Chapter 3
Groundwater resources

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The water resources of Wyoming comprise surface water, groundwater, precipitation (rain, sleet, and snow), snow fields, ice fields, glaciers, and water vapor in the atmosphere. Wyoming's water is used beneficially for agriculture (crop irrigation and livestock watering), domestic supply (private household wells), public water system supply, lawn/garden watering, fish hatching/rearing, environmental purposes (groundwater remediation and monitoring), electric power generation, recreation, and many industrial purposes. At present, data on aquifer recharge rates, groundwater flow rates, aquifer discharge rates, degree of subsurface inter-aquifer hydraulic connection, and total amount of groundwater available for development in the GGRB are sparse relative to the great area and stratigraphic complexity of the basin. This chapter introduces our present assessment of the quantity and quality of groundwater available in the Wyoming GGRB.

The water resources of Wyoming are constitutionally the property of the state. The Wyoming State Engineer's Office (WSEO) regulates beneficial use of both surface water and groundwater. A WSEO permit is issued for use of state water: for example, a groundwater-use permit for a water well or spring.

The Wyoming Department of Environmental Quality, Water Quality Division (WDEQ-WQD) regulates both surface water and groundwater quality within the state to protect public health and the environment. The WDEQ-WQD issues permits to regulate activity involving water resources. A permit is required to discharge water into state waters.

The Denver office of the U.S. Environmental Protection Agency (USEPA) Region 8 has primary control (primacy) over Wyoming's public drinking water supplies. Wyoming is the only state in the U.S. where USEPA has primacy over drinking water systems. The USEPA monitors water quality for the several hundred public water systems located in Wyoming (see Chapter 6). Information about Wyoming's public drinking water systems is available on the USEPA Wyoming Drinking Water Web site,

http://www.epa.gov/safewater/dwinfo/wy.htm

The old saying, "Whiskey's for drinking, water's for fighting about," attributed to Mark Twain, applies to water resources in the American West. The West's water is renewable, but commonly limited in renewable volume. Annual precipitation is the ultimate source of both surface water and groundwater. Variations in the amount and distribution of annual precipitation may create water shortages in areas of high demand. Population growth has increased demand and competition for Wyoming's water resources, both within the state and in downstream states.

In the Greater Green River Basin (GGRB) of Wyoming, both unconsolidated deposits and bedrock formations contain groundwater resources in aquifers ranging in geologic age from Quaternary to Precambrian (**Figures 3-1** and **3-2**). The quality and quantity of GGRB groundwater available from the many geologic units that compose the Green River, Great Divide, Washakie, and Sand Wash basins varies widely.

In outcrop areas, shallow groundwater in bedrock formations generally is unconfined. Deeper in the structural basins, groundwater generally is confined by low-permeability strata that sandwich the permeable aquifer beds (sandstone, coal, and limestone/dolomite beds). Confined (artesian) groundwater in some areas of the GGRB flows at the surface from wells, where confining pressure head (height) is greater than the land surface elevation.

Within the GGRB and on the flanks of adjacent uplifts, most of the water-saturated portions of the geologic bedrock formations and unconsolidated deposits may yield groundwater to wells. However, many low-permeability geologic units in the GGRB yield very small quantities of low-quality groundwater, which may not be usable or economically viable for some uses.

Locally, groundwater is under unconfined (water table) conditions (1) on the flanks of uplifts in and near outcrop of otherwise deeply buried geologic units, and (2) in the central basin areas in geologic units (mostly of Cenozoic age) that lie at or near the land surface. Local shallow groundwater flow in the GGRB is generally controlled by topography

and stream drainage patterns: shallow groundwater (less than 300–500 feet below ground surface) flows following topography and discharges to streams and river drainages. Regional groundwater flow also generally follows topography and local stream drainages superimposed on the structural basin areas. The river drainages of the Wyoming GGRB are the Green, New Fork, Big Sandy, Hams Fork, Blacks Fork, Smiths Fork, Henry's Fork, and Little Snake (see **Figure 1-1**).

Groundwater flow within the bedrock formations of the GGRB is commonly structurally and stratigraphically controlled. An aquifer is generally contained within an interstratified sequence of high- and low-permeability sedimentary beds: groundwater is present in the open spaces in the geologic formations, and flows through permeable, interconnected pathways under sufficient head pressure. The GGRB aquifers are commonly heterogeneous and anisotropic in character on both local and regional scales.

Deep regional groundwater flows mostly through permeable formations and fractures *from* aquifer recharge areas (formation outcrops located along the margins of the structural basins) *toward* the axes of the structural basins and generally downgradient (downward in elevation) to the south-southwest into Utah. Discharge occurs along stream drainages as springs or as subcrop flow into overlying geologic units. The subcrop discharge of groundwater into alluvium along stream valleys helps maintain base flow in some reaches of the streams. The Great Divide Basin has internal drainage, and groundwater flows toward the center of the basin (**Figure 1-1**).

In summary, local, topographically controlled groundwater flow zones and outcrop areas are the primary areas of recharge to and discharge from the aquifers. Local groundwater flow, in areas where hills and uplands are higher in elevation than the local stream/river drainages, is dominated by these local topographic features. Local groundwater tends to flow downhill into nearby surface drainages. Complex interactions between surface water and groundwater occur among permeable beds of bedrock, unconsolidated deposits, and surface water drainages (typically lined with alluvial deposits). The groundwater and surface-water resources of the Wyoming GGRB are interconnected: springs, subcrop discharge flow to overlying geologic units, and pumping wells may all discharge groundwater to the surface.

The groundwater resources of the GGRB vary widely in occurrence, hydrogeologic characteristics, quantity, quality, and availability. In some parts of the basin, usable groundwater resources are difficult to nearly impossible to develop. In other areas of the basin, groundwater is the only reliable source of water. An aquifer that may produce good-quality, potable water at shallow depth (less than 1,000 feet deep) in the GGRB may produce petroleum (oil and conventional gas) from the same permeable zones deeper (more than 5,000 feet deep) in the structural basin.

Definitions

Aquifer – A formation, group of formations, or part of a formation that contains sufficient water-saturated, highly permeable material to yield significant quantities of water to wells and springs (modified from Lohman et al., 1972).

Aquifer system – A heterogeneous body of intercalated more permeable and less permeable material that functions regionally as a water-yielding hydrologic unit; it comprises two or more highly permeable aquifers separated at least locally by a less permeable confining unit that impedes groundwater movement but does not greatly affect the regional hydraulic continuity of the system (modified from Poland et al., 1972).

Confining unit – A formation, group of formations, or part of a formation, composed of low-permeability material, that is stratigraphically adjacent to an aquifer. In nature, the hydraulic conductivity of the confining unit may range from nearly zero to some value distinctly lower than that of an adjacent aquifer. Its conductivity relative to that of the aquifer it confines may be specified or indicated by a modifier such as *slightly* permeable or *moderately* permeable (modified from Lohman et al., 1972).

In this report, we use the terms *aquifer*, *water-bearing bed*, and *water-bearing unit* as they are currently used by the U.S. Geological Survey. In USGS usage, an individual water-bearing bed or unit is generally considered thinner and smaller in area than an aquifer. We also use the terms *confining unit* or *confining bed* because they are currently used by the USGS; the use of *aquitard*, an older synonym for *confining unit*, is declining.

Confining units are conventionally treated as impermeable to groundwater flow, but in reality, most confining units seep water at low to very low flow rates. Confined aquifers are overlain and underlain by confining units that limit groundwater flow out of the aquifer. Confined aquifers are under confining pressure or artesian pressure. The terms *semi-confined unit*, *semi-confining unit,* or *leaky confining unit* may be appropriate for beds or formations subject to sufficient seepage.

Aquifers and aquifer systems are generally anisotropic because of interbedded low-permeability confining beds or confining units (shale, claystone, mudstone, bentonite beds or lenses). Groundwater flow rates through permeable aquifers and confining units range from very high to very low. A high flow rate through a gravel-rich, highly permeable deposit may exceed 100 centimeters per second (cm/s) [3.3 feet per second (fps) or 2.9×10^5 feet per day (feet/day)]. A low flow rate within a clay-rich, low-permeability deposit may be less than 10^{-9} cm/s [3.3×10^{-11} fps or 2.9×10^{-7} feet/day]. Although flow rates could thus conceivably vary by as much as 11 or 12 orders of magnitude, the flow of water through an aquifer is typically several orders of magnitude faster than the flow through an adjacent confining bed or unit.

Unconfined aquifers are water-saturated parts of geologic units where groundwater is under atmospheric pressure. The commonly used term *water table,* synonymous with the hydrologic terms *groundwater surface* or *potentiometric surface*, denotes the top surface of the unconfined aquifer. The term *water table* implies a flat, horizontal groundwater surface, but an actual groundwater (potentiometric) surface is generally tilted or contoured like a topographic land surface. Conceptually, groundwater flow (like surface flow, the result of potentiometric-surface relief) is generally topographically controlled – as described above.

The slope of the groundwater surface defines the *hydraulic gradient*; it has both direction and magnitude, and is commonly expressed in feet of elevation change per foot of horizontal distance (feet/foot). The direction of slope from high to low elevation indicates the potential direction of groundwater flow, provided permeable interconnected pathways exist to allow such flow. Steep hydraulic gradients are common in low-permeability geologic units, and shallow to nearly flat hydraulic gradients are common in high-permeability units.

Perched water or *perched aquifer* refers to unconfined groundwater lying on top of a confining bed (it is the same as ponded (trapped) groundwater). Perched groundwater is located above deeper aquifers that may be either unconfined or confined. The saturated thickness of a perched groundwater zone may range from a few inches to more than 10 feet.

Groundwater flows in aquifers as porous flow, conduit flow, fracture flow, or a combination of these flow types.

- *Porous flow* – water moving through interconnected, open, intergranular/intercrystalline pore spaces within a rock unit (conglomerate, sandstone, siltstone, limestone, or dolomite bedrock, or unconsolidated mixture containing loose gravel, sand, silt, and clay). The size of the sediment grains or mineral crystals influences flow rate through pore spaces. Larger open pore spaces between larger grains/crystals allow greater flow due to less friction, the result of lower surface-area-to-volume ratios. In a mixed deposit with clay to gravel grain sizes, greater amounts of fine-grained matrix in the pore spaces reduces permeability and flow.

- *Conduit flow* – water moving through large discrete open spaces (such as pathways, pipes, cavities, channels, caves, or karstic zones) within a rock unit (normally limestone or dolomite). Conduits may form by the dissolution of soluble minerals in a rock unit or by subsurface sediment

transport (piping) through a loosely consolidated formation.

• *Fracture flow* – water moving through interconnected fractures within a geologic unit. The fractures are created by structural deformation – folding, faulting, jointing (cleating in coal) across or along bedding planes – or physiochemical alteration (bedrock weathering, soil formation).

Groundwater flows from areas of higher pressure (greater hydraulic head, higher elevation) to areas of lower pressure (lesser hydraulic head, lower elevation). However, groundwater flows in directions inferred from potentiometric surface maps only if permeable pathways exist to allow such flow.

