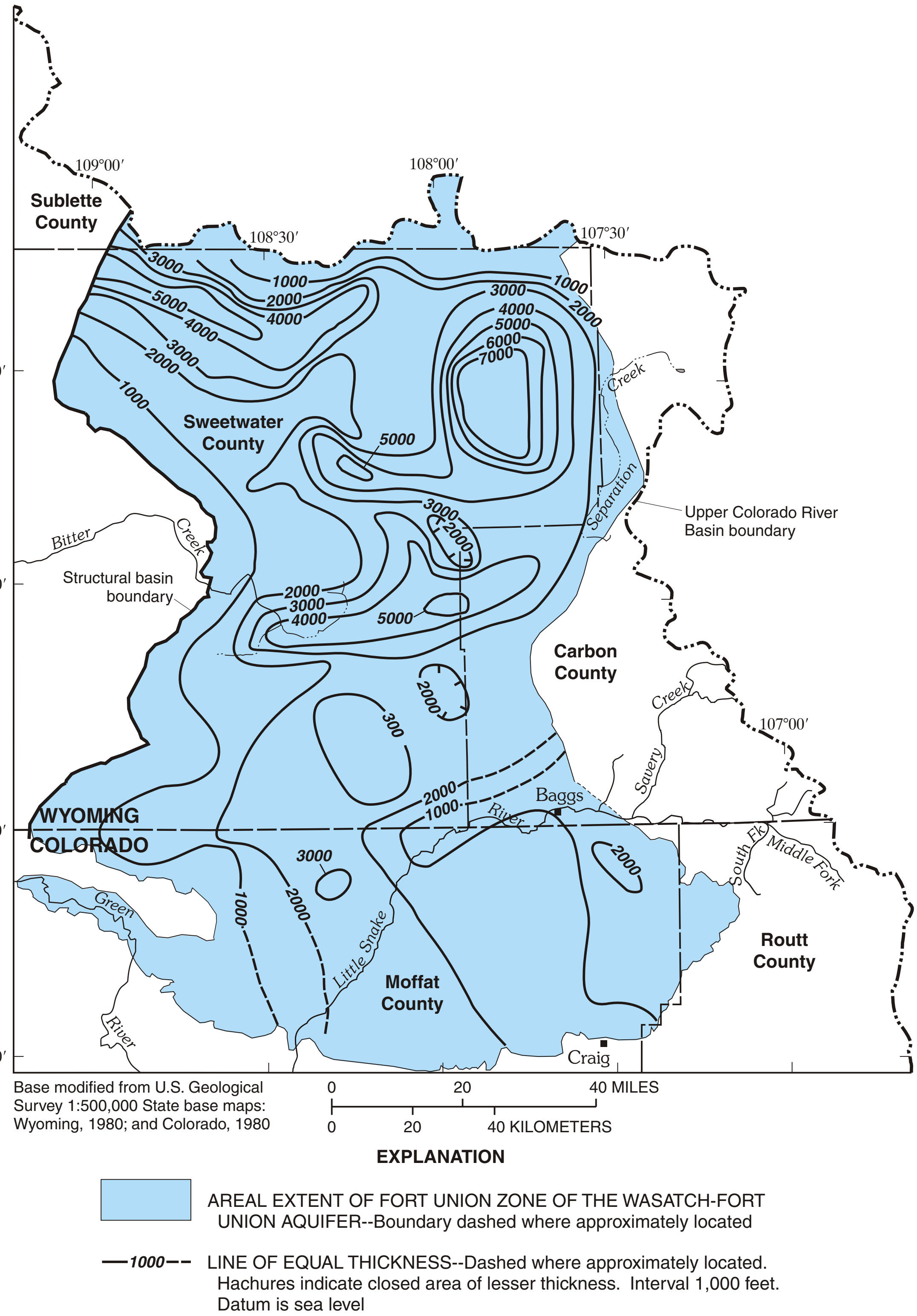


Figure 5-32. Area and thickness of the Fort Union zone of the Wasatch-Fort Union aquifer, Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Glover et al. (1998).*

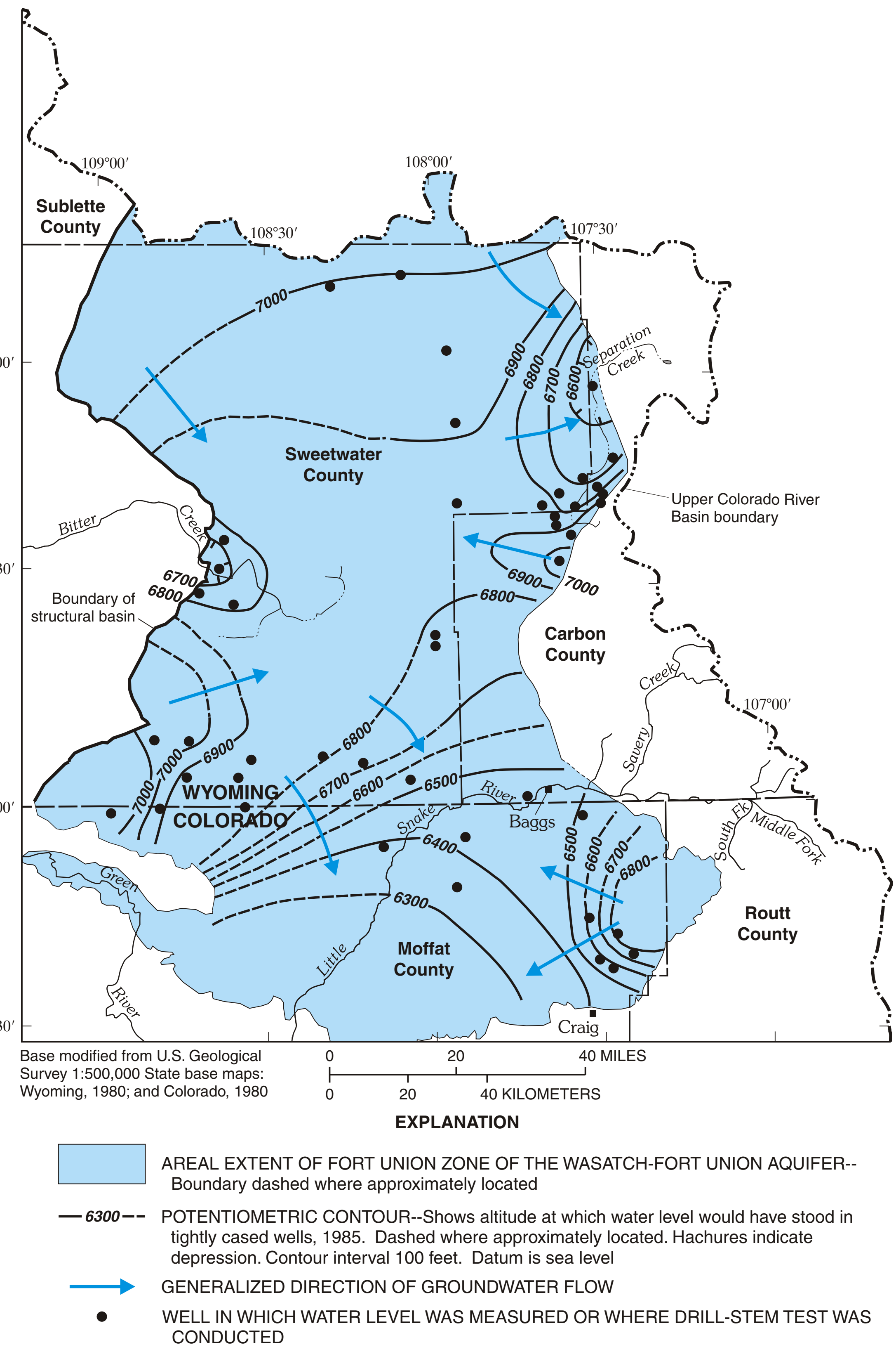


Figure 5-33. Potentiometric surface (1985) of the Fort Union zone of the Wasatch-Fort Union aquifer, Great Divide/Washakie/Sand Wash basins lower Tertiary aquifer system. *Modified from Glover et al. (1998).*

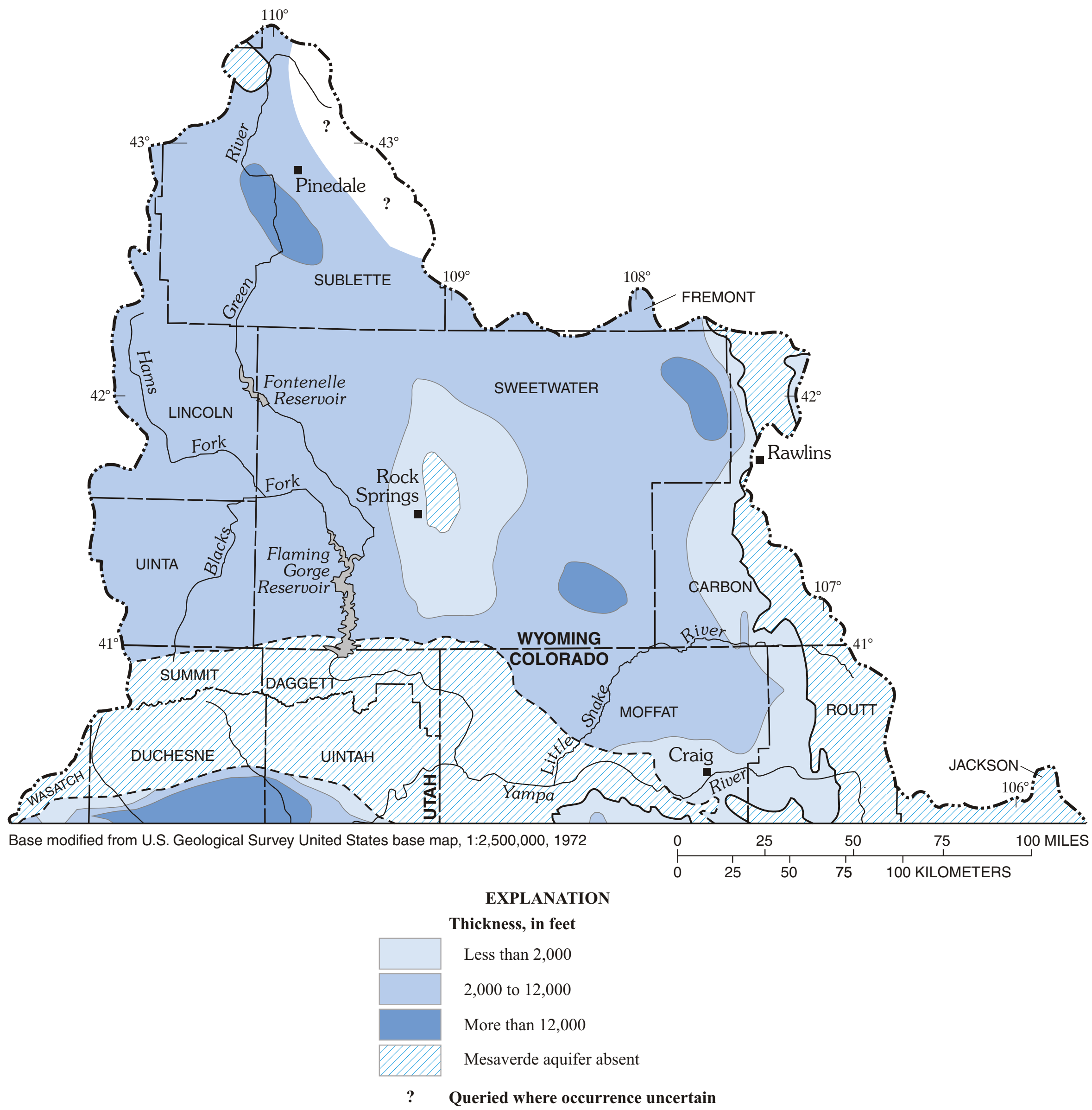


Figure 5-34. Total thickness of rock overlying the Mesaverde aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

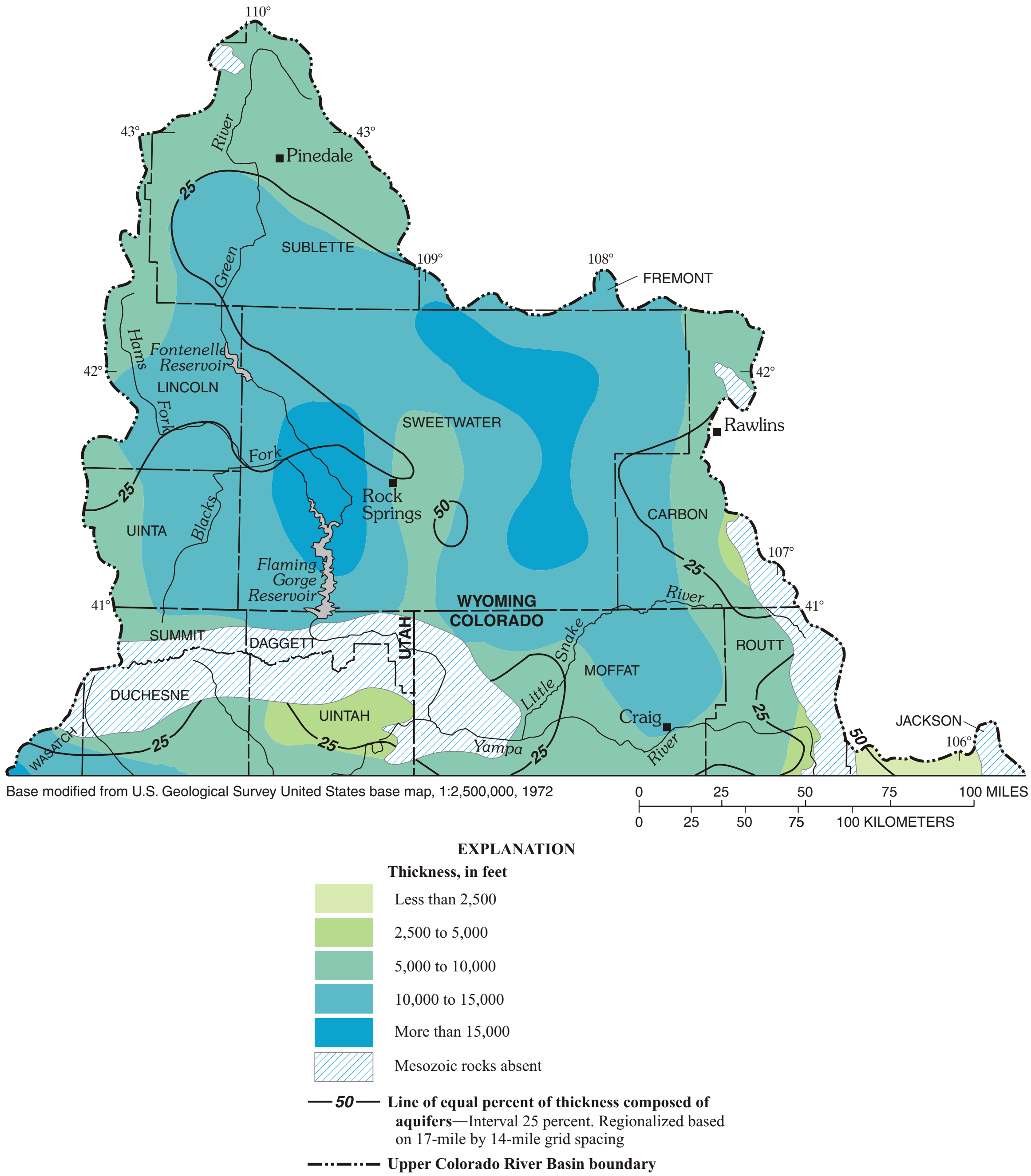


Figure 5-35. Thickness of Mesozoic rocks and the percentage of that thickness composed of aquifers (generalized on the basis of 17-mile × 14-mile grid spacing) in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

