South Park Groundwater Quality Scoping Study

Prepared for the Coalition for the Upper South Platte

By

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EXECUTIVE SUMMARY

South Park is a high altitude intermontane valley spanning a large portion of Park County and forms the watershed of the South Fork of the South Platte River. The region has experienced considerable population growth in recent decades with development becoming increasingly reliant on local groundwater resources. South Park, with its diverse geology, has long been recognized for its energy resource potential including historic coal and peat mining and recent interest in petroleum resources and uranium resources. Recent interest in petroleum potential in the Niobrara Formation sparked local concern over possible harmful impacts to local water resources. The Coalition for the Upper South Platte (CUSP) requested the Colorado Geological Survey (CGS) and the United States Geological Survey (USGS) to prepare a scoping study to address baseline water quality monitoring in South Park in anticipation of future energy development. The purpose of this scoping study is to determine the number and optimal locations for the installation of shallow monitoring wells across the greater South Park area. The study summarizes the stratigraphic and tectonic setting with respect to potential fresh water aquifers and describes potential vulnerability of groundwater resources to potential energy resource extraction. Finally, the study proposes a network of 105 monitoring wells (Figure E1) in vulnerable aquifers in the central part of South Park in the area where petroleum resource development is most likely to occur.

The basin consists of eastward-dipping Paleozoic and Mesozoic sedimentary rocks preserved between uplifts of Precambrian igneous and metamorphic rocks on either side. Locally, Cretaceous and Tertiary igneous stocks, sills, and dikes intrude these rocks. Tertiary volcanic, lacustrine, and fluvial deposits overly the older rocks in many parts of the basin. The high ranges bordering South Park were subject to Quaternary glaciation with moraine and outwash deposits extending well into the basin. The basin is structurally complex being dominated by the Laramide Sawatch uplift on the west and Front Range uplift on the east. Internally, the basin contains faulting and folding attributed by many to Late Cretaceous to Eocene Laramide deformation. Deformation styles attributed to the Laramide event include thrust faulting, folding, and possible strike-slip faulting with widespread zones of deformation affecting most of the basin. The Neogene Rio Grande Rift system follows the upper Arkansas River valley just to the west. In addition, there is evidence of ongoing local deformation related to dissolution and possible collapse of Paleozoic evaporite deposits (Kirkham and others, 2012).

The many rock units in South Park are grouped into general hydrogeologic units in this scoping study. These units are based on similarities in geologic history and characteristics related to

groundwater occurrence and flow conditions, based on available data. The units defined herein include:

(1) Alluvial aquifers

(2) Sedimentary bedrock aquifers and confining units

(a) Post-Laramide hydrogeologic units

(b) Cretaceous and Tertiary hydrogeologic units associated with the Laramide uplift, hereafter referred to as “Laramide hydrogeologic units”

(c) Cretaceous hydrogeologic units associated with the Western Interior Seaway, hereafter referred to as “Cretaceous seaway hydrogeologic units”

(d) Paleozoic hydrogeologic units

(3) Crystalline-rock aquifers

(a) Post-Laramide volcanic rocks

(b) Cretaceous and Tertiary igneous intrusions

(c) Precambrian igneous and metamorphic rocks

There were 4,163 water wells the South Park study area as of December 19, 2012. Of these wells, about 5 percent appear to be completed in alluvial aquifers, 6 percent in post-Laramide hydrogeologic units, 14 percent in Laramide hydrogeologic units, 7 percent in Cretaceous seaway hydrogeologic units, 16 percent in Paleozoic hydrogeologic units, 5 percent in post-Laramide volcanic rocks, 2 wells in Cretaceous and Tertiary igneous intrusions, and 47 percent in Precambrian igneous and metamorphic rocks. Most are permitted for domestic use or household use only.

The potentiometric surface based on reported water level data generally reflects the topography of the ground surface with highest altitudes along the margins of the South Park basin and beneath upland areas and ridges. Groundwater flows generally from the topographically high areas toward the stream valleys and tributaries of the South Platte River and Tarryall Creek. A groundwater divide that separates the direction of groundwater flow toward the South Platte River from flow toward Tarryall Creek is located approximately along the topographic divide between the two drainage basins. Groundwater south and west of the divide flows toward the South Platte River and its tributaries, whereas groundwater north and east of the divide flows toward the stream valley of Tarryall Creek.