Pumping water from a well causes groundwater to flow toward the well. During pumping, the water level in the pumping well deepens, correspondingly lowering the water pressure locally in the aquifer(s) surrounding the well (zone of influence). After pumping stops, the water level in the well rises back approximately to a static (non-pumping) level. The rate of water-level decline or rise in a well between pumping and non-pumping periods provides data useful for determining the hydrologic properties of the well and the aquifer system.

Groundwater flow to a pumping well may be either laminar or turbulent. Most natural and artificial groundwater flow is laminar: flow along a relatively straight path through the aquifer and into the well. A few examples of turbulent flow exist in nature, where groundwater cascades and roils through a subsurface bedrock formation or an unconsolidated deposit. Wells may be subject to turbulent flow when pumped at higher discharge rates than the maximum rate at which an aquifer will yield laminar-flowing water to the well. Turbulent flow may mobilize sediment within the aquifer, causing it to enter the pumping well, resulting in production of pebbly, sandy, silty, clayey, or muddy (highly turbid) water. In a pumping coalbed natural gas well, turbulent flow may yield abundant coal fines in the produced water.

Other groundwater-related definitions are listed below.

• *Water table* – an old term: the groundwater surface within an unconfined aquifer. In popular usage, the water table is the first, shallowest occurrence of unconfined or confined groundwater below the ground surface; technically, this may be inaccurate.

• *Potentiometric surface* – a theoretical and conceptual surface that represents the static head pressure of groundwater and replaces such older terms as *piezometric surface* and w*ater table*. A synonym is *groundwater surface*. The potentiometric surface is expressed in terms of elevation in feet above mean sea level (feet-msl).

• *Static head or static water level* – the level of water in a well when the well and surrounding wells are not being pumped and the groundwater in the aquifer is at rest, not flowing toward the well. Static head or level is commonly expressed in feet, as depth below land surface (or below a conventional reference level such as a kelly bushing or drill floor, correlated to land surface). Also, the static head or level may be converted to elevation in feet above mean sea level (feet-msl).

• *Drawdown* – the lowering of the groundwater (potentiometric) surface artificially (well pumping) or naturally (seasonal variations, annual variations, drought). Drawdown is expressed in feet of water-level change. A rise in groundwater level is the opposite of drawdown.

• *Gaining stream* – a stream, or reach (part of a stream), in which the discharge of groundwater from the geologic unit(s) underlying (or adjacent to) the stream adds to the surface-water flow of the stream.

• *Losing stream* – a stream, or reach (part of a stream), in which surface water leaks into the geologic unit(s) underlying (or adjacent to) the stream, recharging the groundwater and decreasing the surface-water flow of the stream.

• *Well yield* – a measure of the rate of groundwater discharge (pumped or flowing)

from a well, expressed in gallons per minute (gpm).

- *Porosity* – the proportion of open-space volume (pores, pipes, conduits, voids, or fractures) with respect to the total volume of an earth material (soil, unconsolidated deposit, or bedrock), expressed as a percentage.

- *Permeability* – a measure of the amount of water flowing through the interconnected open spaces of an aquifer or aquitard, expressed in gallons per day per square foot (gpd/ft^2).

- *Specific capacity* – the pumping discharge rate of a well divided by the feet of drawdown of the water level measured in the well during pumping, expressed in gallons per minute per foot of drawdown (gpm/ft).

- *Specific yield* – the drainable porosity, reported as the volume of water that will drain under gravity from a total volume of earth material (alluvium), expressed as a proportion (percent). Specific yield is appropriately calculated only for unconfined aquifers, such as alluvial deposits.

- *Transmissivity* – the rate at which groundwater of the prevailing kinematic viscosity is moving through a unit width of the water-saturated portion of the aquifer under a unit hydraulic gradient, expressed in gallons per day per foot (gpd/ft).

- *Total dissolved solids (TDS)* – a measure of the concentration of dissolved chemical species (mineral salts). TDS is generally expressed as either milligrams per liter (mg/l) or parts per million (ppm).

- *Geochemical water type* – an expression of the dominant cations and anions dissolved in the groundwater.

The availability of a groundwater resource depends on the quantity, quality, and depth of the water, and on its intended use. These factors also determine the cost of developing the resource, and if the groundwater cannot be developed economically, the resource will not be used. Groundwater quality depends primarily on the natural geochemistry of the water, the result of a variety of geologic factors; in addition, groundwater may be contaminated through human activity.

An unknown number of water wells may have connected various aquifers and water-bearing zones by perforating through confining units separating the aquifers. Some of these wells may have been improperly completed or incompletely plugged and abandoned, which has allowed water to leak through the well boreholes from one aquifer to another.

In general, groundwater quality in the GGRB decreases with depth and with distance from outcrop. Also, permeability generally decreases with depth, because compaction increases with greater bedrock thickness and heavier lithostatic load with depth, and because infilling of open pore spaces by mineral cements increases with depth. Chapter 6 of this memorandum provides a detailed discussion of the highly variable quality of groundwater in the aquifers and other hydrogeologic units in the GGRB.

Hydrogeologic unit classification

A stratigraphic stack of geologic formations within the GGRB forms a chronological sequence with the oldest rock unit on the bottom and the youngest unit on top (**Plate 1a**). This geologic age-relationship holds true for any undisturbed basin sequence, following the Principle of Superposition as defined by Nicholaus Steno around 1669.

The hydrogeologic units – aquifers and confining units – within the GGRB comprise unconsolidated sedimentary deposits and consolidated (lithified) bedrock formations, ranging in age from Quaternary to Precambrian, that vary widely in lithology and water-bearing properties. In this memorandum, we group these hydrogeologic units on the basis of geologic eras and the stratigraphy of the sub-basins (**Plate 1b**; **Figure 3-1**).

The 2001 Green River Basin Water Plan groundwater technical memorandum (Hahn and Jessen, 2001) defined eight major water-bearing systems, in descending stratigraphic order:

1. Quaternary-age sands and gravels associated with major river courses
2. Tertiary-age aquifers
3. Mesaverde-Adaville aquifers
4. Frontier aquifer
5. Upper Jurassic-Lower Cretaceous-age aquifers
6. (Sundance-) Nugget aquifer system
7. Paleozoic-age aquifer system (including the Madison Limestone)
8. Flathead aquifer

In updating the 2001 memorandum, we redefined the elements of the GGRB groundwater regime to include all the hydrogeologic units in the basin, while combining some of the units of Hahn and Jessen (2001). We grouped all the aquifers and confining units in the basin on the basis of the four geologic eras – the Cenozoic, Mesozoic, Paleozoic, and Precambrian (**Figure 3-1**):

- Cenozoic hydrogeologic units (includes Hahn and Jessen groundwater systems #1-2)
- Mesozoic hydrogeologic units (includes Hahn and Jessen groundwater systems #3-6)
- Paleozoic hydrogeologic units (includes Hahn and Jessen groundwater systems #7-8)
- Precambrian hydrogeologic units (not identified by Hahn and Jessen)

This comprehensive classification allows inclusion of any geologic unit (listed in **Appendix 1** and shown on **Plate 2**) in one (or two) of the four groups based on the geologic eras. This approach applies across Wyoming, although discrepancies occur where there are combined time-transgressive units (for example, *Paleozoic-Mesozoic rocks*) or geologic units that cross time boundaries. Where this occurs in the GGRB, the thickest portion of a combined unit determined which hydrogeologic unit we assigned it to. This grouping of Wyoming GGRB hydrogeologic units also applies to the hydrogeologic units in the Colorado and Utah GGRB.

The four groups of hydrogeologic units are divided variously as described below, and shown in outcrop on **Figure 3-2**. The divisions are shown as hydrogeologic units and aquifer systems on **Plate 1b**. **Tables 3-1 and 3-2** show the outcrop areas of the four groups and their divisions in the Wyoming GGRB and in the whole GGRB, respectively. Geologic units in the older systems (Paleozoic and Precambrian) crop out only along the basin margins, on the mountain uplifts surrounding the basin.

The Precambrian rock units generally underlie all younger geologic formations at depth, and the Paleozoic formations generally underlie the Cenozoic and Mesozoic formations; there are exceptions, produced by folding and faulting.

The Cenozoic hydrogeologic units (outcrop on **Figures 3-1 and 3-3**) consist of the water-saturated portions of the unconsolidated deposits and consolidated bedrock formations of Quaternary age (Holocene and Pleistocene Epochs) and Tertiary age (Pliocene, Miocene, Oligocene, Eocene, and Paleocene Epochs). The Cenozoic group of hydrogeologic units is the most heavily used of the four groups in the GGRB.

The Quaternary hydrogeologic units (outcrop on **Figures 3-2 and 3-3**) in the GGRB consist mostly of unconsolidated deposits: alluvial, landslide, eolian, lacustrine, glacial, gravel, and terrace deposits – they are thus classified as geologic units in Chapters 2, 5, and 6 and in **Appendix 1**. Many of these Quaternary unconsolidated deposits are less than 50 feet thick, but some units may be more than 100 feet thick locally. The water-saturated portions of the sand, gravelly sand, and gravel beds of these Quaternary deposits yield groundwater to wells.

The Tertiary hydrogeologic units (outcrop on **Figures 3-2 and 3-3**) are divided into upper Tertiary and lower Tertiary hydrogeologic units. Tertiary sedimentary rocks contain the most abundant and widely used shallow aquifers in the GGRB. These Tertiary and overlying Quaternary rocks are exposed over about 83 percent of the Wyoming

Table 3-1. Map (outcrop) area percentages of hydrogeologic units in the Wyoming GGRB
[20,792 square miles total area]

Unit	*Area (square miles)*	*Area (percentage)*
Surface water and ice	104.0	0.50
Volcanic rocks (Mesozoic and Cenozoic)	8.4	0.04
Cenozoic hydrogeologic units	17,177.1	82.62
Quaternary hydrogeologic units	4,190.6	20.16
Upper Tertiary hydrogeologic units	774.0	3.72
Lower Tertiary hydrogeologic units	12,212.5	58.74
Mesozoic hydrogeologic units	2,504.3	12.04
Upper Cretaceous hydrogeologic units	1,962.3	9.44
Lower Cretaceous hydrogeologic units	179.5	0.86
Jurassic hydrogeologic units	181.8	0.87
Triassic hydrogeologic units	180.7	0.87
Paleozoic hydrogeologic units	181.6	0.87
Precambrian hydrogeologic units	816.2	3.93

Table 3-2. Map area (outcrop) percentages of hydrogeologic units in the GGRB of Wyoming, Colorado, and Utah
[24,613 square miles total area]

Unit	*Area (square miles)*	*Area (percentage)*
Surface water and ice	127.8	0.52
Volcanic rocks (Mesozoic and Cenozoic)	29.3	0.12
Cenozoic hydrogeologic units	19,772.1	80.33
Quaternary hydrogeologic units	4,689.4	19.05
Upper Tertiary hydrogeologic units	1,543.8	6.27
Lower Tertiary hydrogeologic units	13,538.9	55.01
Mesozoic hydrogeologic units	2,703.1	10.98
Upper Cretaceous hydrogeologic units	2,088.1	8.48
Lower Cretaceous hydrogeologic units	201.9	0.82
Jurassic hydrogeologic units	216.4	0.88
Triassic hydrogeologic units	196.7	0.80
Paleozoic hydrogeologic units	297.6	1.21
Precambrian hydrogeologic units	1,683.4	6.84

GGRB (**Figures 3-2** and **3-3**). The groundwater quality in the Tertiary aquifers varies widely, reflecting the highly complex stratigraphy and interfingering and intertonguing of the nonmarine Tertiary sedimentary rock units in the GGRB.