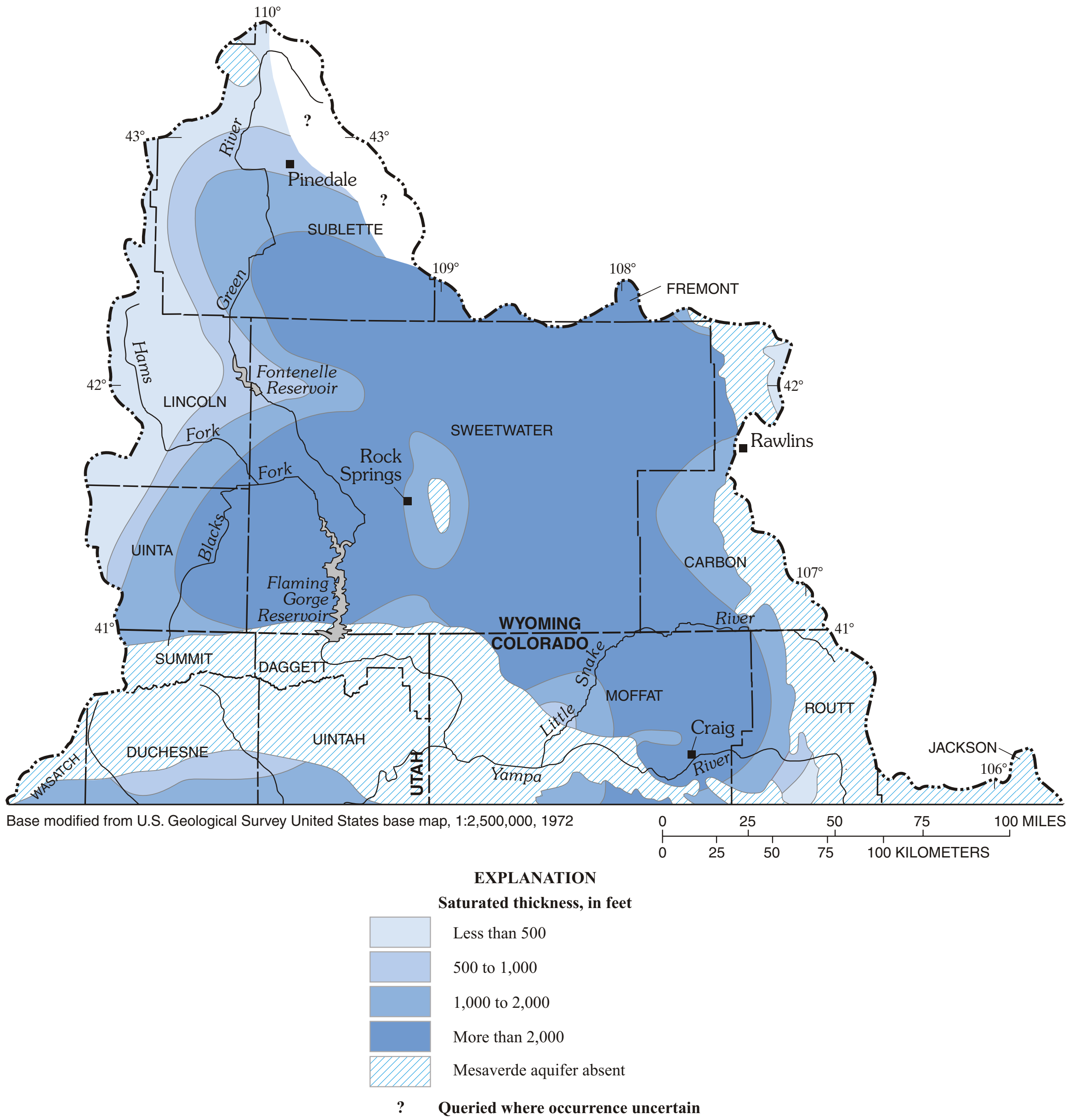


Figure 5-36. Saturated thickness of the Mesaverde aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

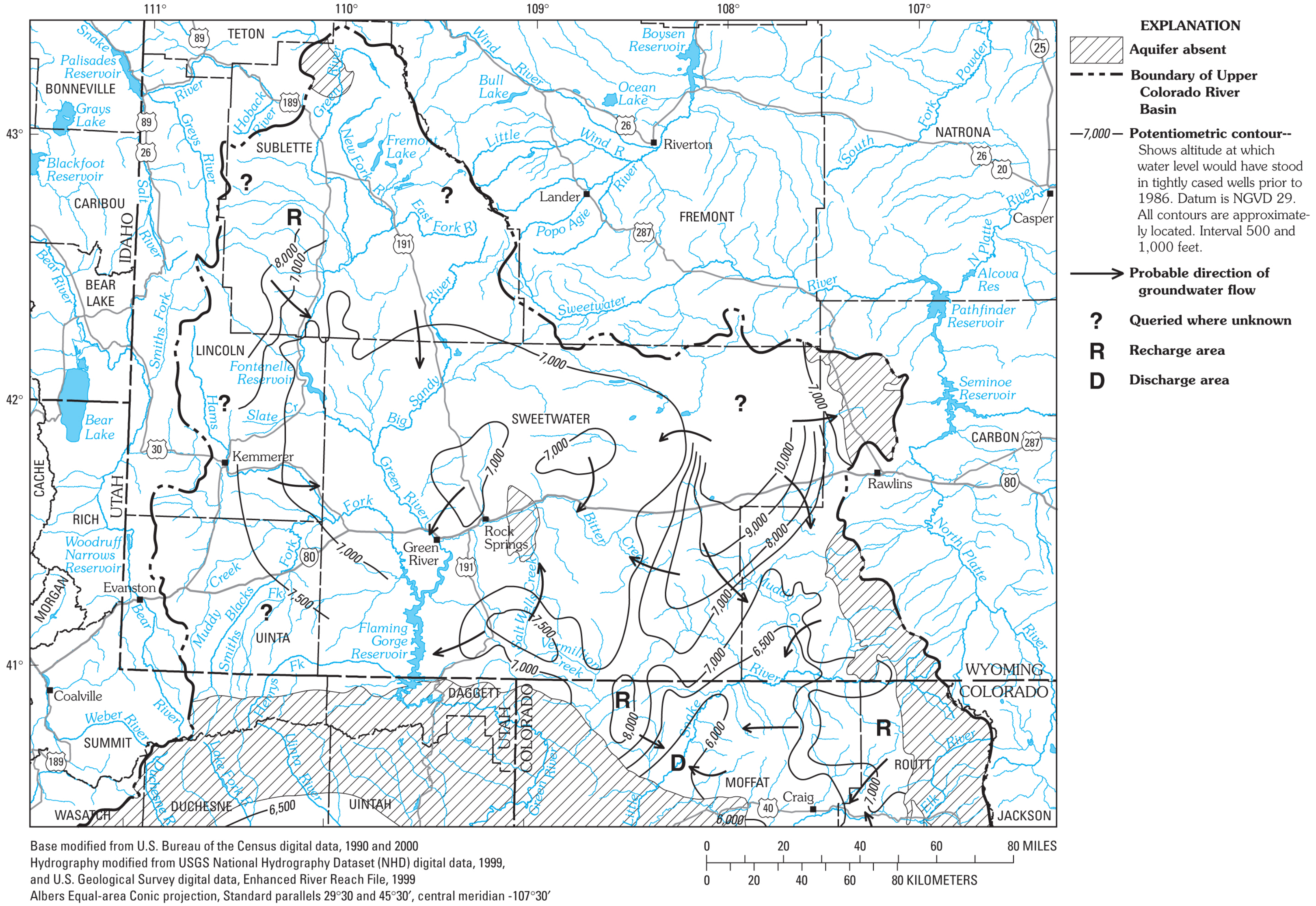


Figure 5-37. Generalized potentiometric surface, recharge and discharge areas, and inferred flow paths of the Mesaverde aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

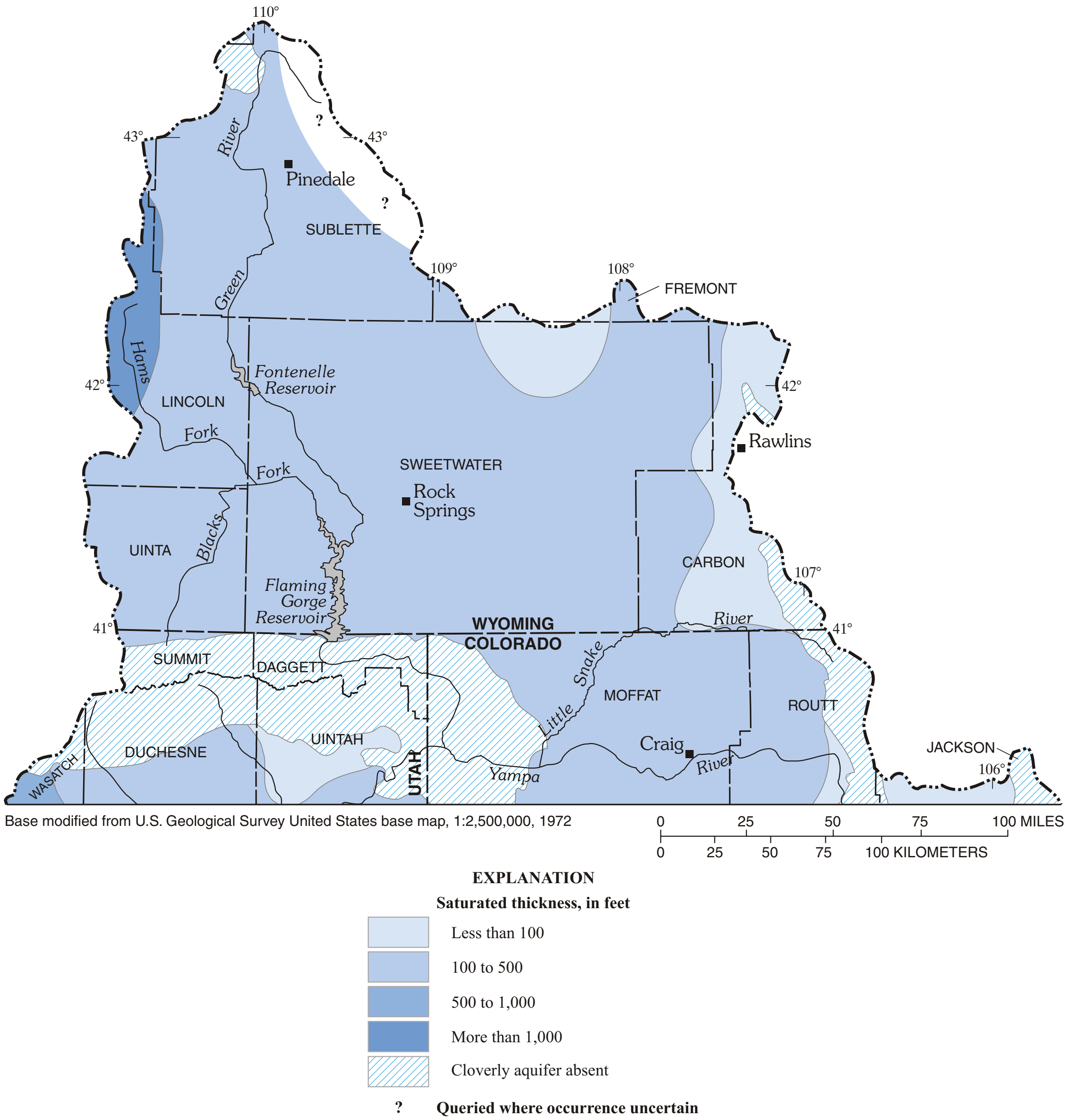


Figure 5-38. Saturated thickness of the Cloverly aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

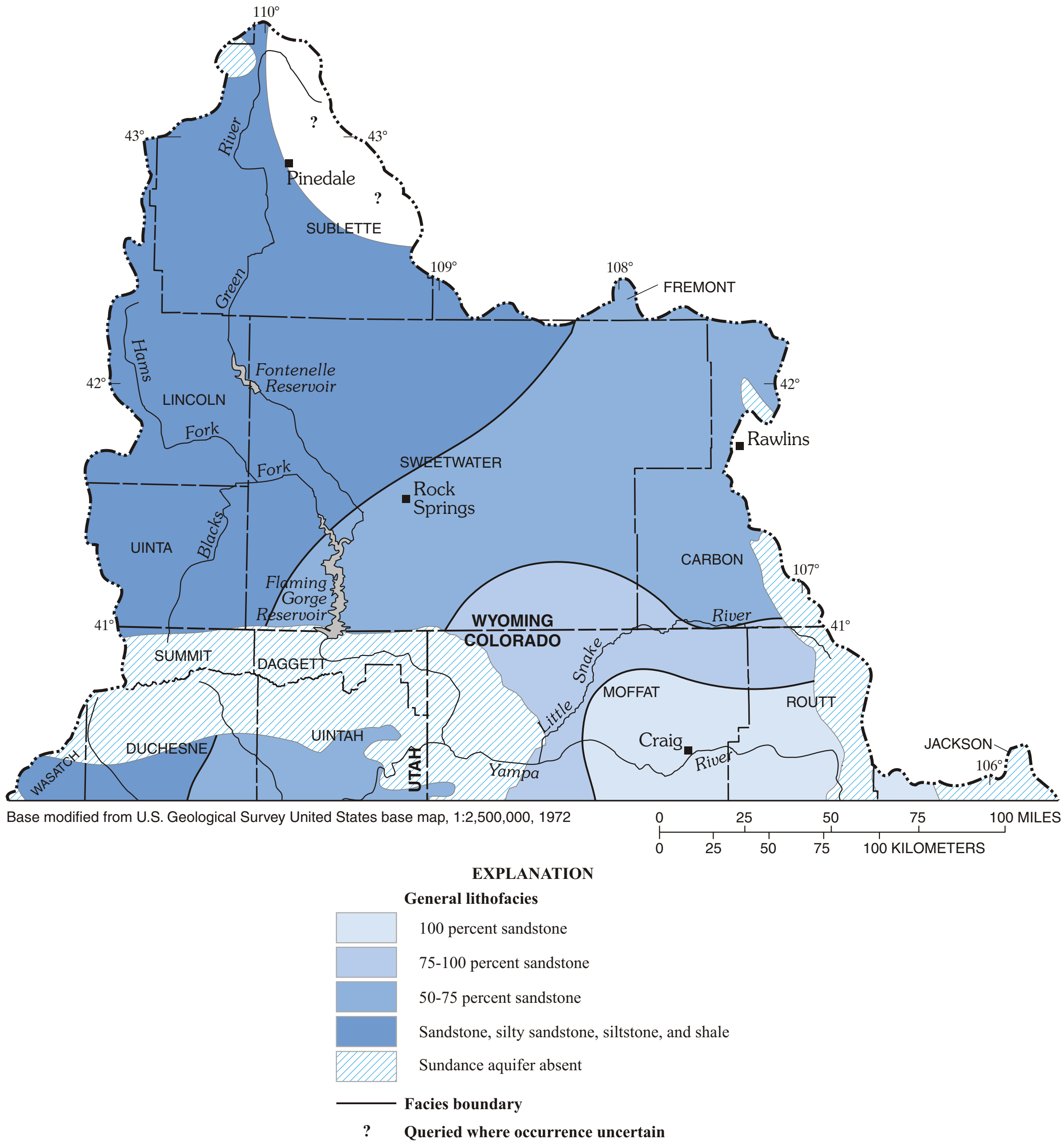


Figure 5-39. General lithofacies of the Sundance aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