Thirty sites in the South Park study area have been permitted for drilling oil and gas wells as of November 2010. Twenty-two of the well sites have been abandoned and are not in use, five sites are planned for development and have not yet been drilled, and three sites have no status indicated. In addition to permitted wells, 15 locations covering a total area of about 2,923 acres were offered for lease by the U.S. Bureau of Land Management in February 2013 for oil and gas development in the South Park study area (Bureau of Land Management, 2013; Figure E1). These sites all lie within the area underlain by the Mesozoic sedimentary units.

The vulnerability of aquifers to oil and gas development in South Park depends on several conditions, including the aquifer's location relative to oil and gas development sites, hydraulic conductivity of aquifers and confining units, and direction of groundwater flow. Aquifers penetrated by oil and gas wells or located in hydrogeologic units in direct contact with surface operations of oil and gas development are most vulnerable to potential water-quality effects. Aquifers having high hydraulic conductivity are more vulnerable to the effects of oil and gas development than those having low hydraulic conductivity because of their greater ability to transport chemical constituents over relatively long distances. Aquifers or parts of aquifers located downgradient from oil and gas development sites are more vulnerable to the effects of development than those that are upgradient because groundwater transports chemical constituents in a downgradient direction.

Oil and gas wells and lease areas offered for oil and gas development primarily are located where alluvium, Laramide hydrogeologic units, Cretaceous seaway hydrogeologic units, and Precambrian igneous and metamorphic rocks are present at the land surface. In addition, groundwater in these units occurs downgradient from areas of proposed oil and gas development. As such, these units likely are the most vulnerable to the potential effects of oil and gas development in South Park. Groundwater in Precambrian igneous and metamorphic rocks generally is upgradient from oil and gas sites except along the stream valleys of Tarryall Creek and Martland Gulch (Figure E1) consequently is unlikely to be vulnerable to the potential effects of oil and gas development except in these areas. Groundwater in post-Laramide hydrogeologic units and Cretaceous and Tertiary intrusions occurs in only very limited areas downgradient from oil and gas sites. Potentially vulnerable aquifers in post-Laramide hydrogeologic units are the Antero and Wagontongue aquifers.

Well networks generally were designed for monitoring groundwater in (1) alluvium, (2) Laramide hydrogeologic units, (3) Cretaceous seaway hydrogeologic units, and (4) Precambrian igneous and metamorphic rocks. Well networks were designed using 30 wells completed in each hydrogeologic unit to provide broad areal coverage for characterizing water-quality conditions in areas of current or potential oil and gas development. Because of the relatively small area of Precambrian igneous and metamorphic rocks downgradient from oil and gas development sites, the well network for these rocks includes only 15 wells. Existing wells were used in the networks wherever possible to minimize the number of new wells to be drilled for monitoring. Where existing wells were not located within about 2 miles downgradient from areas of oil and gas development or do not have suitable construction for monitoring groundwater quality, locations for new wells generally are proposed. Well networks include wells from the existing monitoring network used by CUSP wherever possible to provide continuity with previous sampling efforts undertaken by CUSP. Well networks were designed to monitor groundwater conditions primarily downgradient from areas of current or potential oil and gas development. However, some wells upgradient from areas of oil and gas development also are included in the network to provide for comparison to any changes potentially observed in downgradient wells. Well networks developed for each of the four priority hydrogeologic units are shown in Figure E1. Existing wells were considered to provide sufficient coverage for monitoring water quality in Cretaceous seaway hydrogeologic units and Precambrian igneous and metamorphic rocks. One new well is proposed for monitoring water quality in Laramide hydrogeologic units (South Park aquifer), and nine new wells are proposed for monitoring water quality in alluvial aquifers.