The upper Tertiary hydrogeologic units include the Miocene and Oligocene formations that crop out along the southern flank of the Wind River Range, the southern flank of the Rock Springs Uplift, and flanks of the Uinta Mountains and the Sierra Madre. These formations include Upper Miocene rocks (undivided), the Browns Park Formation, Miocene rocks (undivided), the Bishop Conglomerate, and the White River Formation. The upper Tertiary hydrogeologic units also include areas of the South Pass Formation and Split Rock Formation; however, these two units are not mapped as named units on the geologic map (**Plate 2**), but are included in the upper Tertiary geologic unit descriptions in **Appendix 1**. The Upper Tertiary aquifers yield water from the sandstone, conglomerate, and conglomeratic sandstone beds within the hydrogeologic units.

The lower Tertiary hydrogeologic units (outcrop on **Figures 3-2** and **3-3**) include the water-saturated portions of the Ice Point Conglomerate, Bridger Formation, Washakie Formation, Green River Formation, Wasatch Formation, Battle Spring Formation, Pass Peak Formation, Conglomerate of Roaring Fork, Hoback Formation, Devils Basin Formation, Fort Union Formation, Pinyon Conglomerate, and Evanston Formation. The combined thickness of these Paleocene-Eocene formations generally ranges between about 5,000 and 8,000 feet, with a maximum thickness estimated at more than 12,000 feet in the Wyoming Green River Basin.

The primary water-yielding beds in the lower Tertiary hydrogeologic units are sandstones, conglomeratic sandstones, conglomerates, and coal beds. The outcrop area of the Lower Tertiary hydrogeologic units is the largest within the GGRB. Most of the existing water wells in the GGRB yield water from the various interfingered members and tongues of the Green River and Wasatch Formations and their lateral equivalents, and the overlying Bridger and Washakie Formations.
The sandstone and conglomerate beds in the Battle Spring Formation form a shallow aquifer in the eastern Great Divide Basin (Collentine, et al., 1981). The interbedded and permeable sandstone beds in the upper part of the Laney Member of the Green River Formation form an aquifer in the western Washakie Basin (Collentine et al., 1981). In the Great Divide and Washakie basins, the sandstone beds of the Wasatch Formation are aquifers in the central basin areas, and the Fort Union sandstone beds are major aquifers near the basin margins (Collentine et al., 1981).

The Mesozoic hydrogeologic units (outcrop on **Figures 3-2** and **3-4**) consist of the water-saturated portions of the consolidated bedrock formations of Cretaceous, Jurassic, and Triassic age. This group is the second most used of the four groups in the GGRB. The Cretaceous hydrogeologic units are divided into the Upper Cretaceous and Lower Cretaceous hydrogeologic units. As shown in **Figure 3-4**, the central exposure on the Rock Springs Uplift consists of Upper Cretaceous formations, as do exposures on the western and eastern basin margins. Outcrop exposures of the Lower Cretaceous, Jurassic, and Triassic formations are limited to the margins of the GGRB. The combined thickness of the Mesozoic hydrogeologic units averages about 12,000 feet, with a maximum thickness estimated at 29,000 feet in the Wyoming GGRB.

The Mesozoic hydrogeologic units yield water mostly from the sandstone, conglomeratic sandstone, and conglomerate beds in the following formations (**Plate 1b**):

- The Upper Cretaceous Lance Formation, Fox Hills Sandstone, Adaville Formation, Blind Bull Formation, Sohare Formation, members of the Mesaverde Group, Bacon Ridge Sandstone, and Frontier Formation

- The Lower Cretaceous Sage Junction Formation, Quealy Formation, Cokeville Formation, Thomas Fork Formation, Smiths Formation, Bear River Formation, Gannett Group, Muddy Sandstone, and Cloverly Formation

- The Jurassic Morrison Formation, Sundance Formation, Stump Formation, Preuss Sandstone (Redbeds), and Jurassic (?) and Triassic (?) Nugget Sandstone

- The Triassic Chugwater Formation, Ankareh Formation, Woodside Shale, and Dinwoody Formation.

Some thin carbonate (limestone and dolomite) beds in the Morrison Formation, Twin Creek Limestone, Gypsum Spring Formation, Thaynes Limestone, and Alcova Limestone Member of the Chugwater Formation also yield water.

These Mesozoic aquifers yield water to wells within or close to formation outcrops (**Figure 3-4**). *Close to* formation outcrops is here defined as within a fraction of a mile for structural dips greater than 5°, or as much as 11 miles for structural dips between 1° and 5°. The sandstone beds of the Mesaverde Group members are important local aquifers where they are exposed on the Rock Springs Uplift (Collentine et al., 1981).

The Mesozoic hydrogeologic units also include these Cretaceous, regionally extensive, thick marine shale confining units:

- The Upper Cretaceous Lewis Shale (the youngest marine shale)

- The Upper Cretaceous Hilliard Shale, Blind Bull Formation, Baxter Shale, Cody Shale, Steele Shale, Niobrara Formation, and parts of the Mancos Shale in Colorado and Utah

- The Lower Cretaceous Aspen Shale, Upper Cretaceous Mowry Shale, and parts of the Lower-Upper Cretaceous Mancos Shale in Colorado and Utah

- The Lower Cretaceous Bear River Formation, Thermopolis Shale, and parts of the Lower-Upper Cretaceous Mancos Shale in Colorado and Utah.

The group of Paleozoic hydrogeologic units (outcrop on **Figure 3-1**) is the third most used of the four groups, and consists of the water-saturated portions of the bedrock formations of Permian, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian ages. In the Wyoming Green River Basin, the Paleozoic formations have a combined thickness averaging about 5,000 feet and a maximum thickness estimated at 9,800 feet.

As shown in **Figures 3-2** and **3-5**, the outcrop exposures of the Paleozoic formations occupy small areas of the western, northern, and southern margins of the GGRB, and of the Rawlins Uplift. The Paleozoic hydrogeologic units are accessible in or close to these outcrop areas along the basin margins and mountain flanks. Here again, *close to* means within a fraction of a mile for structural dips greater than 5°, or as much as 11 miles for structural dips between 1° and 5°. The Paleozoic aquifers produce water from the carbonate (limestone and dolomite) and sandstone beds within the hydrogeologic units.

The Precambrian hydrogeologic units (outcrop on **Figures 3-2** and **3-6**) consist of the water-saturated portions of formations ranging in age from Proterozoic to Archean. This group of hydrogeologic units is the least used of the four groups in the GGRB. The Precambrian rock units, ancient crystalline crustal rocks, generally underlie all other geologic formations at depth in the GGRB, and are exposed in the cores of the mountain uplifts surrounding the basin, particularly the Wind River Range, Uinta Mountains, and Sierra Madre. Wells and springs in the Precambrian hydrogeologic units are located within their outcrop areas. Where the Precambrian formations are buried beneath overlying geologic units, the Precambrian aquifers are not likely to yield usable quantities of water to wells.

Inferred regional groundwater flow patterns generally show flow from higher elevation areas toward the Green River or Little Snake River drainages. In the Great Divide Basin, the groundwater generally flows toward the center of the topographic basin.

Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering, 2007) presented a highly generalized aquifer classification for the entire state, and classified the following aquifers and confining

units in the Wyoming GGRB by geologic formation:

Major aquifer – Alluvial – Highly permeable sand and gravel beds in alluvial deposits located along rivers and streams – some of the highest-yield aquifers in the state. In areas where the deposits are thin or contain abundant clay, silt, or mud, productivity is greatly reduced.

- Quaternary alluvium (sand and gravel)

Major aquifer – Sandstone – Bedrock formations with mostly permeable sandstone and conglomerate lithologies, with the potential for development of large quantities of good-quality groundwater.

- Bridger Formation and Battle Spring Formation (sandstone and conglomerate)
- Wasatch Formation (sandstone and conglomerate)
- Fort Union Formation (sandstone)
- Mesaverde Formation or Group and related rock units (sandstone)
- Cloverly (Dakota) Formation (sandstone and conglomerate)
- Nugget Sandstone (sandstone)

Major aquifer – Limestone – Bedrock formations with mostly carbonate (limestone or dolomite) lithologies, with the potential to develop large quantities of good-quality groundwater.

- Tensleep Sandstone (sandstone and some carbonate)
- Madison Limestone and Bighorn Dolomite (carbonate)
- Flathead Sandstone (sandstone)

Minor aquifer – These geologic units have low-yield wells (50 gpm or less); water quality is various, good to poor. These minor aquifers typically have thinner beds that are less permeable and less laterally extensive than beds in major aquifers.

- Quaternary non-alluvial deposits (sand and gravel)
- Frontier Formation (sandstone)
- Evanston Formation (sandstone and conglomerate)
- Lance Formation and Fox Hills Sandstone (sandstone)
- Twin Creek Limestone and Thaynes Limestone (carbonate)
- Phosphoria Formation (carbonate)

Marginal aquifer – Could also be termed minor confining unit. These geologic units are bedrock formations with very-low-yield wells (1 to 5 gpm) and little potential for development of even moderate quantities of good-quality groundwater. Locally, these aquifers may be suitable for low-yield domestic or stock wells.

- Woodside Formation and Dinwoody Formation (sandstone)

Major confining unit – Commonly, these geologic units contain a high percentage of shale (claystone, mudstone), and show little potential for producing usable quantities of groundwater. Many of these low-permeability confining units consist of thick, laterally extensive sequences of marine shale. These thick confining units act as regional seals between aquifers, greatly hindering vertical groundwater flow. The Precambrian aquifer system is typically a major basal confining unit where the Precambrian rocks underlie sedimentary rock formations. Locally, in or near outcrop, even major confining units may be suitable for low-yield production.

- Cody Shale, Steele Shale, Niobrara Formation, and Baxter Shale (shale)
- Thermopolis Shale, Mowry Shale, and Aspen Shale (shale)
- Precambrian rock units (basal confining unit) in the structural basins

Unclassified – These geologic materials are present in small areas without adequate hydrologic data for classification.

This 2007 Wyoming Statewide Framework Aquifer Classification System (WWC Engineering, 2007) gives a clear overview of the groundwater resources of the state and of the seven major river basin areas. However, effective river basin planning requires increasingly greater levels of hydrogeologic detail and delineation of aquifers and confining units.