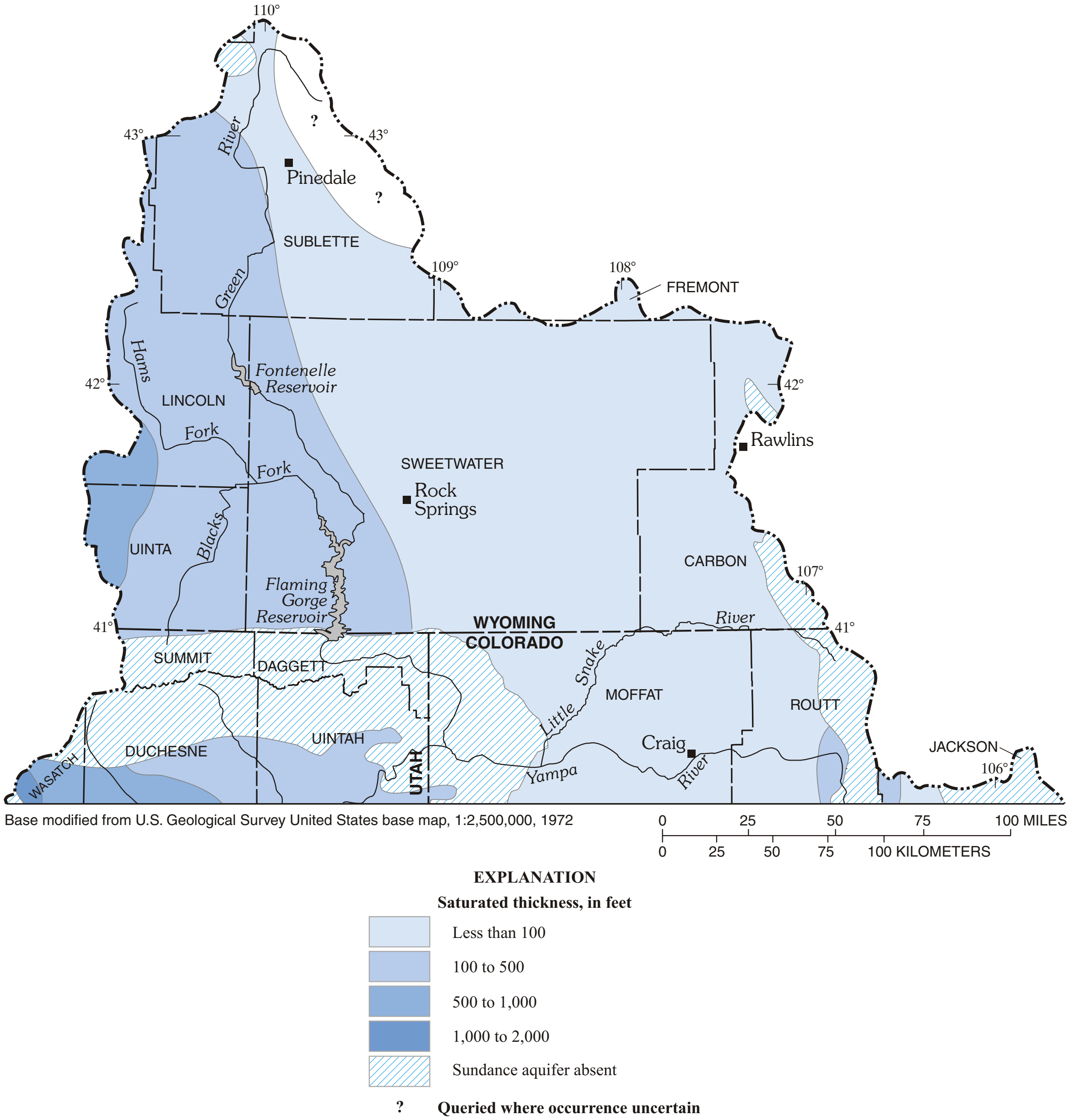


Figure 5-40. Saturated thickness of the Sundance aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

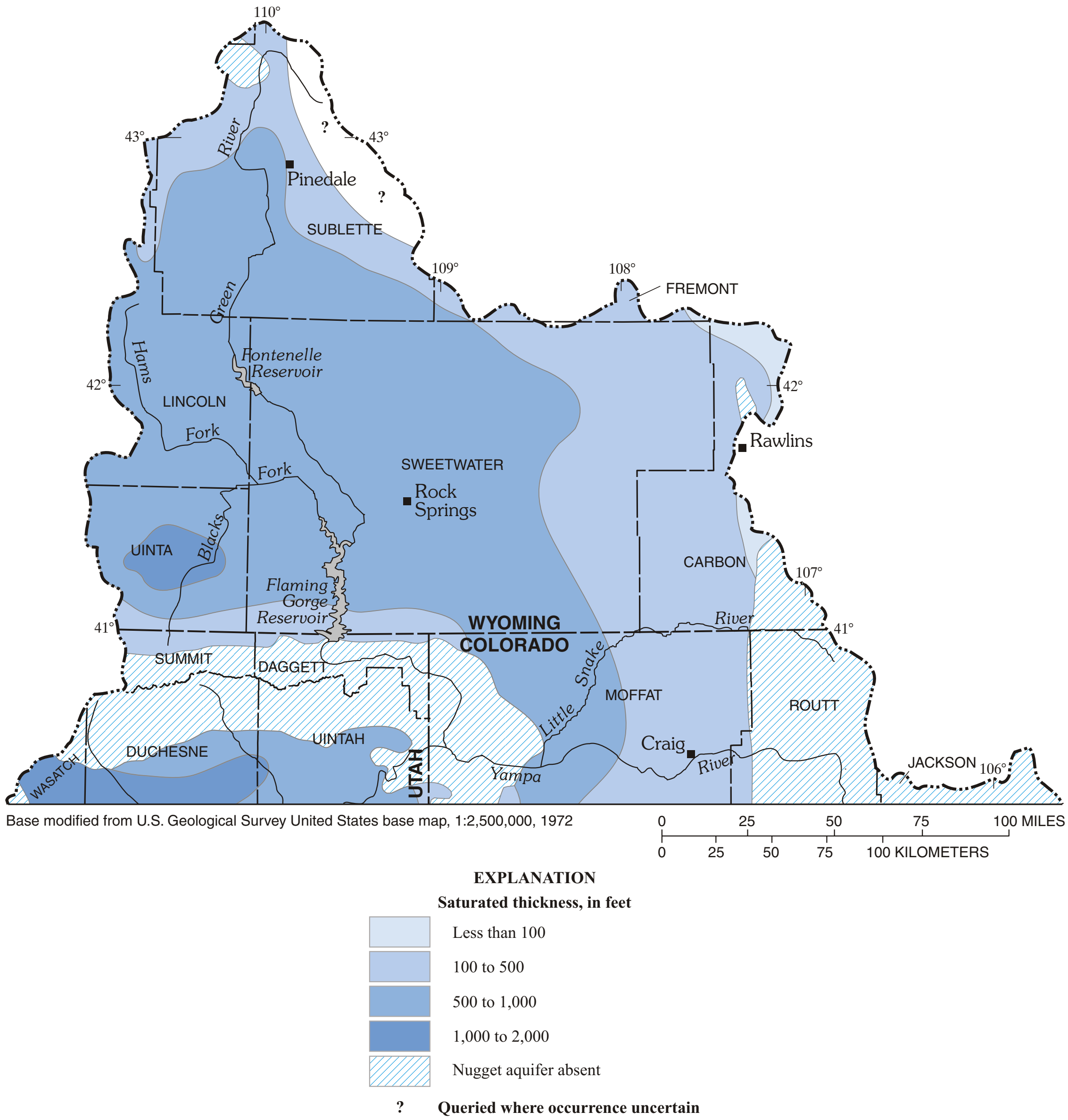
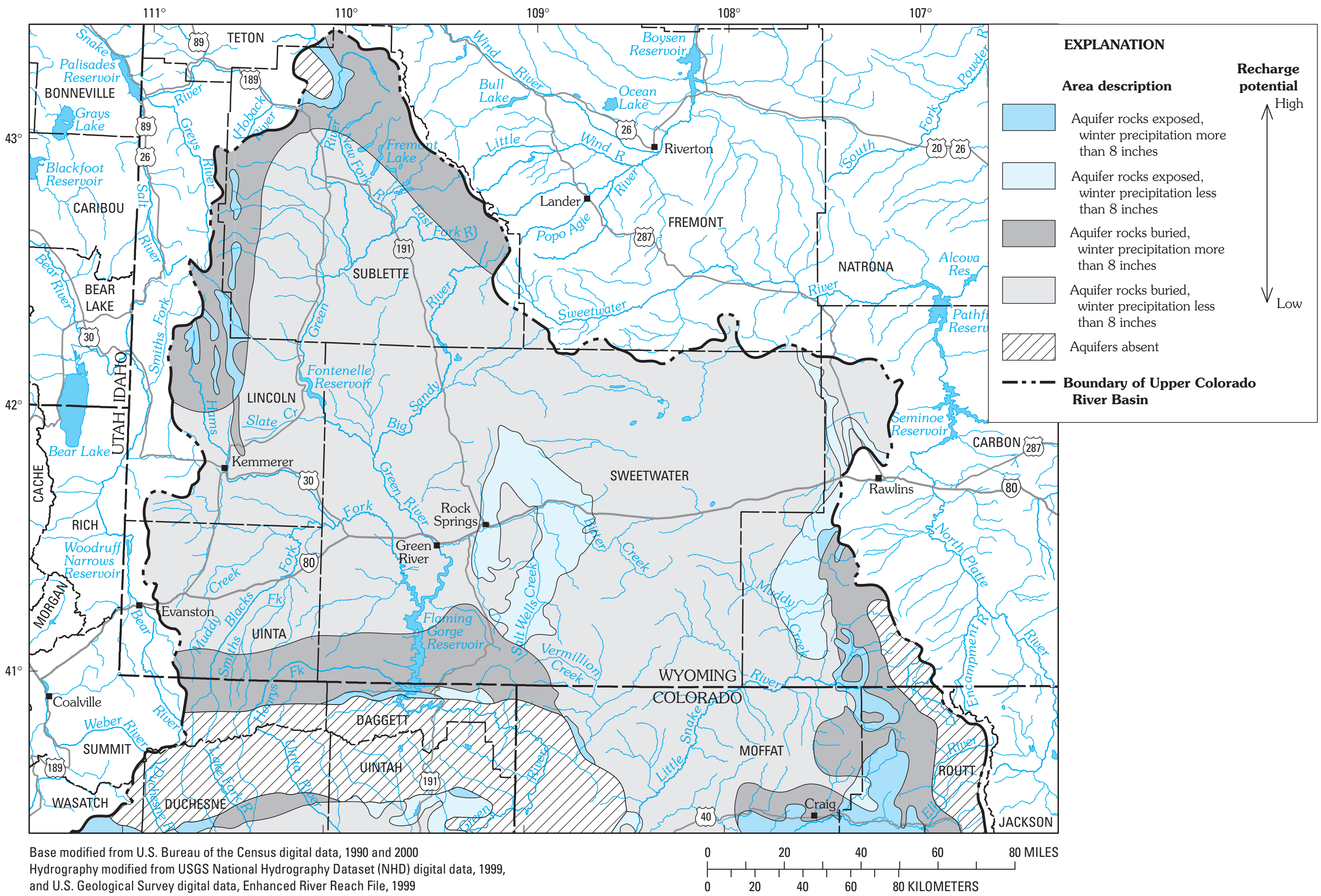


Figure 5-41. Saturated thickness of the Nugget aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*



Base modified from U.S. Bureau of the Census digital data, 1990 and 2000
Hydrography modified from USGS National Hydrography Dataset (NHD) digital data, 1999,
and U.S. Geological Survey digital data, Enhanced River Reach File, 1999
Albers Equal-area Conic projection, Standard parallels 29°30′ and 45°30′, central meridian -107°30′

Figure 5-42. Potential for recharge by direct infiltration of precipitation to Mesozoic hydrogeologic units in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

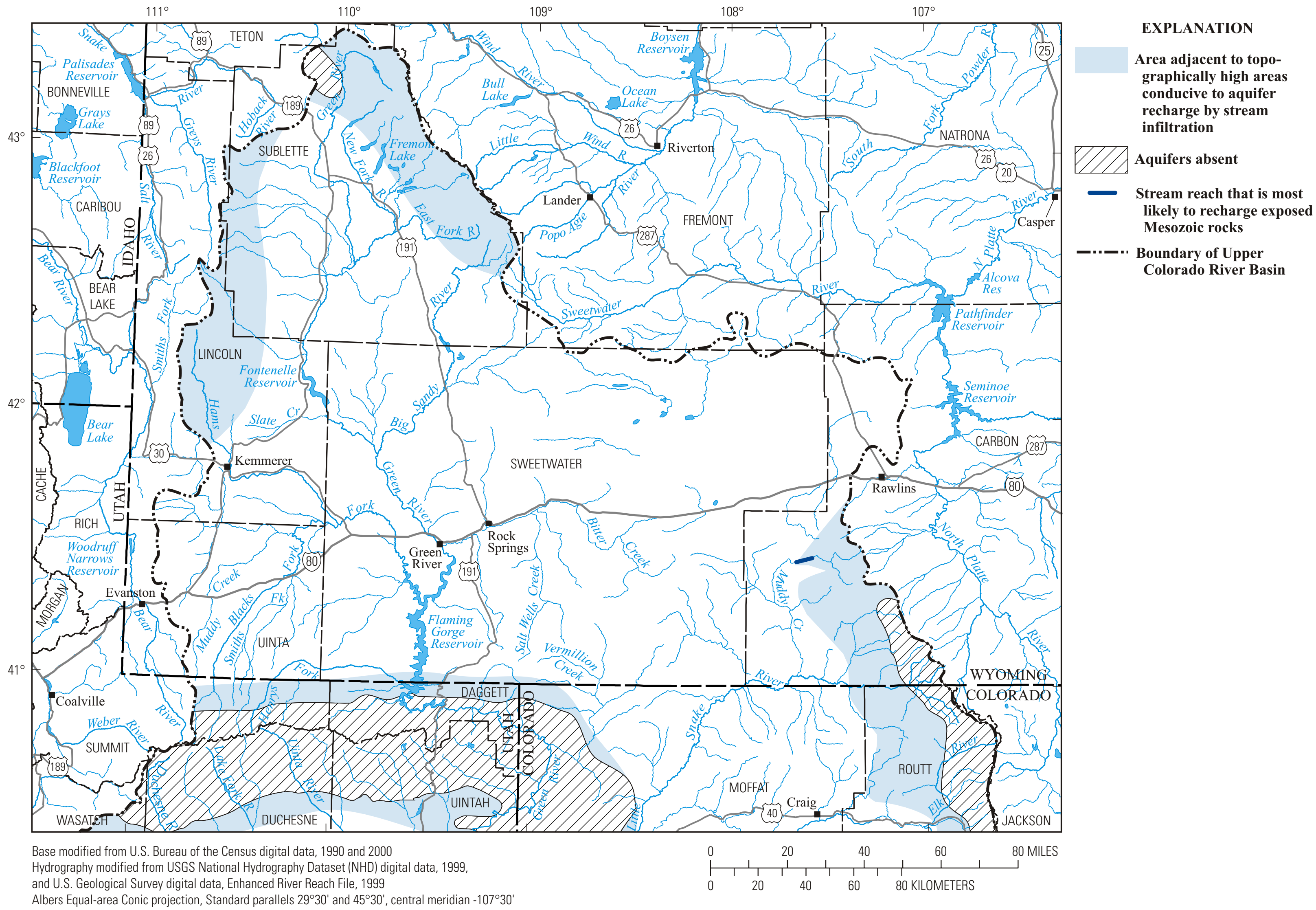


Figure 5-43. Areas of streamflow recharge to aquifers in Mesozoic rocks in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

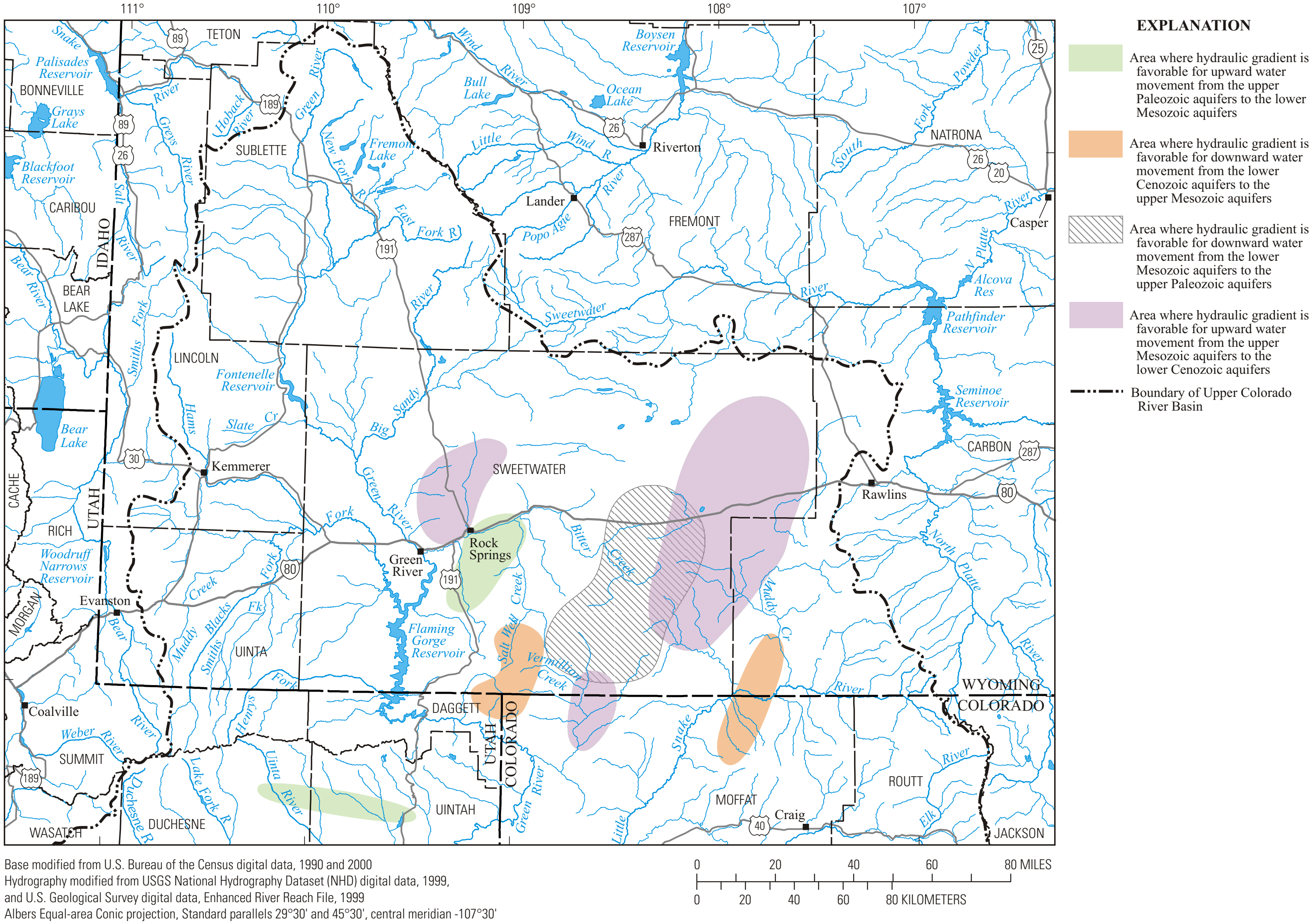


Figure 5-44. Areas of possible vertical flow into aquifers in Mesozoic rocks from underlying and overlying rocks, and from aquifers in Mesozoic rocks into underlying Paleozoic and overlying Mesozoic rocks in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

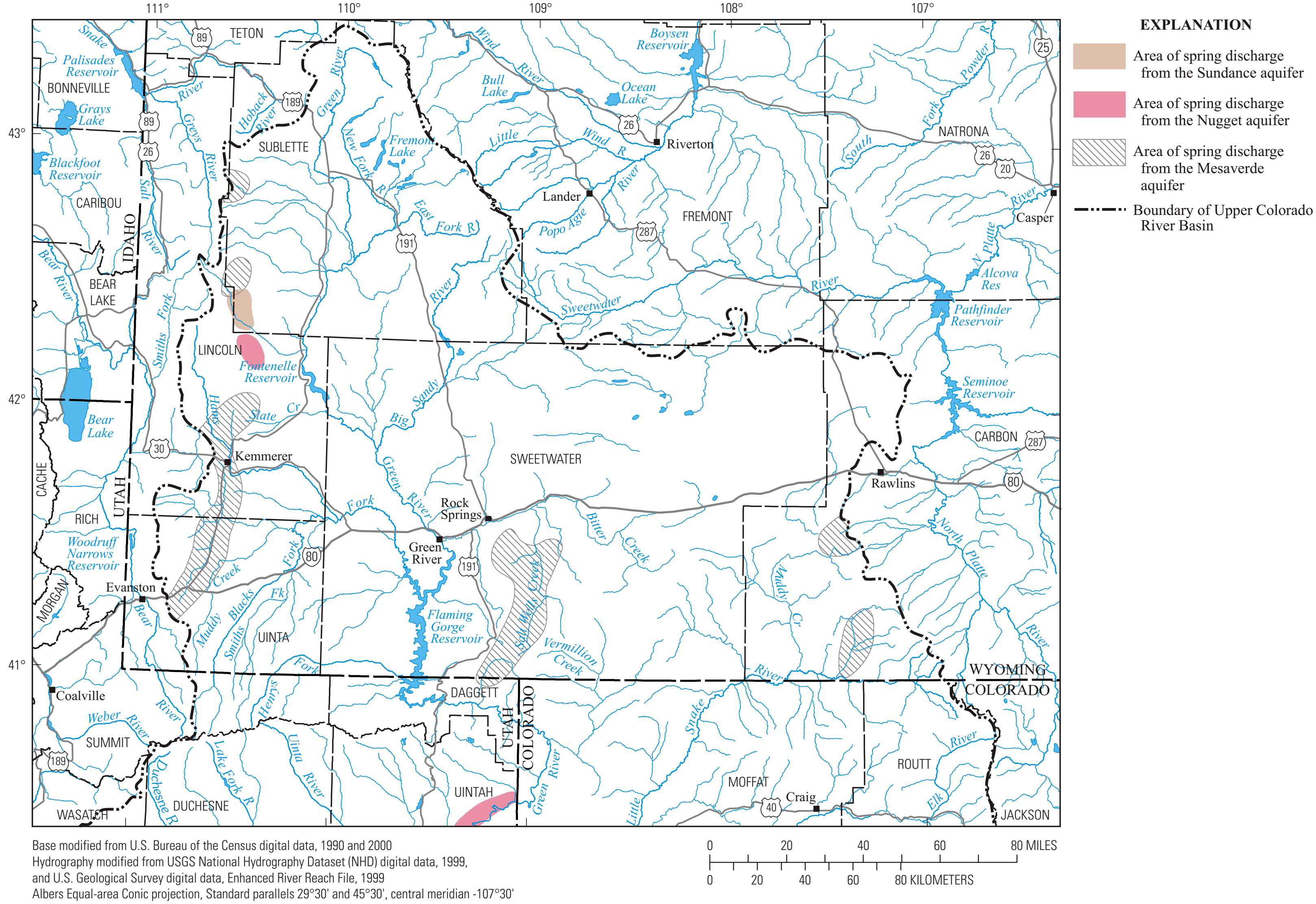
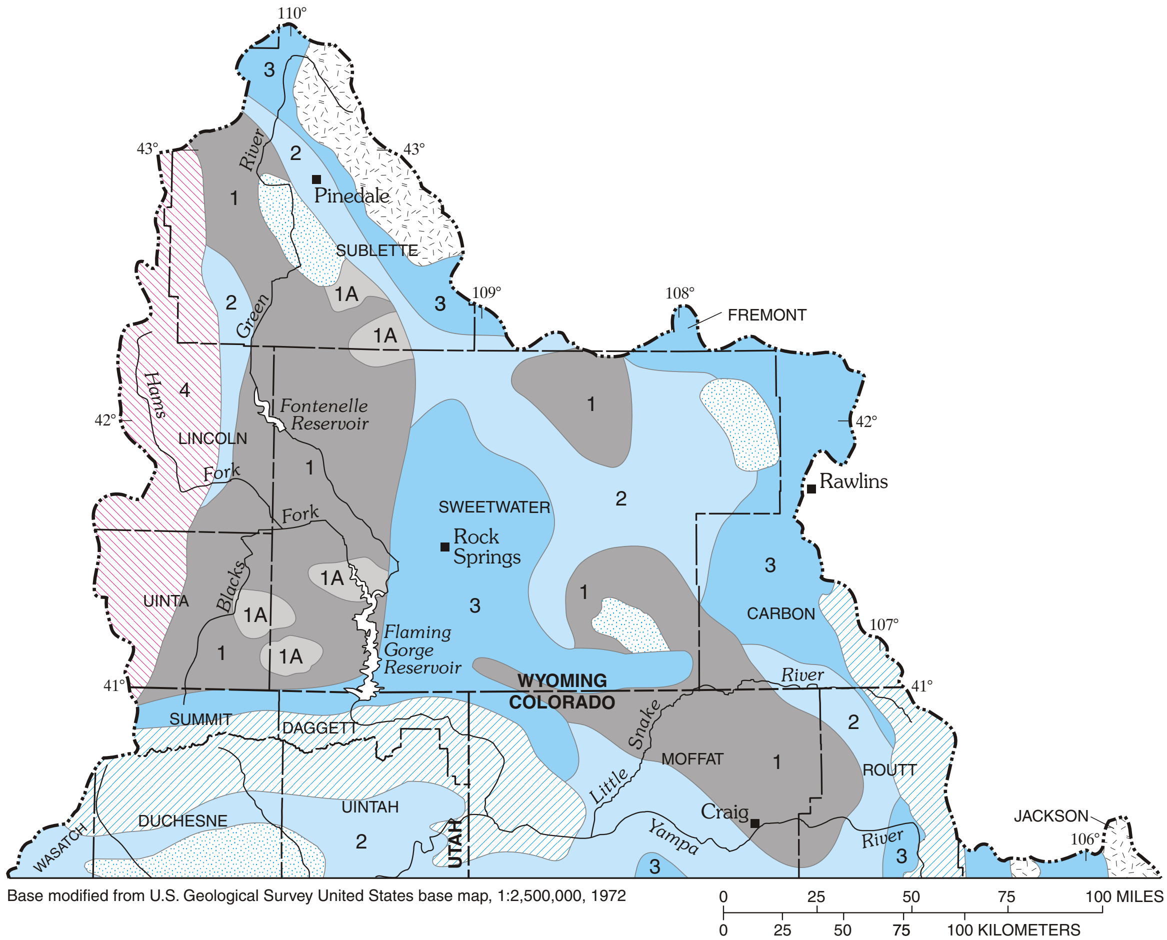


Figure 5-45. Areas of largest spring discharge from the Sundance, Nugget, and Mesaverde aquifers in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*



EXPLANATION

Category--Inferred fracture permeability increases with increasing category number

- Negligible inferred fracture permeability. Thickness of overlying rock more than 12,000 feet
- 1A — Smaller inferred fracture permeability than category 1 based on distribution of linear features
- 1 — Mainly structurally low areas in basins with few mapped faults; relatively flat lying rocks of the Colorado Plateaus province
- 2 — Arches, platforms, flanks of basins, and uplifts with less extensive faulting than category 3; basins with some faulting and (or) folding; anticlines between basins (category 1) and uplifts (category 3)
- 3 — Areas of extensive faulting and folding associated with uplifts, monoclines, anticlines, arches, and flanks of basins
- 4 — Tightly folded and faulted Wyoming thrust belt and southern Park Range in Colorado; areas where salt is present and movement or removal of salt by solution has increased local fracturing in the overlying rocks
- Precambrian igneous and metamorphic rocks thrust over possible Mesozoic rocks
- No Mesozoic rocks present

Figure 5-46. Inferred fracture permeability of Mesozoic rocks in the Greater Green River Basin and adjacent areas to the south. *Modified from Cooley (1986) and Freethey and Cordy (1991).*