Plate 7 shows the 170 GIS geologic units for the GGRB, symbols used on **Plate 2** and in **Appendix 1**, geologic age, lithology, occurrence, and aquifer classification per the 2007 system (WWC Engineering, 2007).

Water wells in the Wyoming GGRB

Through December 31, 2007, the WSEO issued more than 13,000 groundwater permits for the Wyoming GGRB (**Figure 3-7** and **Table 3-3**). WSEO-permitted CBNG wells make up about 8 percent of this total, or about 1,000 wells. CBNG wells must be permitted by both the Wyoming Oil and Gas Conservation Commission (WOGCC) for gas production and the WSEO for groundwater production (**Figure 3-8**). Some springs with small yields (25 gpm or less) are included in the WSEO groundwater-permit database for the GGRB.

Most wells in the Wyoming GGRB are constructed into the Cenozoic hydrogeologic units (lower Tertiary, upper Tertiary, and Quaternary hydrogeologic units; **Figure 3-3**).

Most of the 13,002 WSEO groundwater permits issued for the Wyoming GGRB (**Table 3-4**) are for wells that are less than 300 feet deep and yield 25 gpm or less. Of these 13,002 permits, 88.6 percent are for wells less than 300 feet deep (**Table 3-4**; **Figure 3-9**). Of the 6,455 permits listing yield, 90.5 percent are for wells with permitted yields of 25 gpm or less (**Table 3-5**; **Figure 3-10**).

Of the 13,002 permits, 3,290 are listed as monitoring wells (**Figure 3-11**). When used for monitoring alone, they have no production (zero yield); however, many wells permitted for monitoring are also permitted for other uses, for which there is permitted yield. (A tally of well yields based on use will thus be inaccurate.) The WSEO required permits for monitoring wells only through 2004; therefore, **Figure 3-7** does not show wells used for monitoring alone installed since the beginning of 2005. **Figure 3-11** and **Figures 3-3** through **3-6**, based on USGS data, do show these wells.

Well yield

Actual well yield is a function of actual groundwater use. Because we have only estimates of groundwater use, as detailed and discussed in Chapter 7, we use other data to estimate yield.

Of the 13,002 WSEO groundwater permits issued through 2007 for the Wyoming GGRB, 6,455 permits listed yield, between 1 and 3,600 gallons per minute (gpm) (**Table 3-5**). The sum of the listed permitted yields is 171,891 gpm, giving an average yield of 26.6 gpm per well. This 172,000 gpm equals 248×10^6 gallons per day, 90.3×10^9 gallons per year, or 277,000 acre-feet per year from the 6,455 wells with listed yield.

We cannot reasonably extrapolate these statistics to include all 13,002 permitted wells. We have no data on how many of the other 6,547 permitted wells have been completed, how many are monitoring wells with zero yield, or how many are inactive for one reason or another. We think it improbable that any of these wells are high-yield wells, so we can't mimic the yield distribution of the listed wells. Therefore, we arbitrarily increase our 277,000 acre-feet-per-year estimated permitted yield by 15 percent to 319,000 acre-feet per year for all 13,002 permitted wells in the Wyoming GGRB.

This 319,000 acre-feet per year of pumped groundwater represents a maximum estimate for 2007, attainable only if all permitted wells had been pumped continuously at their permitted yield rate 24 hours a day, 365 days a year. But, water wells are not pumped continuously; typically, they are pumped in brief, cyclical intervals. Some wells are never pumped during a year. Some wells may remain idle for years, and some wells may have been destroyed, lost, or plugged and abandoned. However, if we assume that all 2007-permitted wells are pumped 10 percent of the time annually, an estimated maximum volume would be 31,900 acre-feet per year of groundwater produced from

Table 3-3. Number of WSEO well permits in the Wyoming GGRB database, by intended use as recorded on permits
[2007 WSEO data]

Well type	*Code*	*Number*
Coalbed methane (or CBNG)	CBM	999
Commercial	COM	3
Culinary	CUL	1
Dewatering	DEW	83
Domestic	DOM	5,288
Drilling	DRI	11
Industrial	IND	225
Irrigation	IRR	115
Miscellaneous	MIS	1,902
Monitoring	MON	3,290
Municipal	MUN	55
Oil refining/production	OIL	16
Railroad	RAI	27
Reservoir supply	RES	74
Stock	STO	2,757
Temporary use	TEM	8
Test well	TST	25
Public utility	UTI	2
TOTAL listed in 13,002 permits, some of them multi-use permits		**14,881**

Table 3-4. Permitted wells in the Wyoming GGRB by depth range
[2007 WSEO data]

Depth range (feet)	*Permits*	*Percentage*	*Cumulative*		*Depth range (feet)*	*Number of permits*	*Well percentage*
			Permits	*Percentage*			
0–50	6,623	50.9	6,623	50.9	>50	6,379	49.1
50–100	2,147	16.5	8,770	67.5	>100	4,232	32.5
100–200	1,983	15.3	10,753	82.7	>200	2,249	17.3
200–300	773	5.9	11,526	88.6	>300	1,476	11.4
300–500	608	4.7	12,134	93.3	>500	868	6.7
500–5,000	847	6.5	12,981	99.8	>5,000	21	0.2
5,000–12,660	21	0.2	13,002	100.0			

Table 3-5. Permitted wells in the Wyoming GGRB by yield range
[2007 WSEO data for the 6,455 permits listing yield]

Yield range (gpm)	*Number of permits*	*Percentage of permits*
0–25	5,841	90.5
[>25]	[614]	[9.5]
25–100	401	6.2
[>100]	[213]	[3.3]
100–300	149	2.3
300–375	12	0.2
[376–399]	[0]	—
400–500	33	0.5
500–3,600	19	0.3
TOTAL	**6,455**	**100**

the Wyoming GGRB. This estimate appears too high, on the basis of previous estimates. Purcell (2000) estimated total groundwater use in the Wyoming GGRB to be between 5,300 and 7,200 acre-feet per year in 2000, depending on the proportion of sprinkler irrigation in total irrigation. To yield 7,200 acre-feet in 2009, considering the 2007 maximum permitted yield of 319,000 acre-feet per year, the 13,002 permitted wells would have been pumped 2.26 percent of the time.

Our approach is to assume that wells are pumped 2.5 percent to 5 percent of the time. Using this assumption, and our 319,000 acre-feet/year estimate of maximum permitted yield, the 2007 estimate for total groundwater withdrawal from the Wyoming GGRB would range between about ***8,000 and 16,000 acre-feet per year***. This is the range we use in Chapter 8 as an estimate of current use.

Springs

Twelve hundred and two mapped springs are located in the Wyoming GGRB (**Figure 3-12**). The springs mapped on USGS 1:24,000-scale topographic sheets covering the Wyoming GGRB are illustrated on **Figure 3-12** and **Figures 3-3** through **3-6**. The WSGS digitized the USGS spring location data and compiled them as a GIS layer. Springs issue from hydrogeologic units in all four geologic-era-based groups in the Wyoming GGRB. **Figures 3-3** through **3-6** show 947 springs located on or near outcrop of the Cenozoic hydrogeologic units, 230 springs on or near outcrop of the Mesozoic hydrogeologic units, 16 springs on or near outcrop of the Paleozoic hydrogeologic units, and 9 springs on or near outcrop of the Precambrian hydrogeologic units in the Wyoming GGRB. GIS data for spring locations in the Colorado and Utah GGRB were unavailable.

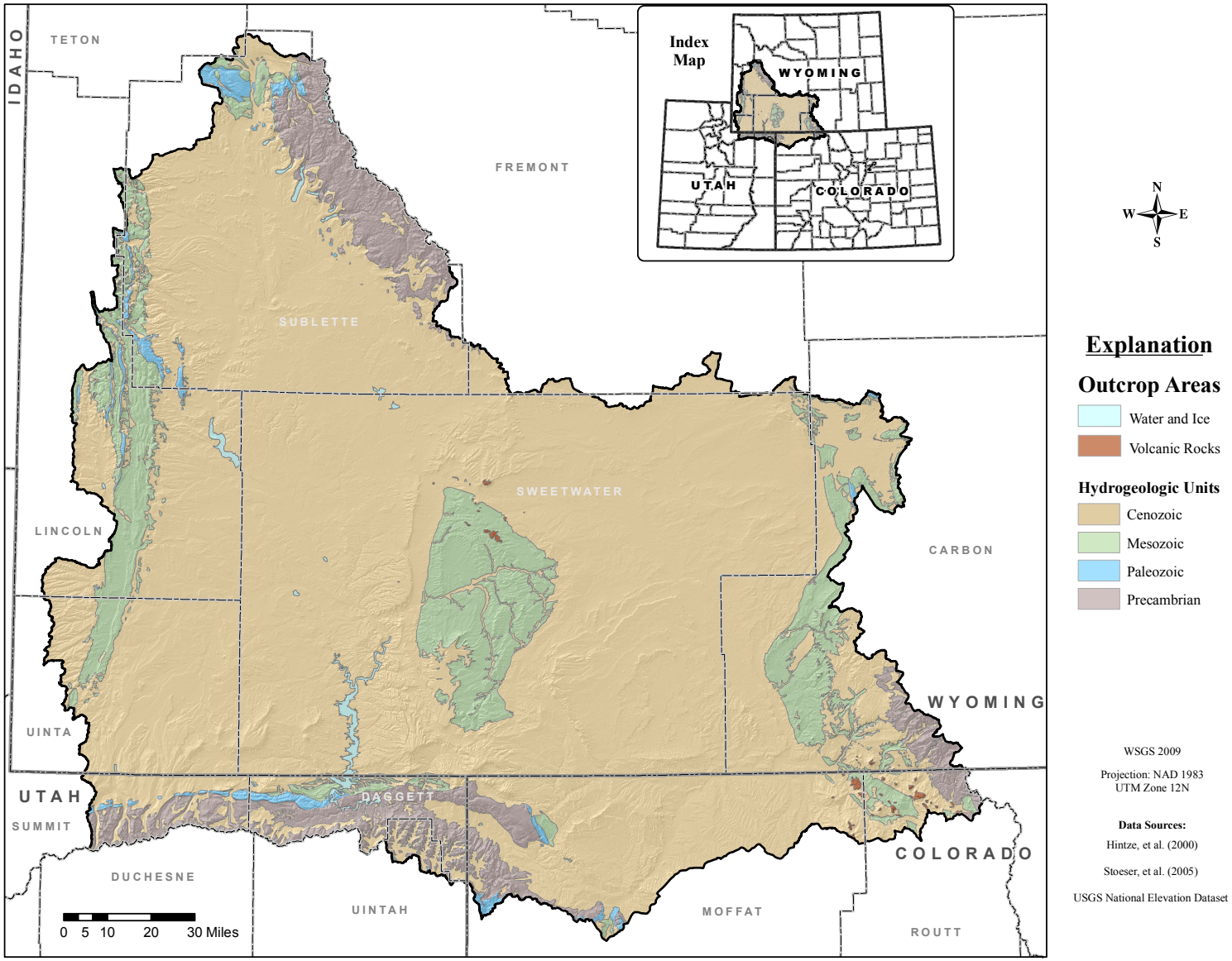

Figure 3-1. Outcrop areas, hydrogeologic units by geologic era, Greater Green River Basin.