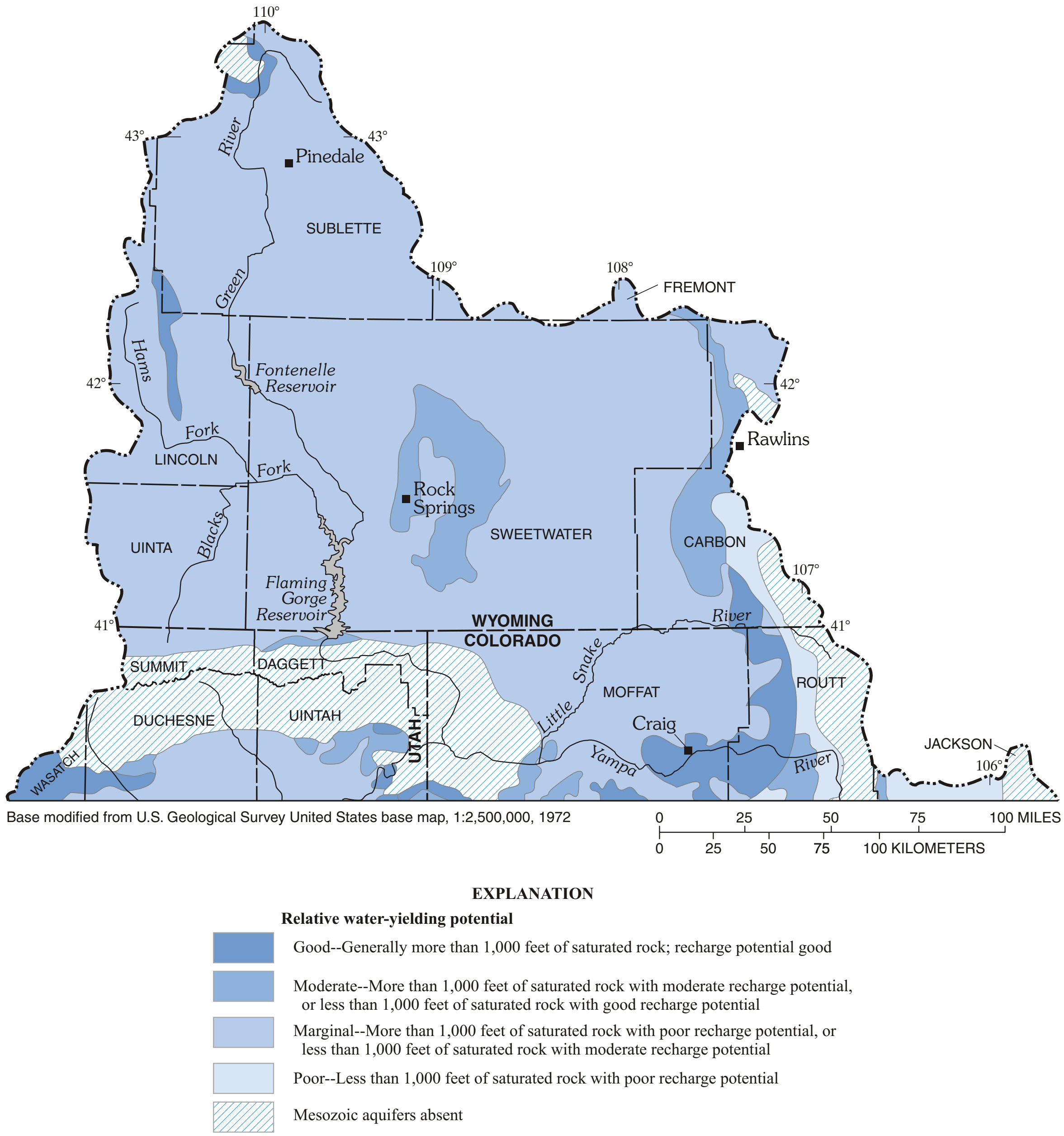


Figure 5-47. Regional water resources in Mesozoic rocks as defined by saturated thickness and recharge potential in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

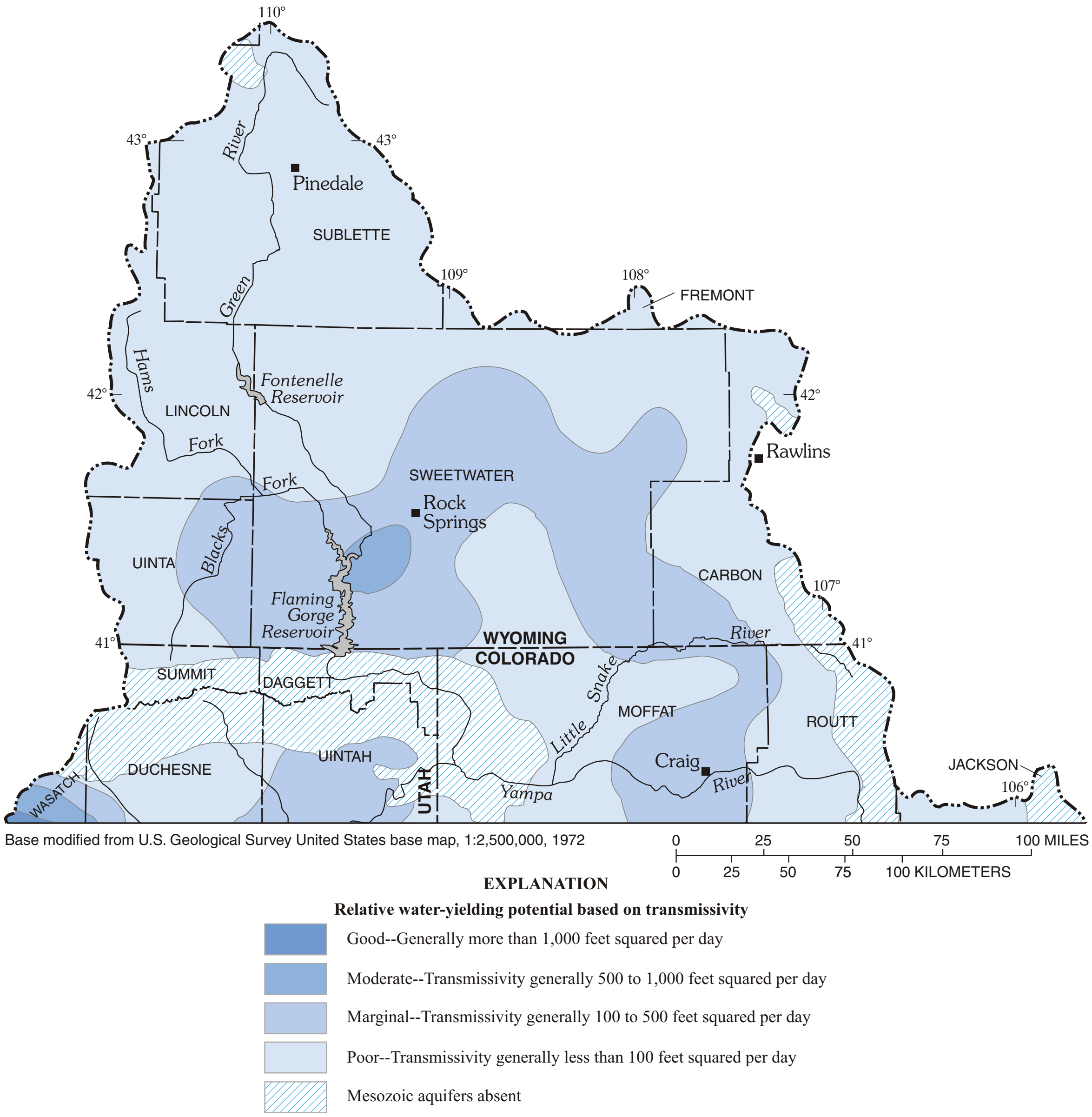


Figure 5-48. Regional water resources in Mesozoic rocks as defined by estimated aggregate transmissivity in the Greater Green River Basin and adjacent areas to the south. *Modified from Freethey and Cordy (1991).*

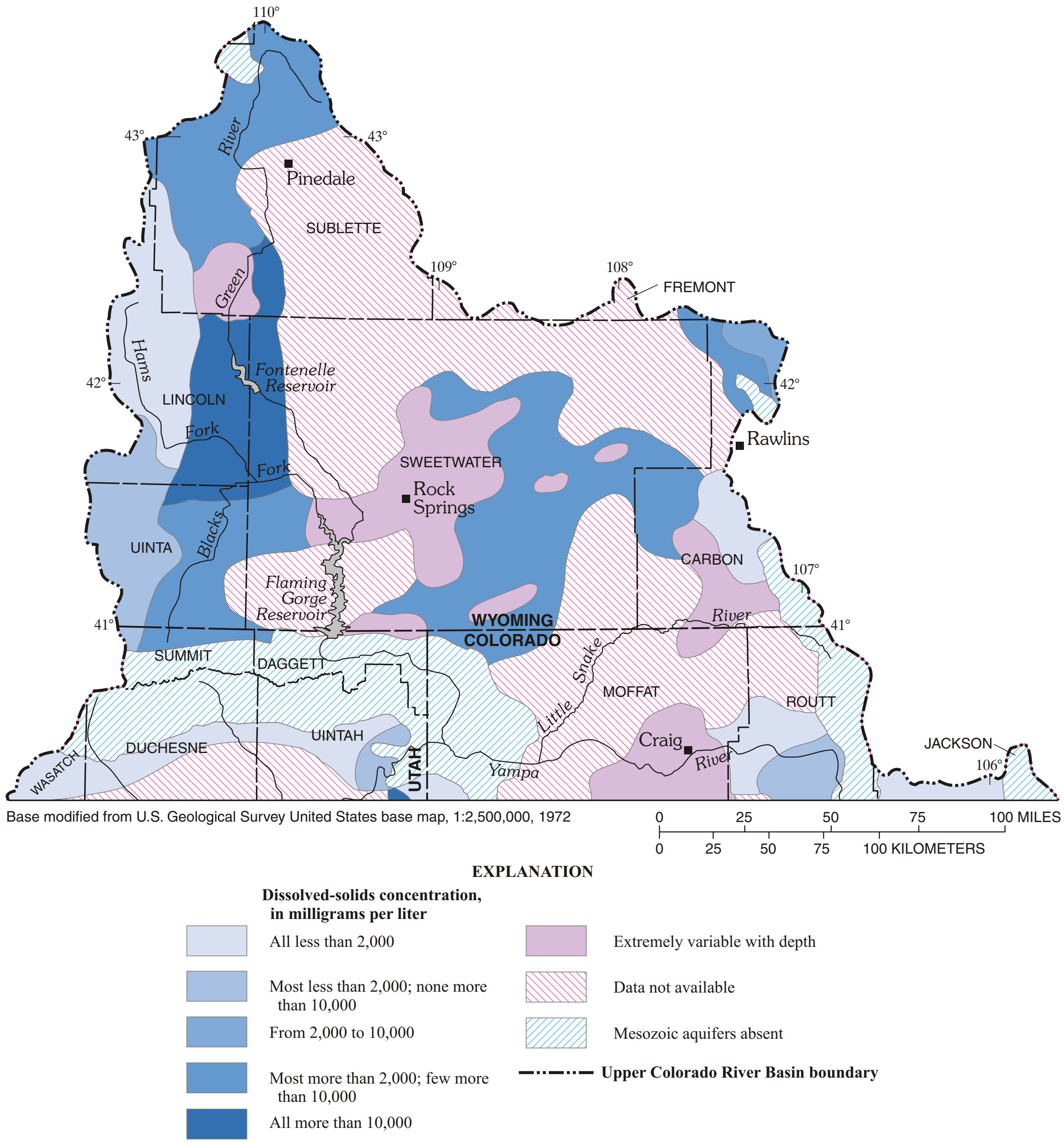


Figure 5-49. Generalized quality of water in Mesozoic rocks in the Greater Green River Basin and adjacent areas to the south, based on the concentration of dissolved solids. *Modified from Freethey and Cordy (1991).*

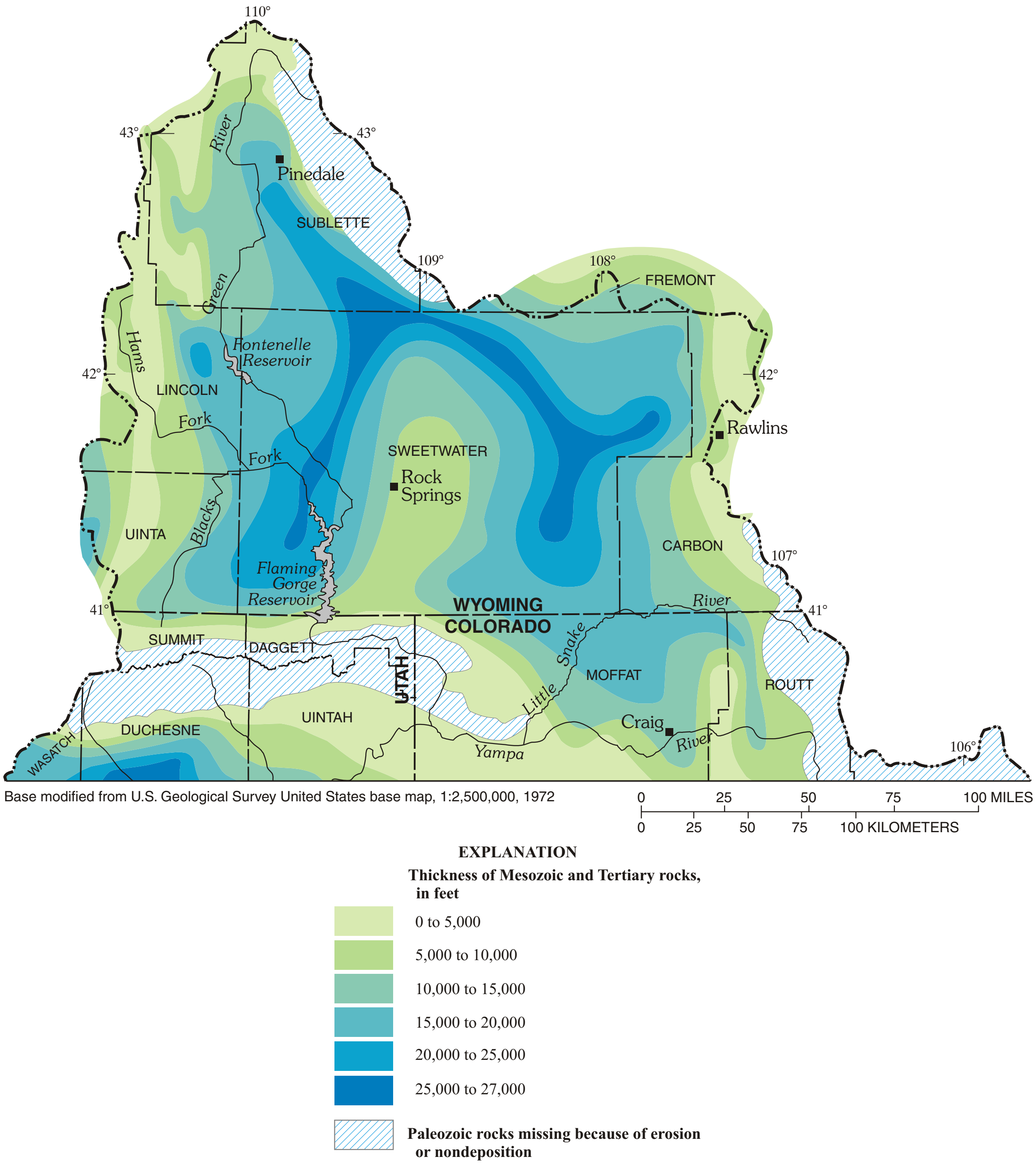


Figure 5-50. Thickness of Mesozoic and Tertiary rocks above the Paleozoic rocks in the Greater Green River Basin and adjacent areas to the south. *Modified from Geldon (2003b).*

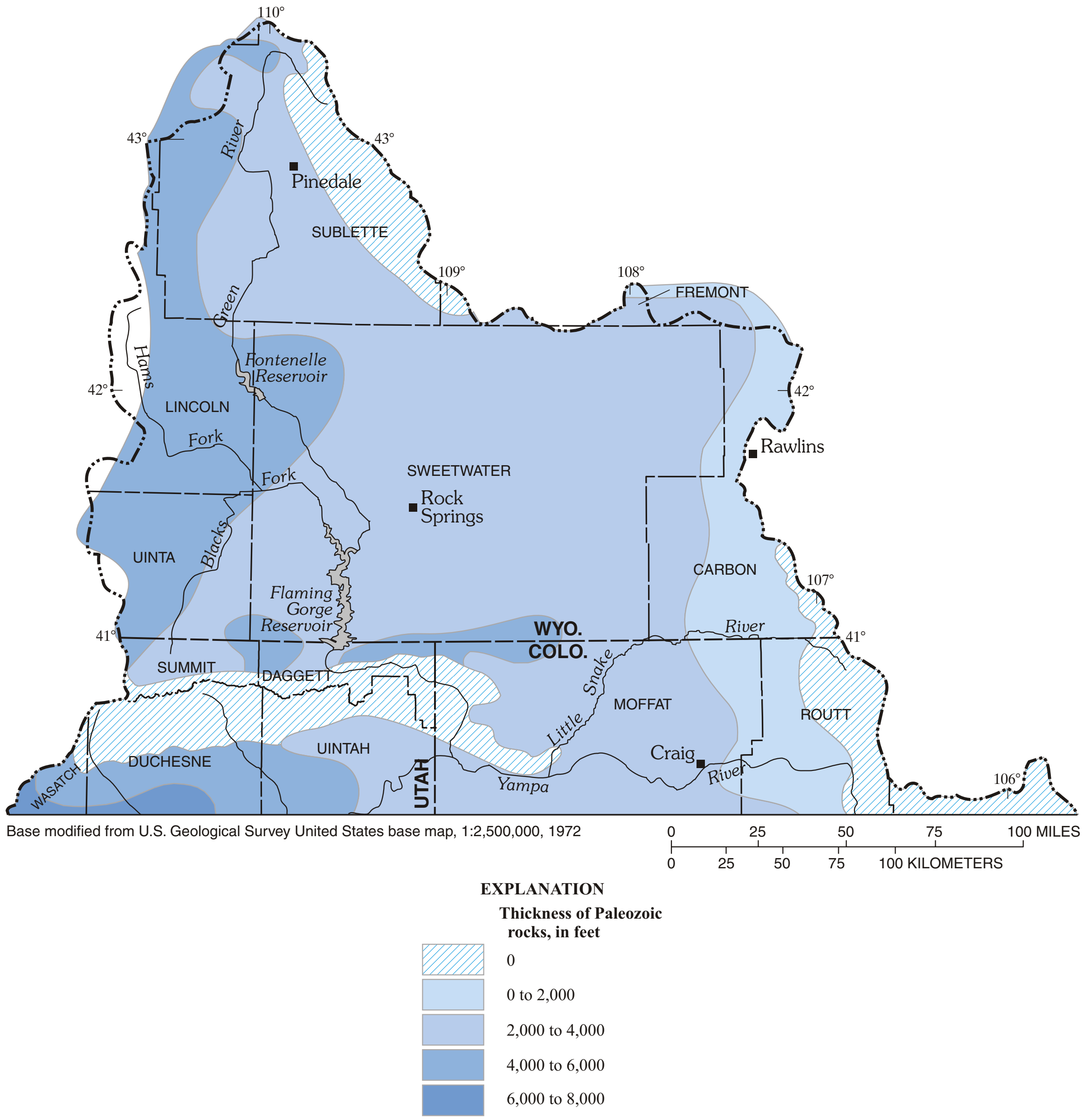


Figure 5-51. Distribution and thickness of the Paleozoic rocks in the Greater Green River Basin and adjacent areas to the south. *Modified from Geldon (2003b).*

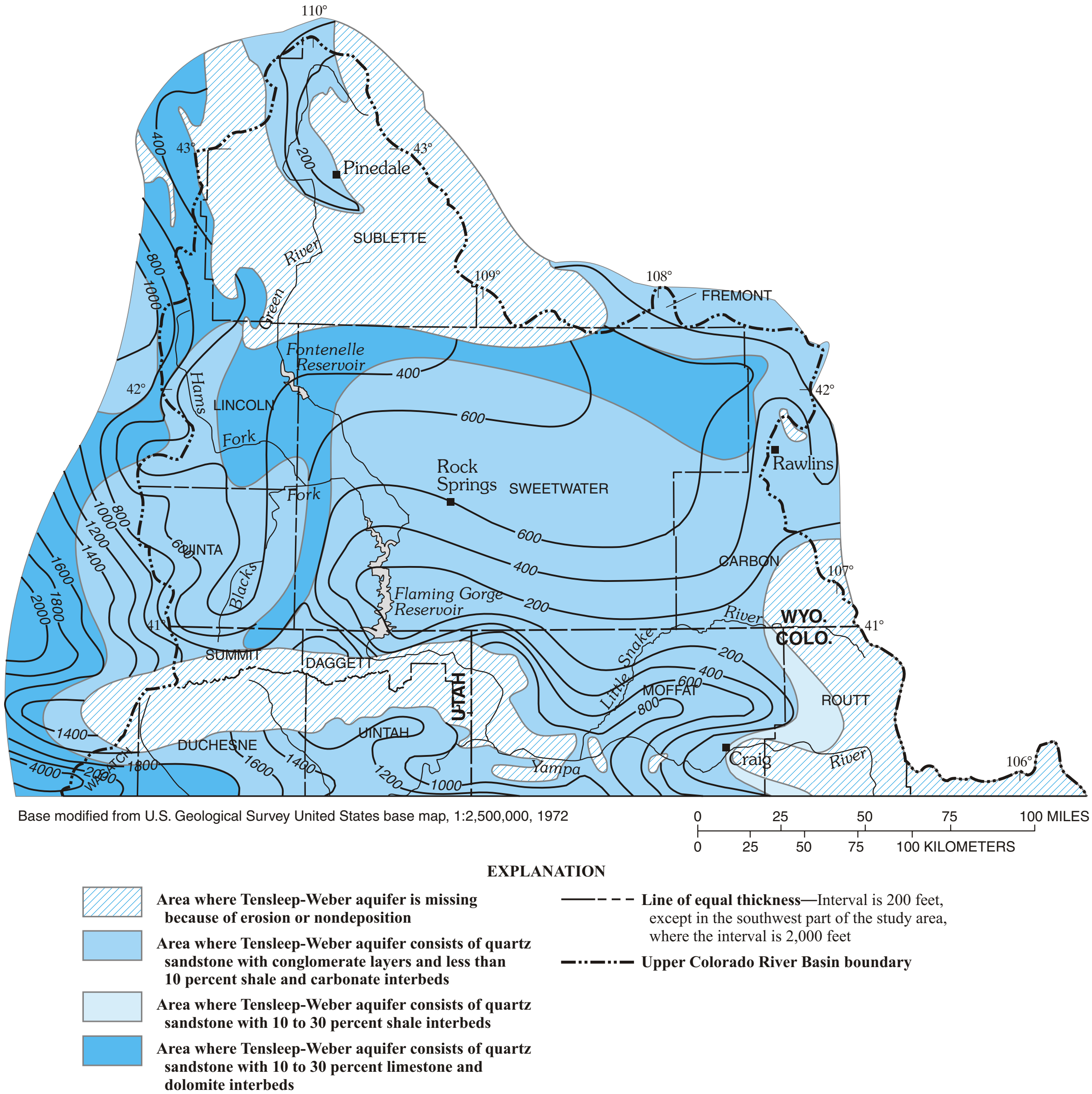


Figure 5-52. Thickness and lithology of the Tensleep-Weber aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Geldon (2003a,b).*

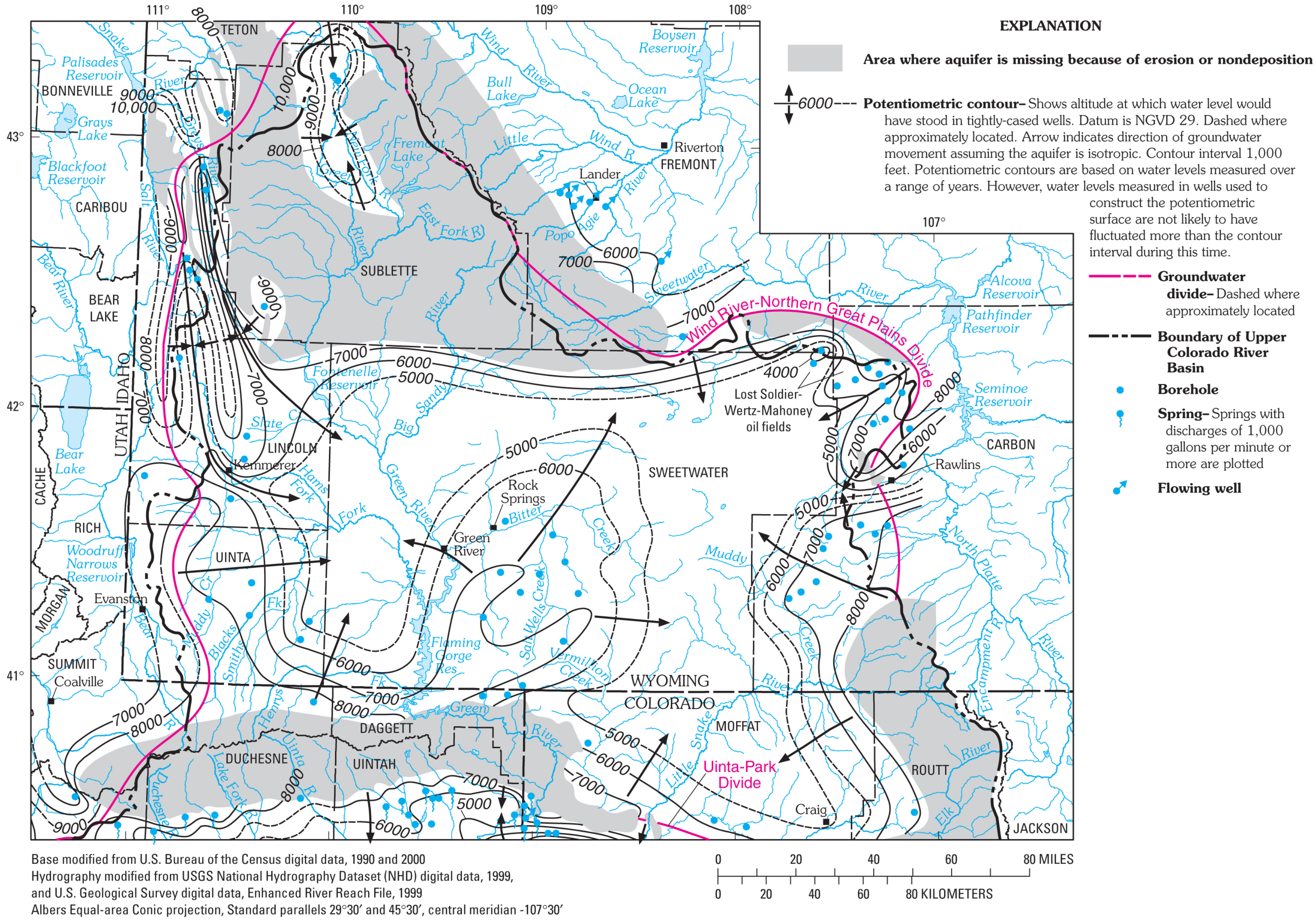


Figure 5-53. Potentiometric surface of the Tensleep-Weber aquifer in the Greater Green River Basin and adjacent areas. *Modified from Geldon (2003b).*

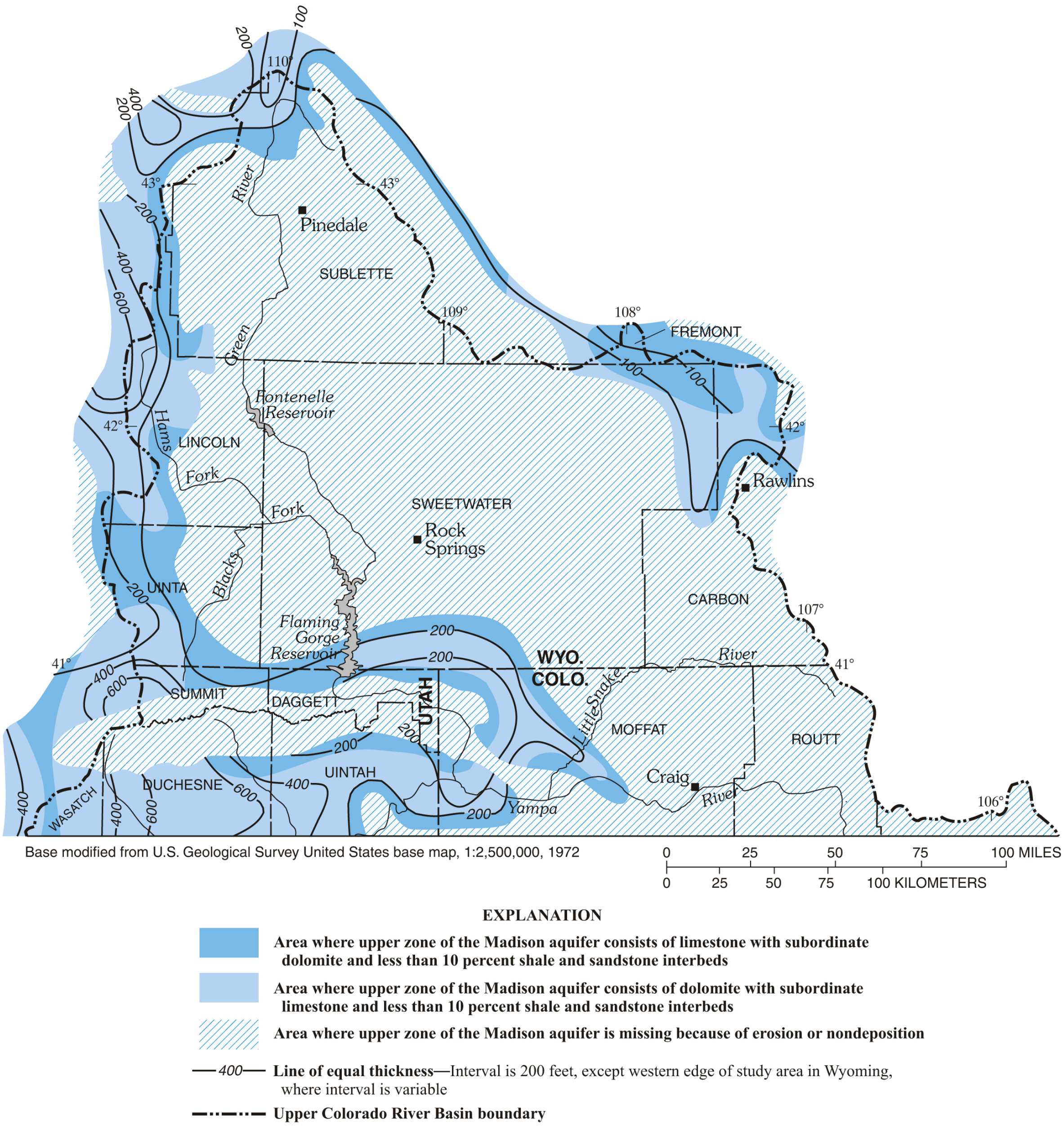


Figure 5-54. Thickness and lithology of the upper zone of the Madison aquifer in the Greater Green River Basin and adjacent areas. *Modified from Geldon (2003a,b).*