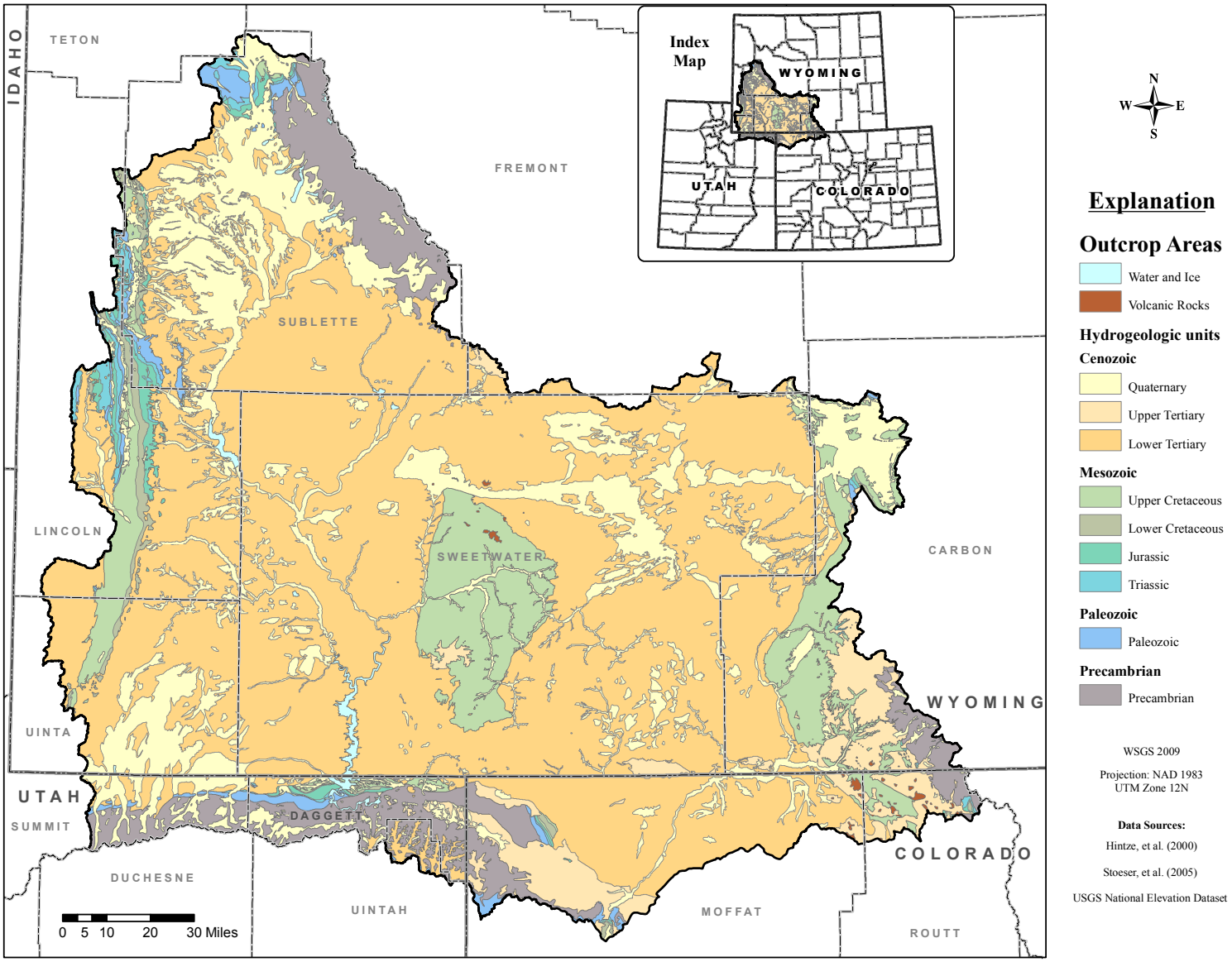

Figure 3-2. Outcrop areas, hydrogeologic units by geologic system or subsystem, Greater Green River Basin.

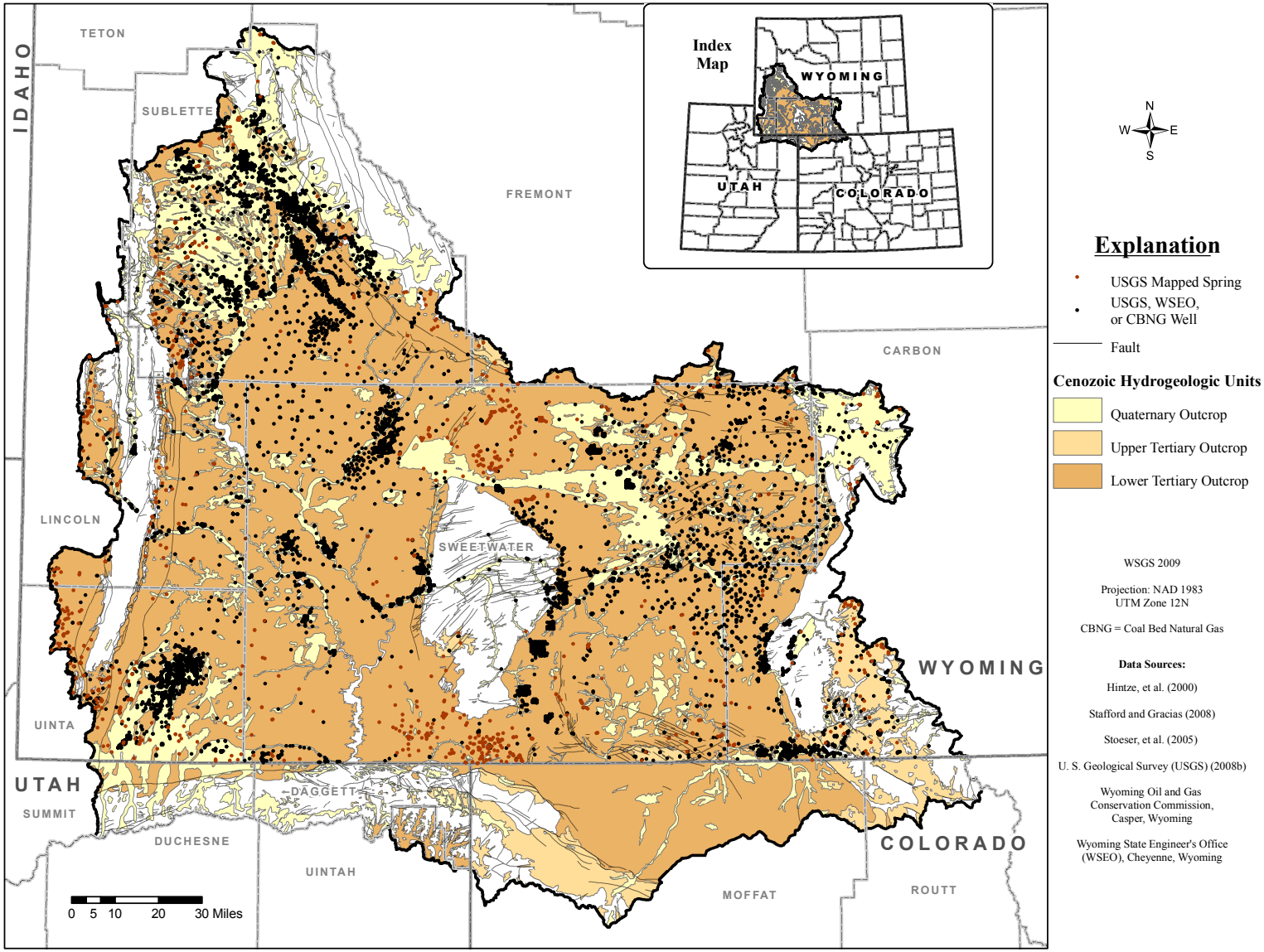

Figure 3-3. Wells and springs in or near Cenozoic outcrop areas, Wyoming Greater Green River Basin.

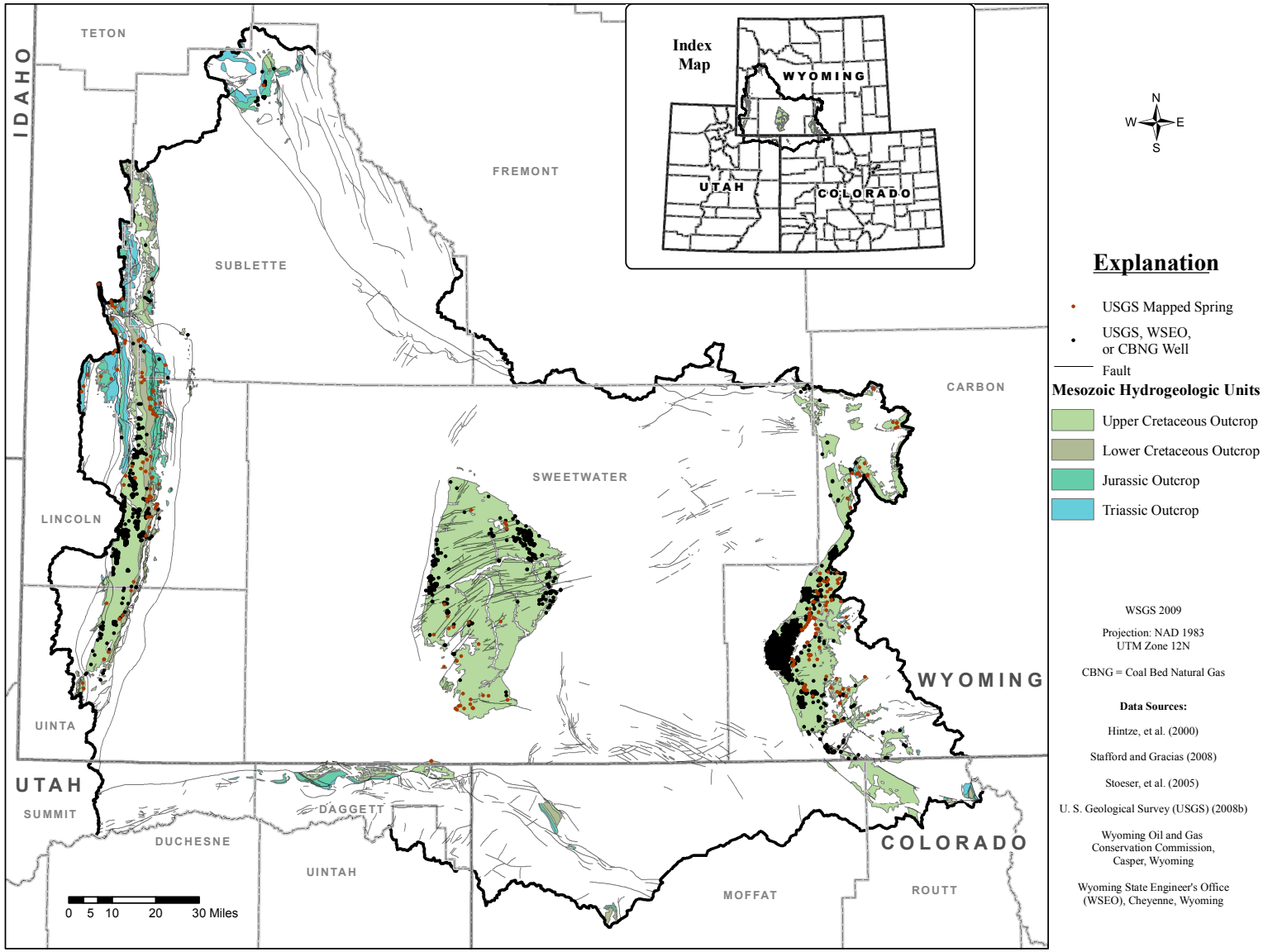

Figure 3-4. Wells and springs in or near Mesozoic outcrop areas, Wyoming Greater Green River Basin.