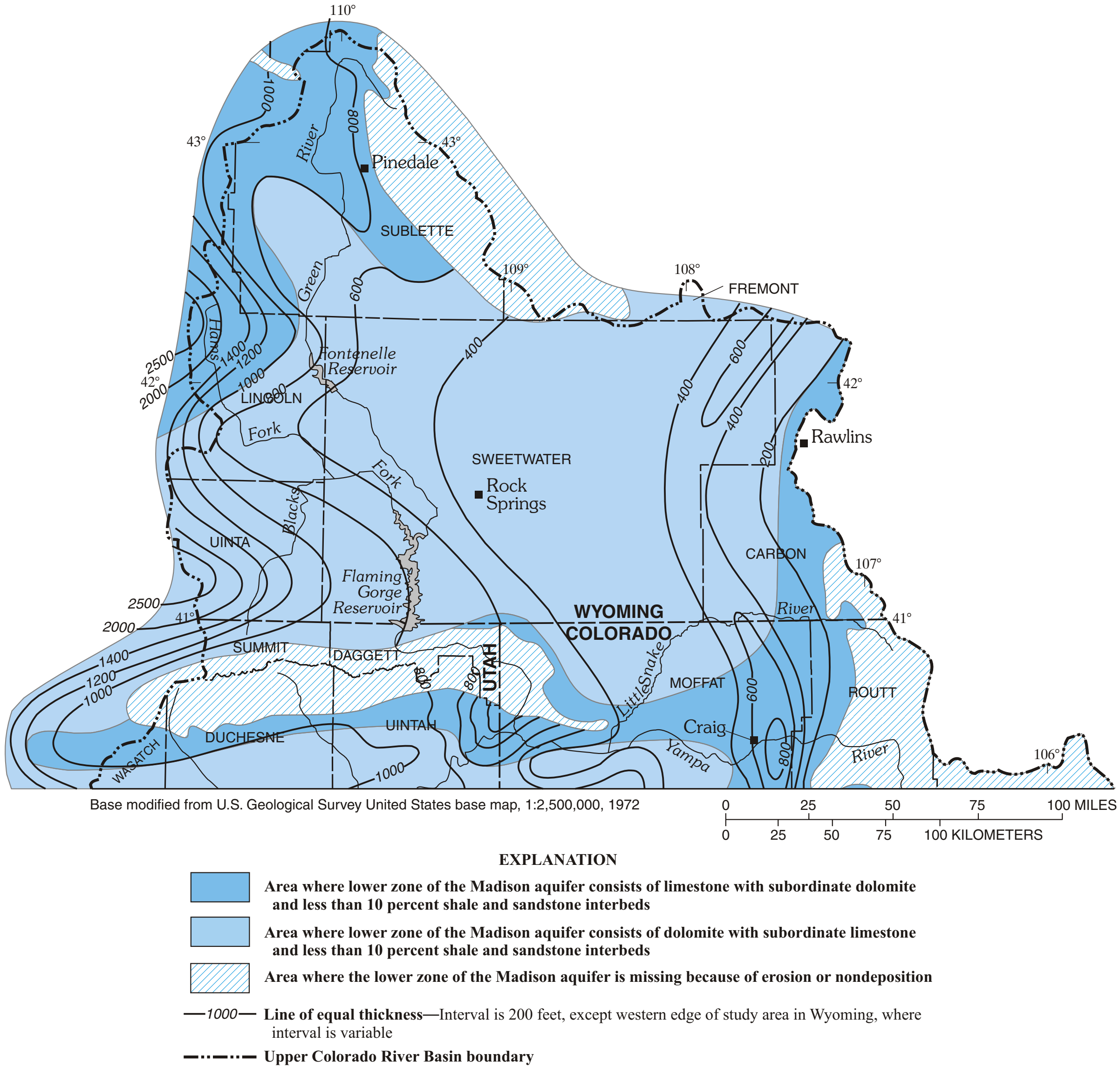


Figure 5-55. Thickness and lithology of the lower zone of the Madison aquifer in the Greater Green River Basin and adjacent areas. *Modified from Geldon (2003a,b).*

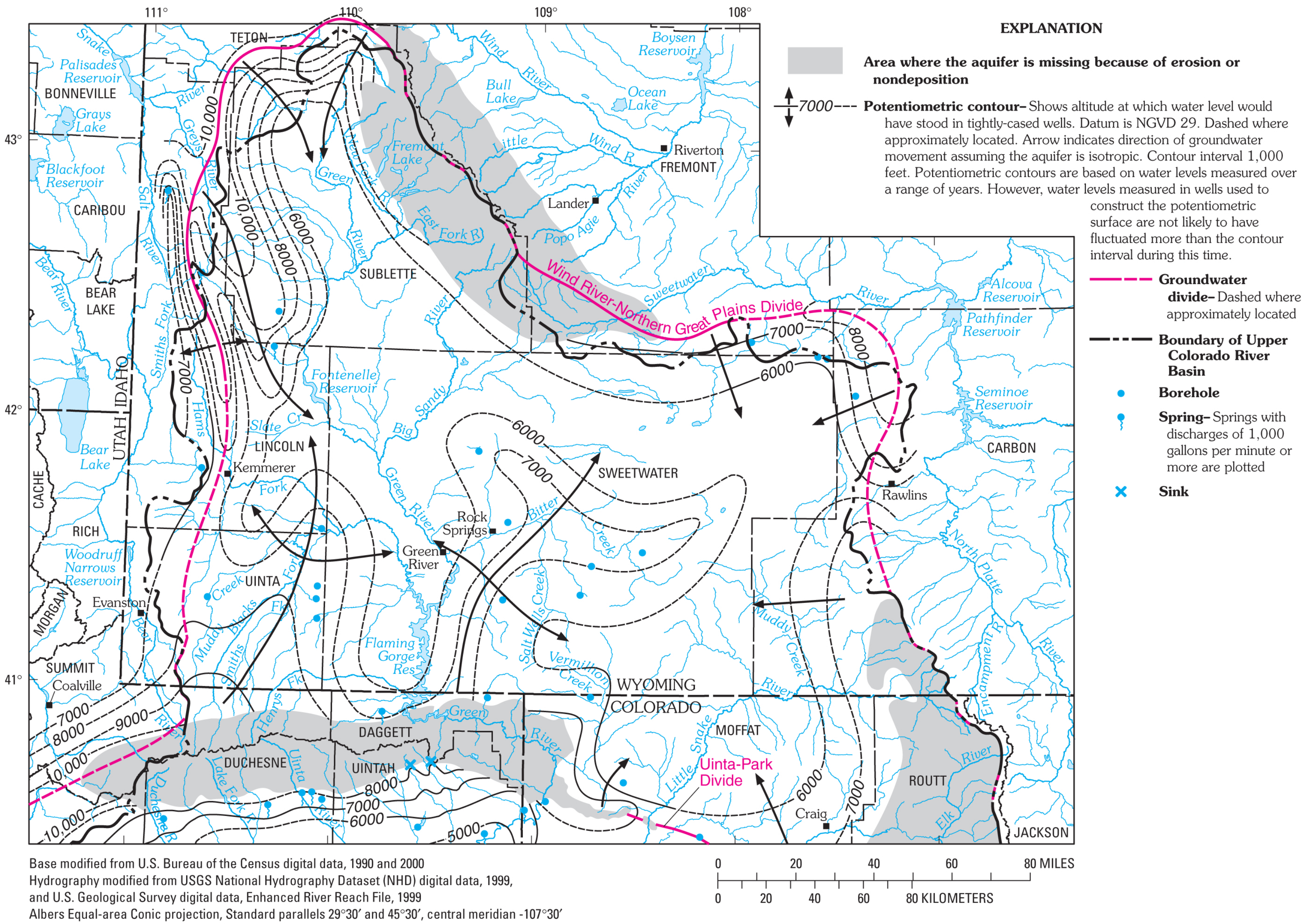
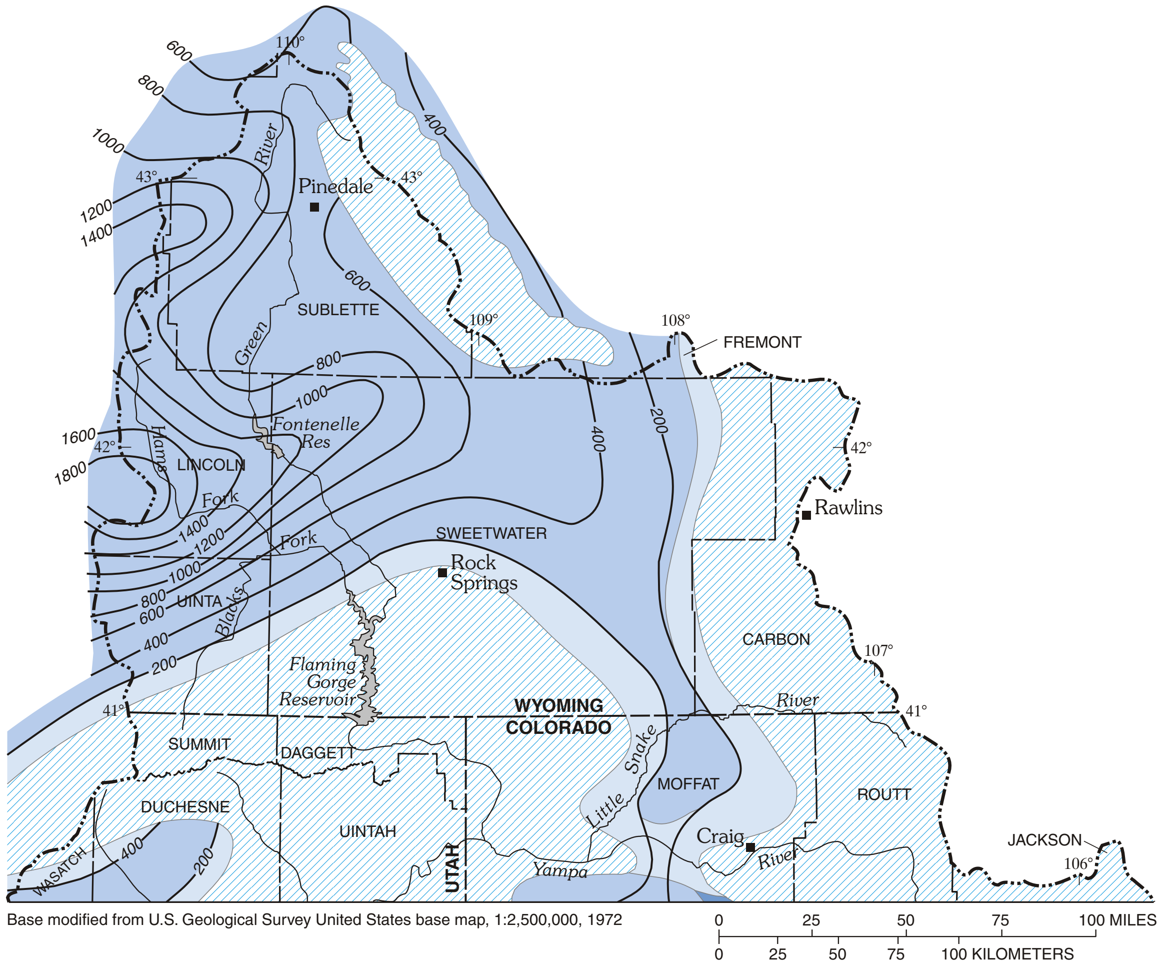


Figure 5-56. Potentiometric surface of the Madison aquifer in the Greater Green River Basin and adjacent areas to the south. *Modified from Geldon (2003b).*



EXPLANATION

Area where Bighorn aquifer consists of limestone and dolomite with subordinate shale interbeds

Area where Bighorn aquifer consists of limestone and dolomite with less than 20 percent shale and sandstone interbeds

Area where Bighorn aquifer consists of limestone and dolomite with subordinate sandstone and shale interbeds

Area where Bighorn aquifer is missing because of erosion or deposition

200 **Line of equal thickness**—Interval is 200 feet

Figure 5-57. Thickness and lithology of the Bighorn aquifer in the Greater Green River Basin and adjacent areas. *Modified from Geldon (2003a,b).*

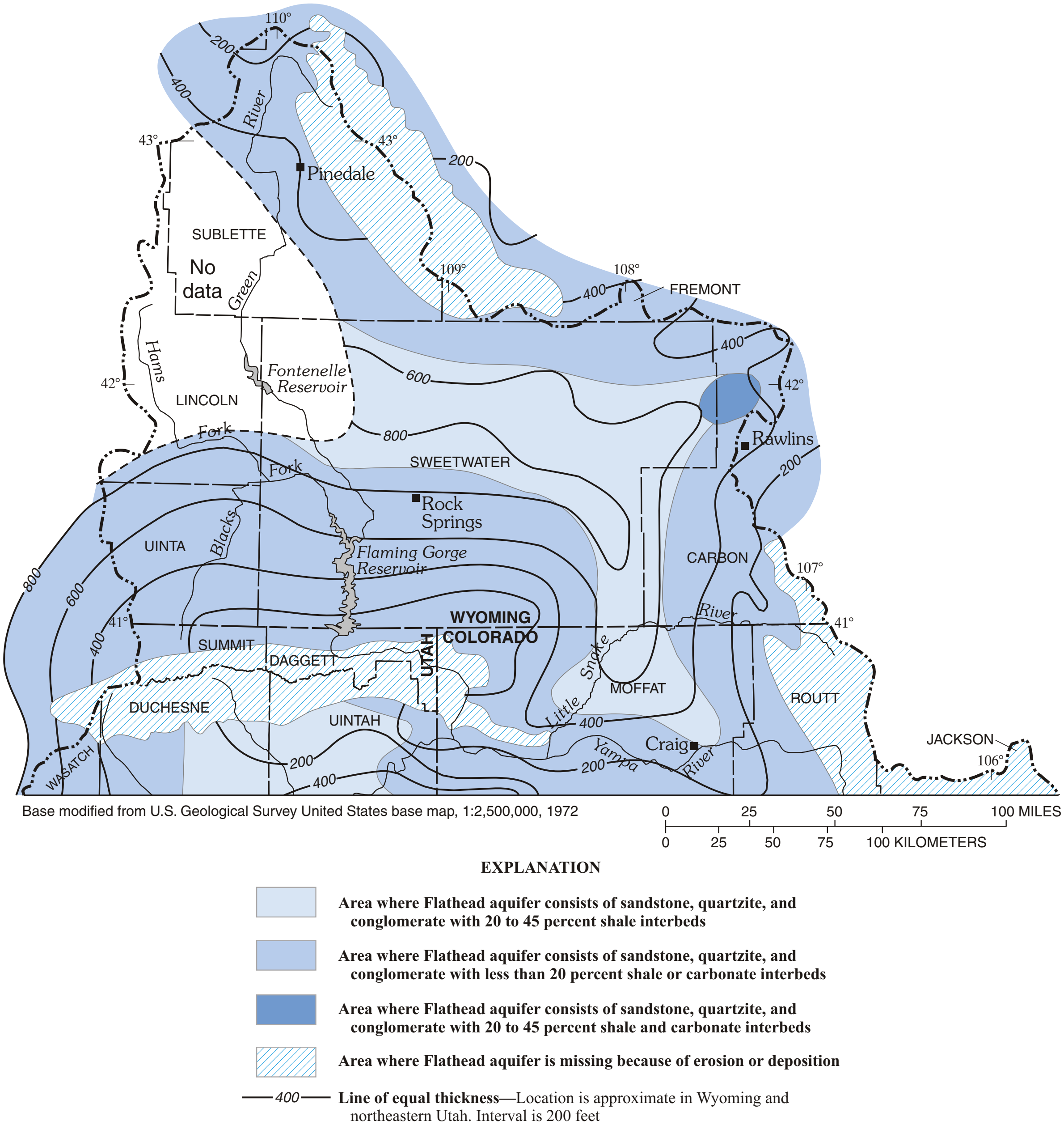


Figure 5-58. Thickness and lithology of the Flathead aquifer in the Greater Green River Basin and adjacent areas. *Modified from Geldon (2003b).*

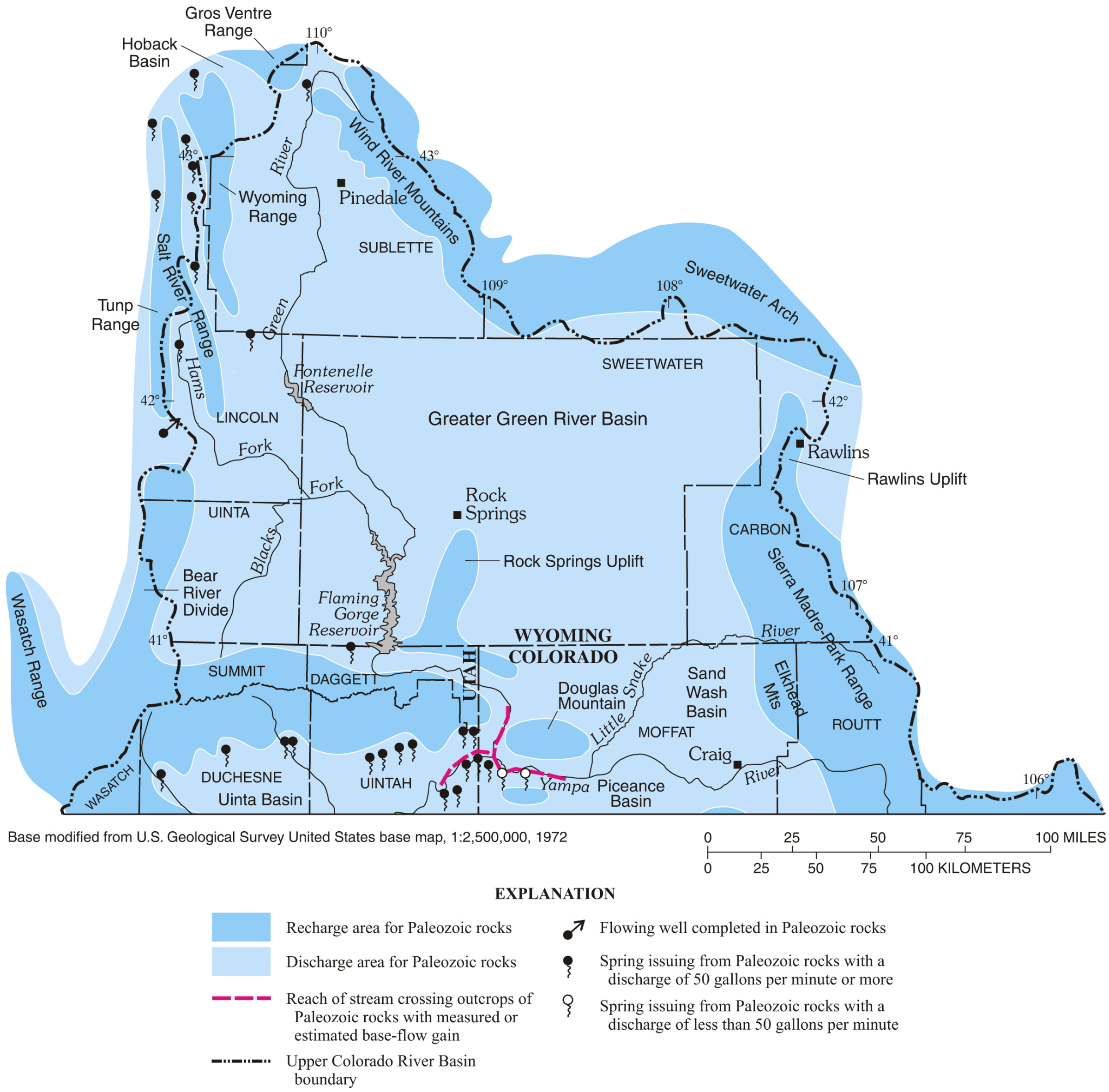


Figure 5-59. Recharge and discharge areas for Paleozoic rocks in the Greater Green River Basin and adjacent areas. *Modified from Geldon (2003b).*

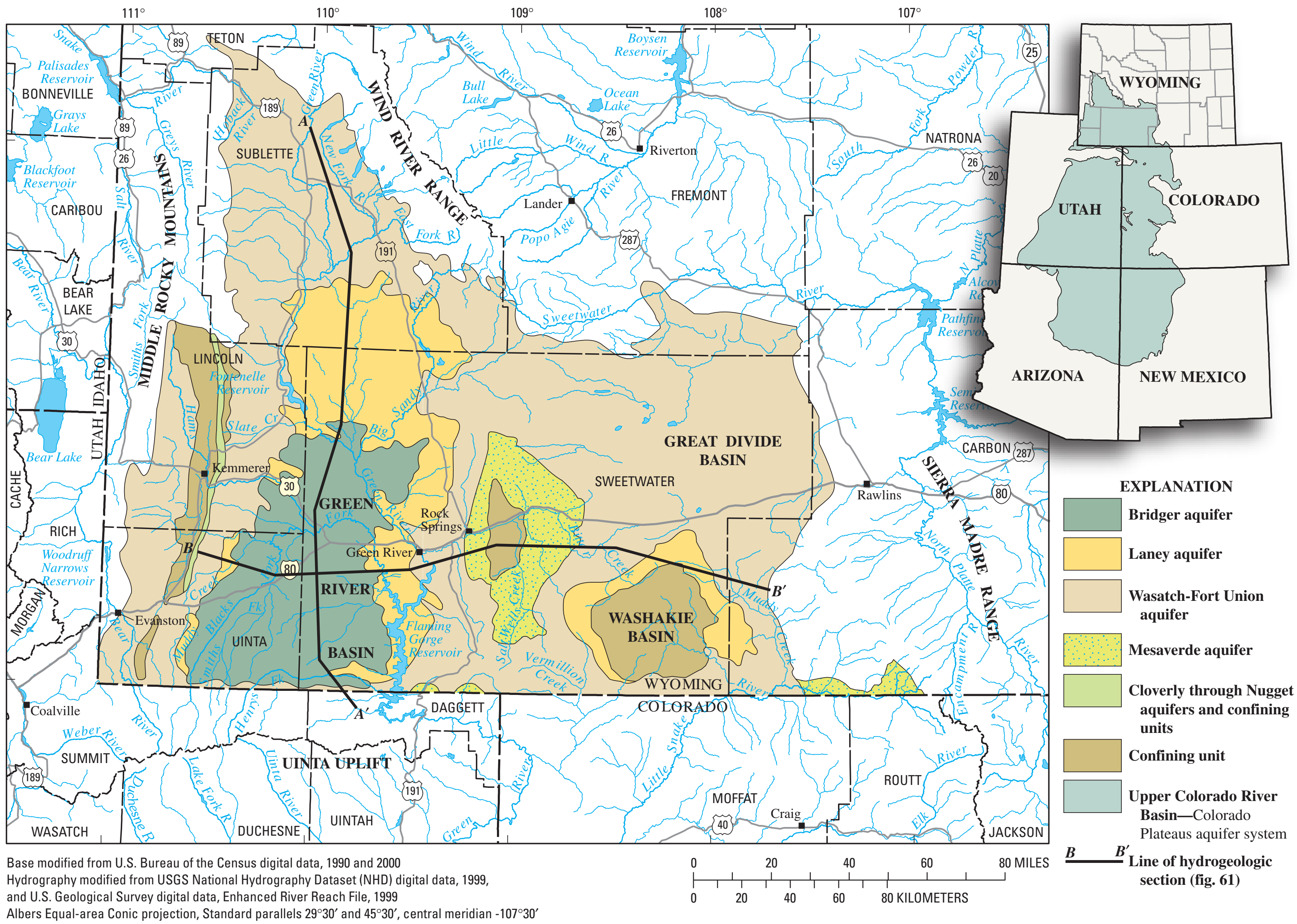


Figure 5-60. Drainages, structural basins, and uplifted mountainous areas in the Wyoming Greater Green River Basin and adjacent areas. *Modified from Love and Christiansen (1985); Roehler (1992a); and Whitehead (1996).*

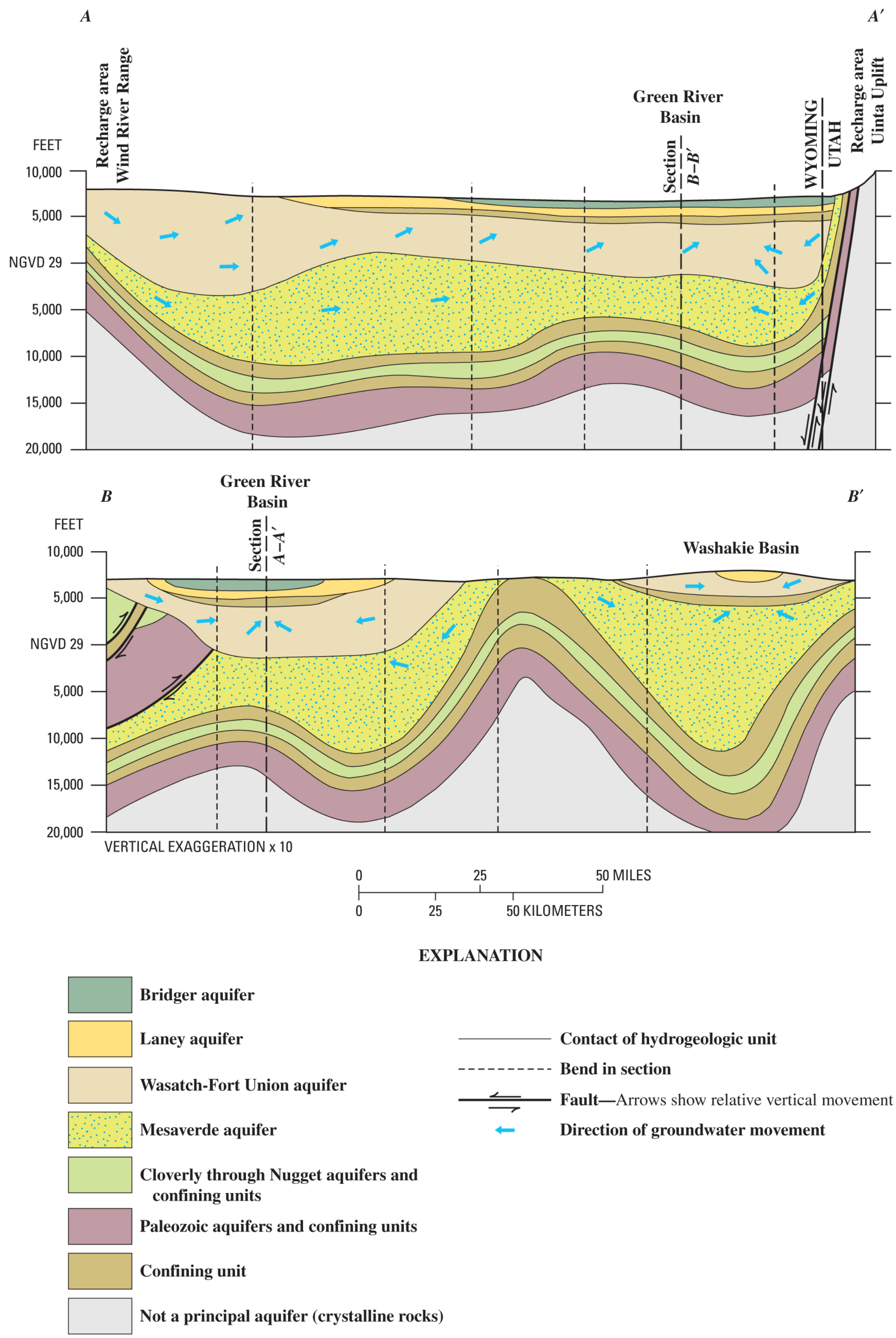


Figure 5-61. Movement of groundwater from aquifer recharge areas toward basin centers in the Greater Green River Basin and adjacent areas. Lines of hydrogeologic section shown on Figure 5-60. *Modified from Freethey et al. (1988), Geldon (1988b), Lowham et al. (1985), Glover et al. (1998), and Whitehead (1996).*