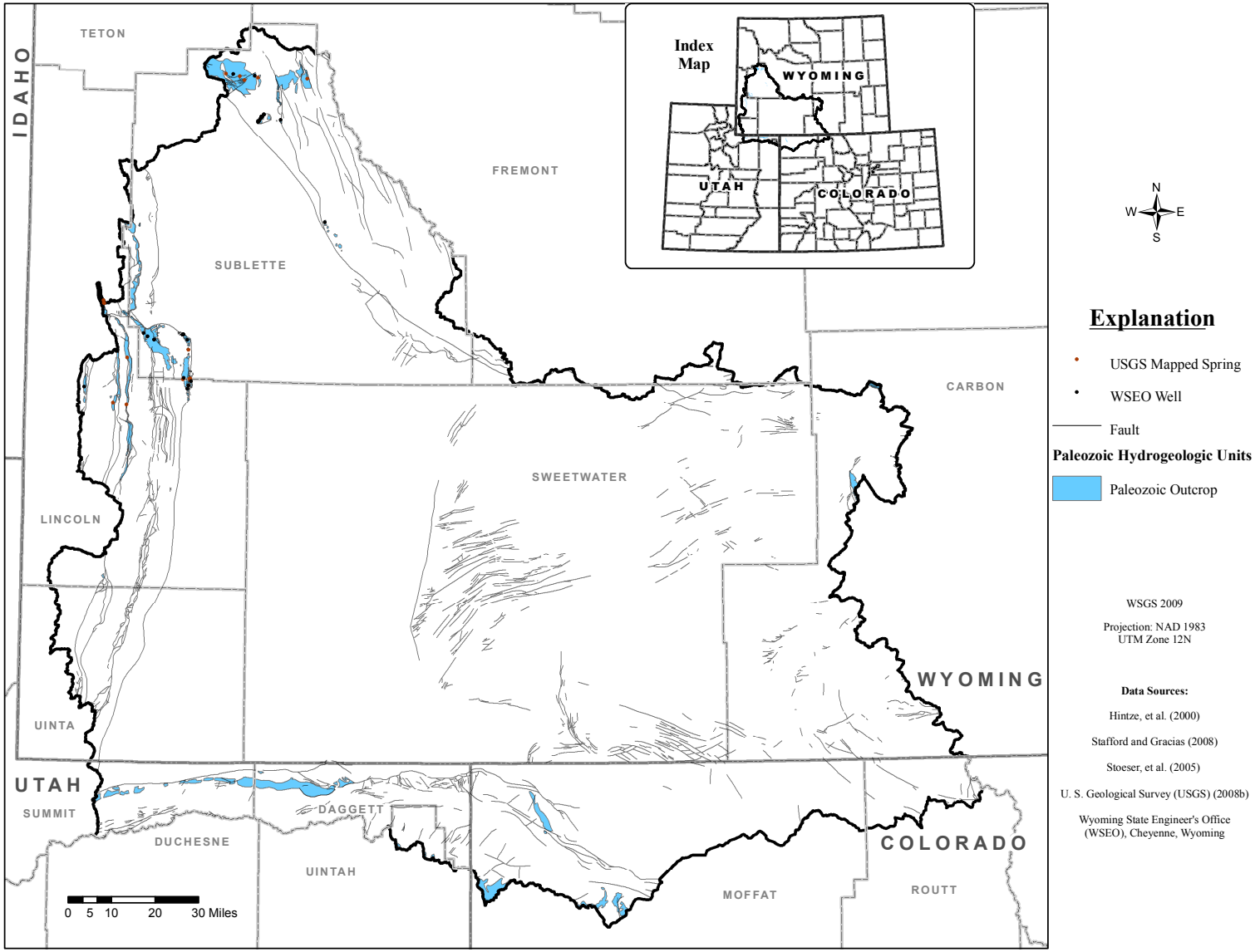

Figure 3-5. Wells and springs in or near Paleozoic outcrop areas, Wyoming Greater Green River Basin.

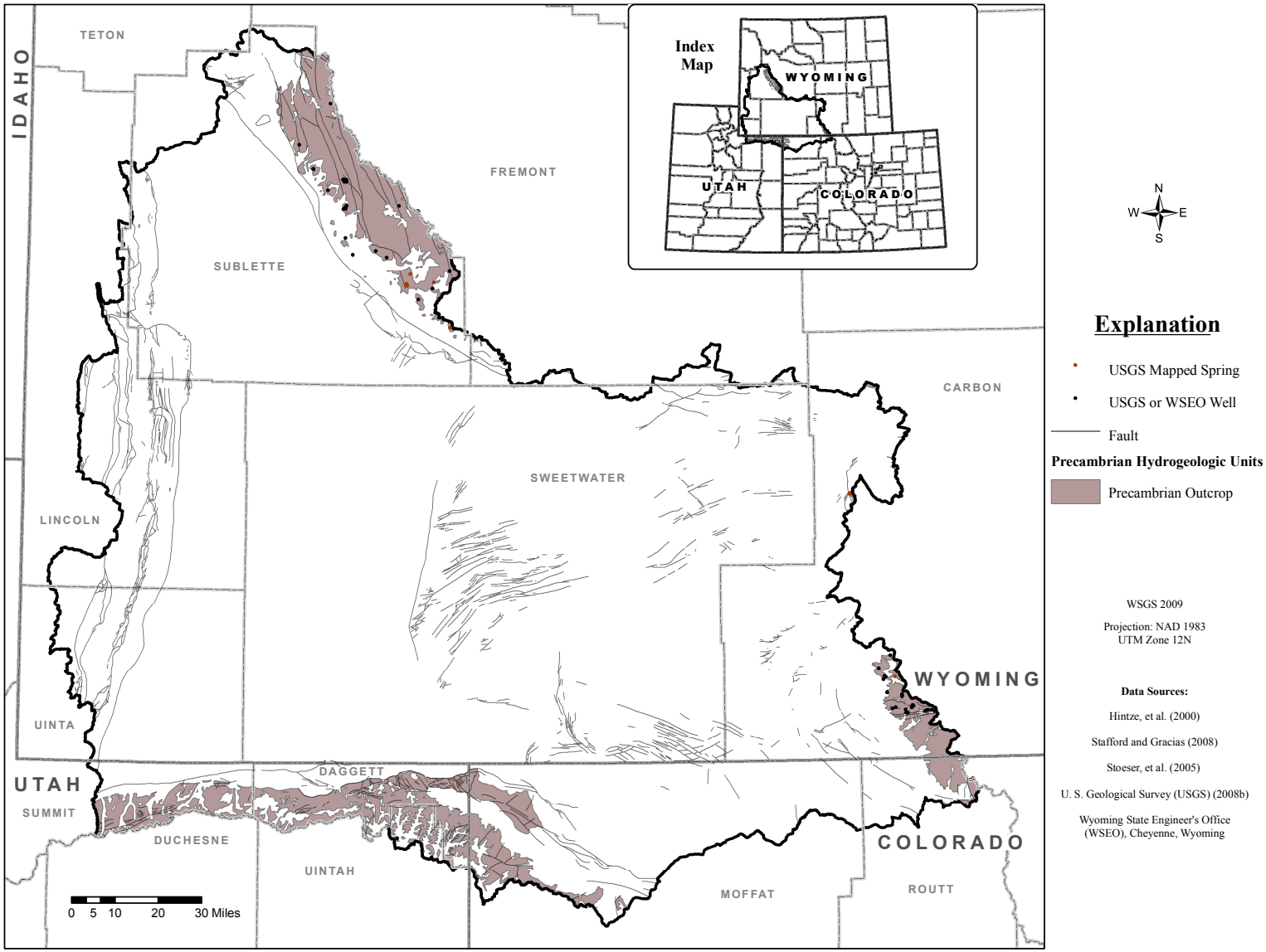

Figure 3-6. Wells and springs in or near Precambrian outcrop areas, Wyoming Greater Green River Basin.

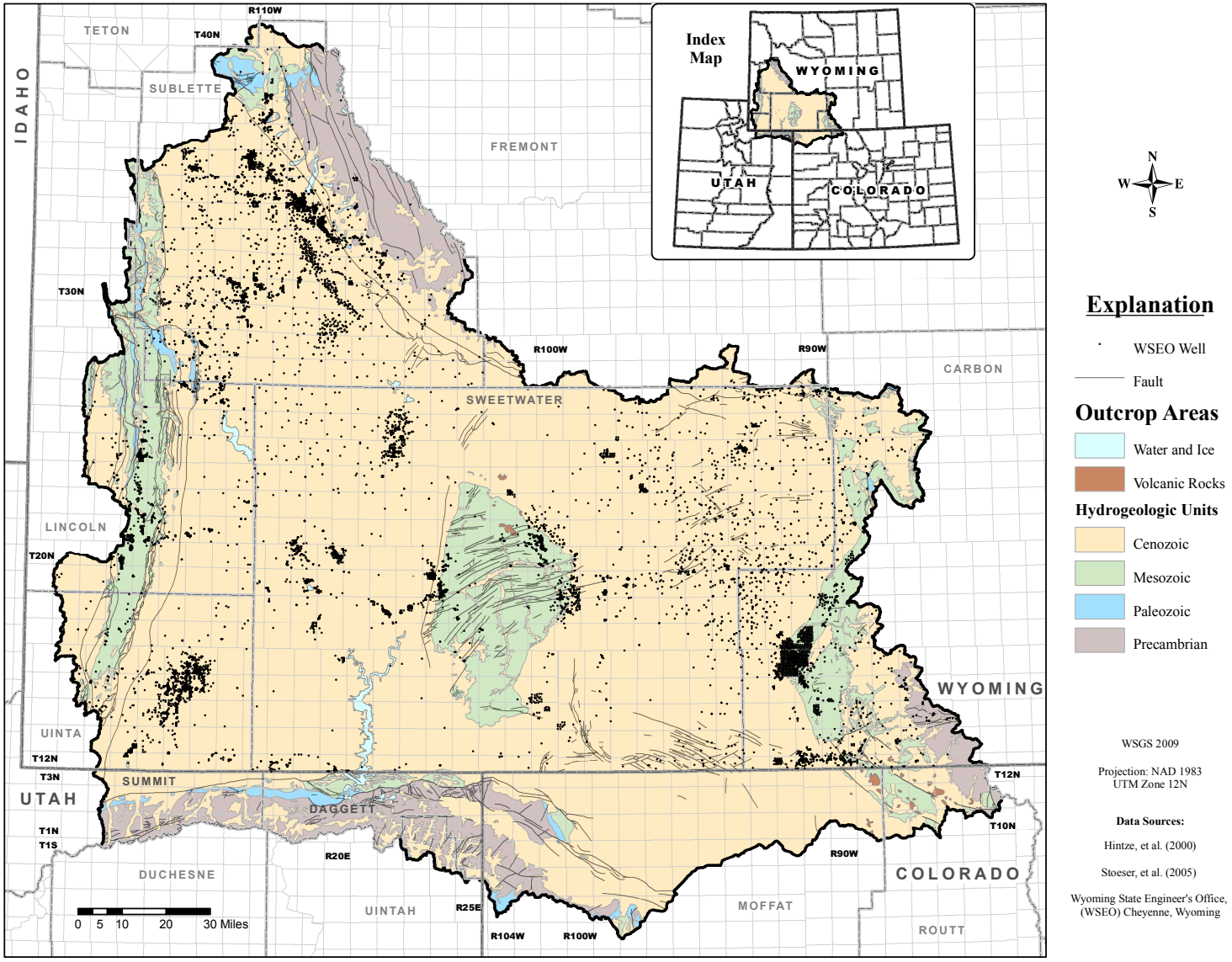

Figure 3-7. Wells permitted by the Wyoming State Engineer's Office, Wyoming Greater Green River Basin.

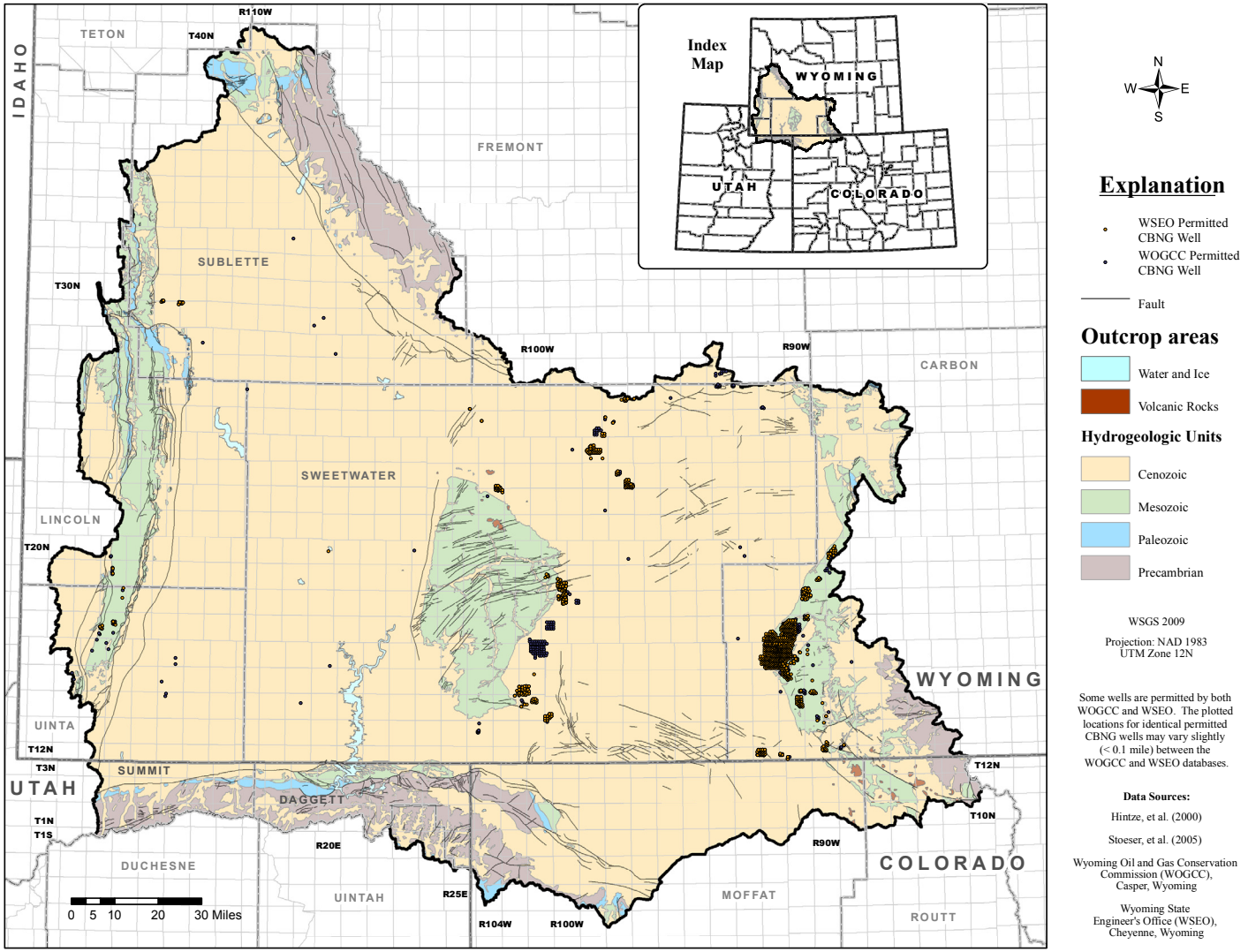

Figure 3-8. Permitted coalbed natural gas (CBNG) wells, Wyoming Greater Green River Basin. CBNG wells must be permitted by both the WSEO (for water production) and the WOGCC (for gas production). On the map, WSEO symbols cover WOGCC symbols where they coincide. A single-permit symbol indicates either the other permit application under review or a lag in updating the data set.

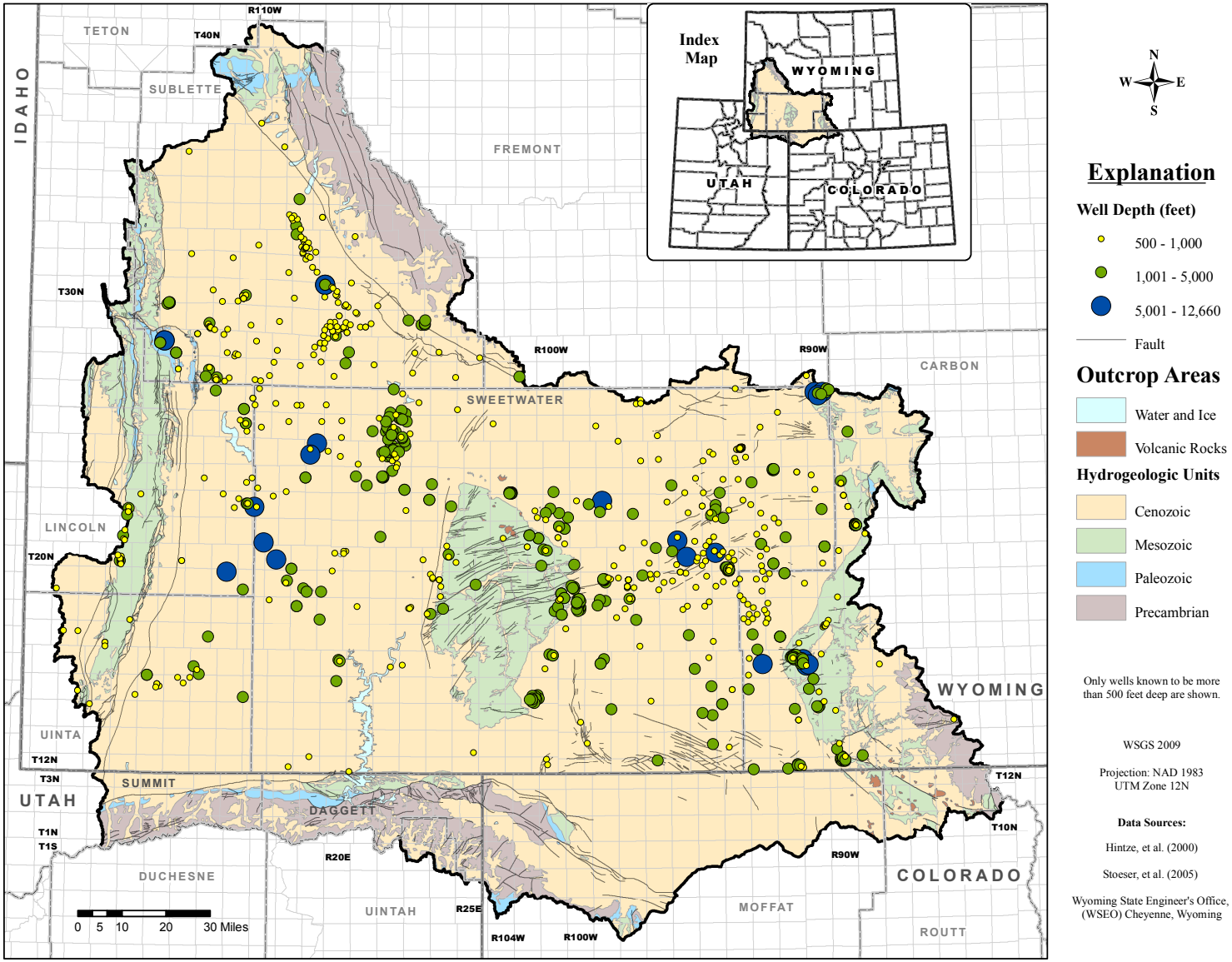

Figure 3-9. Depth of wells more than 500 feet deep permitted by the Wyoming State Engineer's Office, Wyoming Greater Green River Basin.

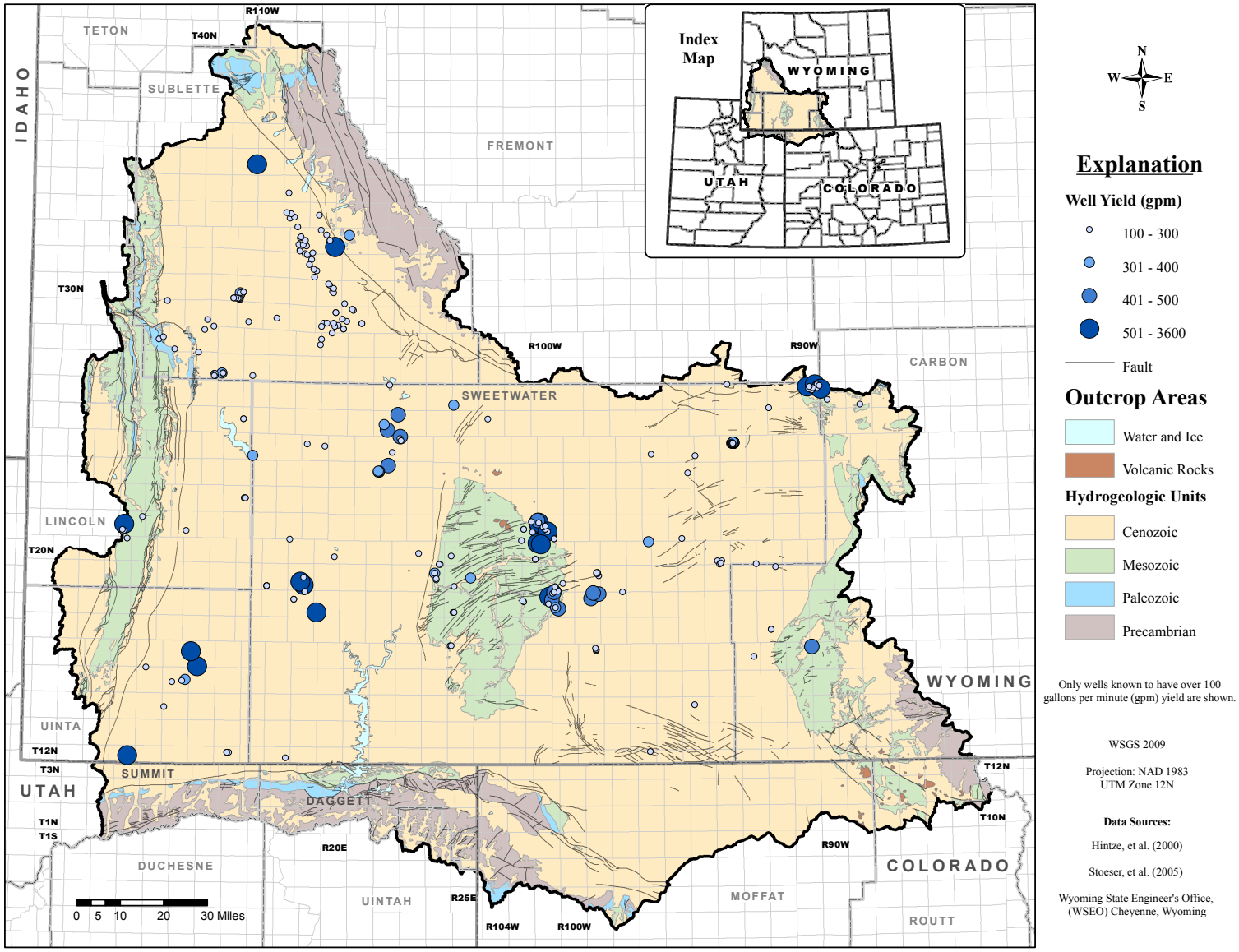

Figure 3-10. Yields greater than 100 gallons per minute from wells permitted by the Wyoming State Engineer's Office, Wyoming Greater Green River Basin.

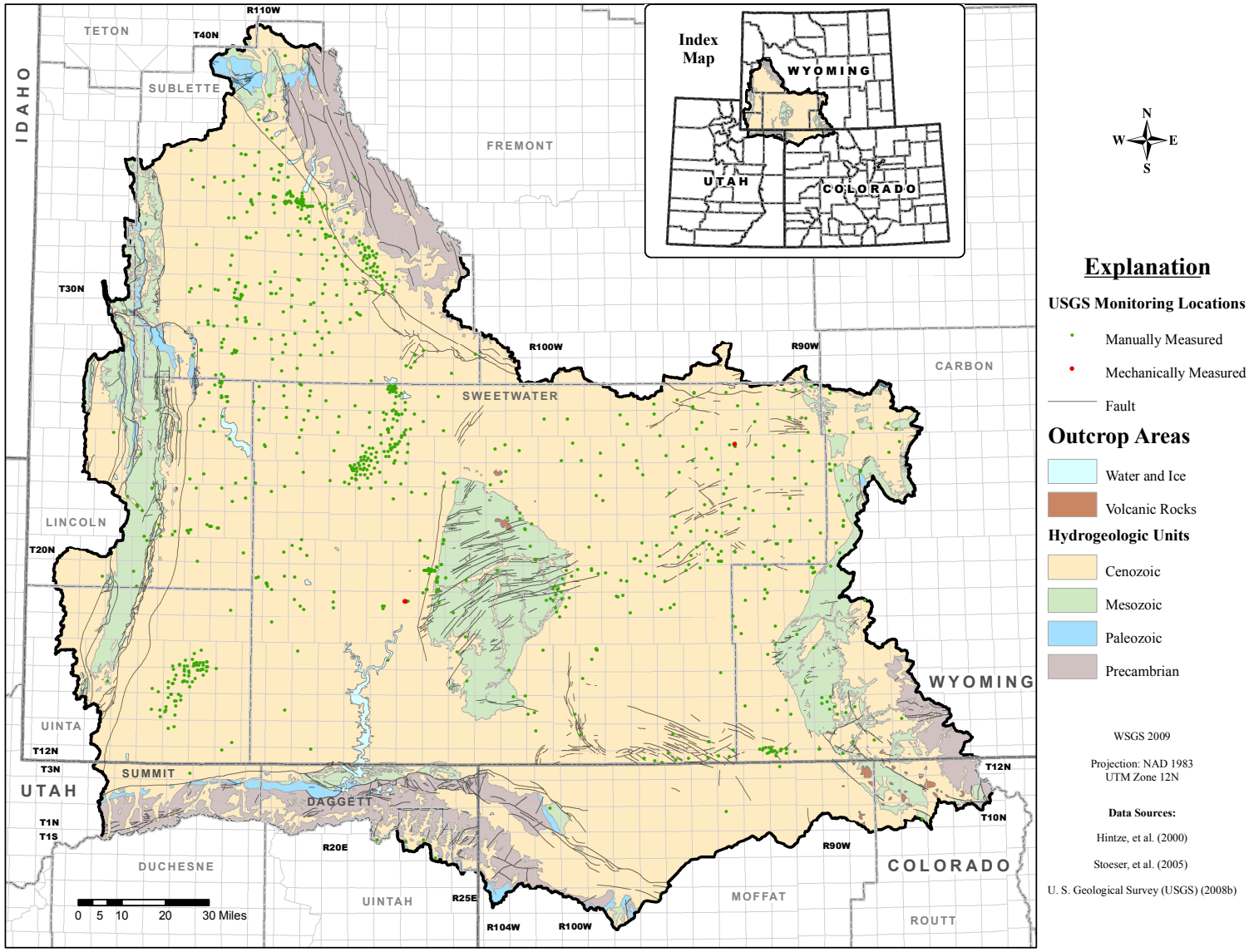

Figure 3-11. U.S. Geological Survey groundwater monitoring wells, Greater Green River Basin.

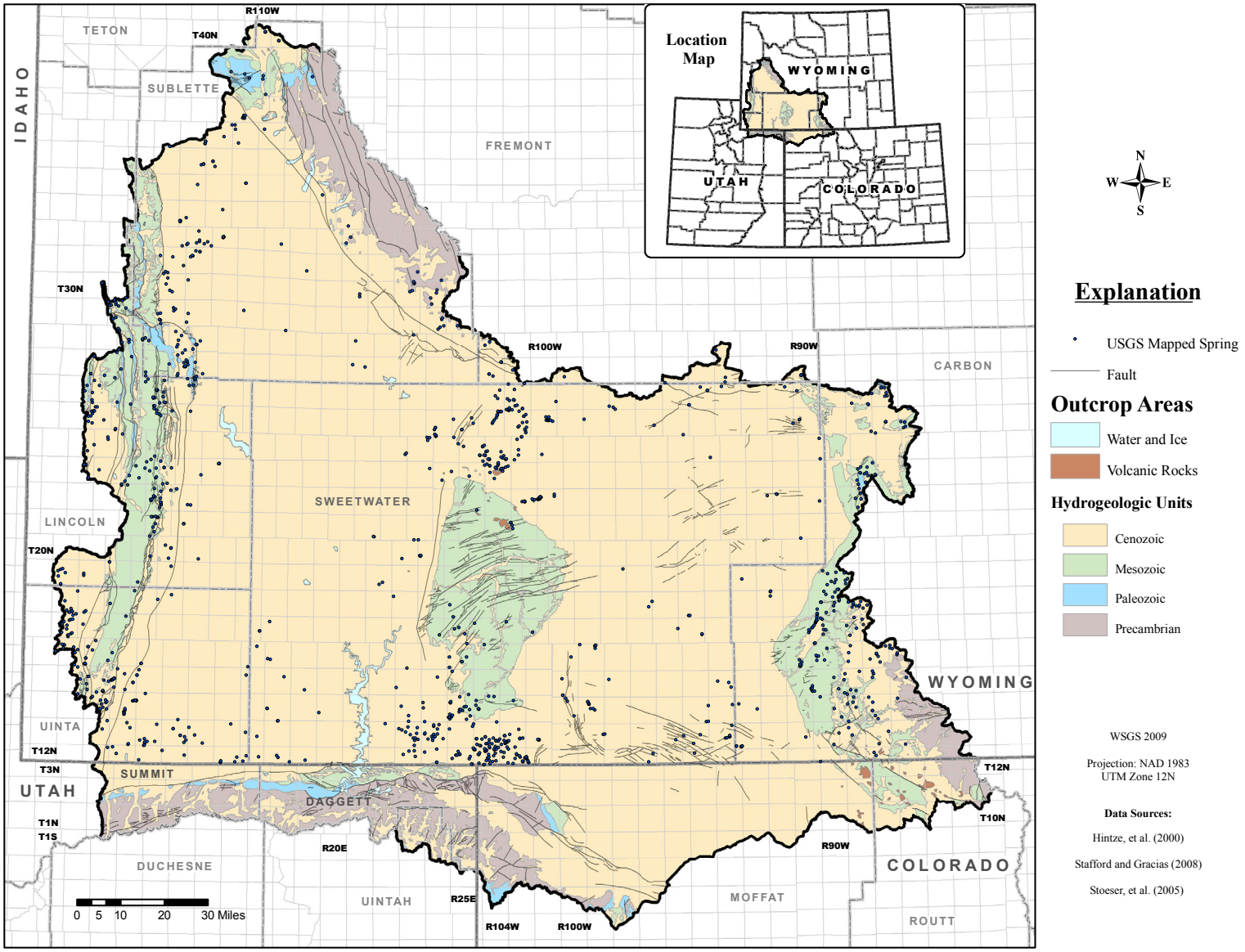

Figure 3-12. U.S. Geological Survey mapped springs, Wyoming Greater Green River Basin.