Collection and analysis of groundwater samples for water quality from the network wells presented in this report would provide for assessment of water-quality conditions in South Park prior to extensive oil and gas development in the basin. Better structural definition of sedimentary bedrock aquifers and confining units at depth in the South Park basin is needed to accurately characterize the location, depth, and geometry of water-bearing units and their relation to adjacent units. Better definition of the surface of the crystalline-rock basement below sedimentary bedrock units in the basin would provide useful information for characterizing the vertical extent of groundwater resources in the sedimentary bedrock units overlying basement rocks. Data concerning hydraulic conductivity and storage properties of hydrogeologic units in the basin are sparse, and additional data from aquifer tests, specific-capacity tests, lab analysis of core samples, or other methods are needed to improve characterization of these hydrologic properties and facilitate understanding of groundwater-flow patterns and responses to hydrologic stresses such as pumping or climate change. Regular water-level measurements using an established well network would provide useful information for monitoring temporal changes to groundwater resources in the basin and provide additional information on directions of groundwater flow for interpreting water-quality data collected at monitoring-well locations. Studies to quantify the exchange of water between surface-water features, such as streams and reservoirs, and underlying aquifers are needed to improve understanding of groundwater-surface water fluxes in the basin and the potential for water-quality constituents in groundwater to enter streams or reservoirs. Lastly, development of a water budget and construction of a numerical groundwater flow model that incorporates pumping and other data (existing and new) could be used to improve management and monitoring of groundwater resources in the South Park basin and form the basis for assessing groundwater flow paths and transport of water-quality constituents near sites of oil and gas development.

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ACKNOWLEDGMENTS

This project was funded by a grant from the Coalition for the Upper South Platte matched by the Colorado Geological Survey through its Severance Tax Operational Funds. Many people contributed to this project indirectly over the years. Development of the generalized geologic map builds on many hours of field mapping by CGS and USGS geologists and special recognition goes to Robert Kirkham, Cal Ruleman, Beth Widmann, and Alex Scarbrough, Jr.. Rick Arnold of the United States Geological Survey contributed to the study by evaluating groundwater use, flow conditions, and vulnerability in South Park and designing the well networks presented in this report.

We are particularly grateful to CUSP, and Carol Ekarius in particular, for putting the important pieces necessary to make the study happen. Special commendation goes to the concerned citizens of South Park for recognizing the importance of gathering baseline water quality data before development happens. It can be very difficult to assess impacts after they occur without basic baseline data.

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INTRODUCTION

BACKGROUND

South Park is a high altitude intermontane valley spanning a large portion of Park County and forms the watershed of the South Fork of the South Platte River. The region has experienced considerable population growth in recent decades with development becoming increasingly reliant on local groundwater resources. The Coalition for the Upper South Platte (CUSP) formed in 1998 to protect the 2,600-square-mile watershed that reaches from the Continental Divide to Strontia Springs Reservoir, southwest of Denver. The watershed is a recreational mecca with over 1.6 million acres of public lands; it provides municipal water for about three quarters of Colorado’s residents; it is renowned for its "gold-medal" fishing streams; and it is home to numerous threatened and endangered species.

South Park, with its diverse geology, has long been recognized for its energy resource potential including historic coal and peat mining and recent interest in petroleum resources and uranium resources. Recent interest in petroleum potential in the Niobrara Formation through leasing by the United States Bureau of Land Management sparked local concern over possible harmful impacts to local water resources. CUSP responded to this concern and formulated a plan to collect background water quality data against which future data could be compared to assess impacts to water quality should petroleum development occur within the valley.

PURPOSE

CUSP requested the Colorado Geological Survey (CGS) and the United States Geological Survey (USGS) to prepare a scoping study to address baseline water quality monitoring in South Park in anticipation of future energy development.The primary purpose of this scoping study is to determine the number and optimal locations for the installation of shallow monitoring wells across the greater South Park area. The study will also formulate a conceptual hydrogeologic framework for a more in-depth groundwater model of the area. The installation of these monitoring wells will allow Park County to collect valuable information about the South Park aquifers and groundwater/surface water interactions. Monitoring wells can be used as a tool to better understand the South Park subsurface including: general and localized groundwater flow systems; aquifer characteristics; water-level conditions; water quality conditions of different intervals and aquifers; and better hydrogeologic characterization needed for a risk assessment of the potential aquifer contaminant pathways.

SCOPE

This study uses existing publications and data, from both public and private domains, to describe the hydrogeologic setting of South Park. The area covered, shown in Figure 1, includes the watershed of the South Fork of the South Platte River from the Mosquito Range on the west to Tarryall Creek on the east and from the Continental Divide south to the watershed boundary separating tributaries of the South Platte River from tributaries of the Arkansas River that runs through Thirtynine Mile Mountain. The study summarizes the stratigraphic and tectonic setting with respect to potential fresh water aquifers. It also summarizes recent developments in energy resource exploration using publically available information. Finally, the study describes potential vulnerability of groundwater resources to potential energy resource extraction, should it eventually happen and recommends development of a monitoring network to collect baseline water quality data.

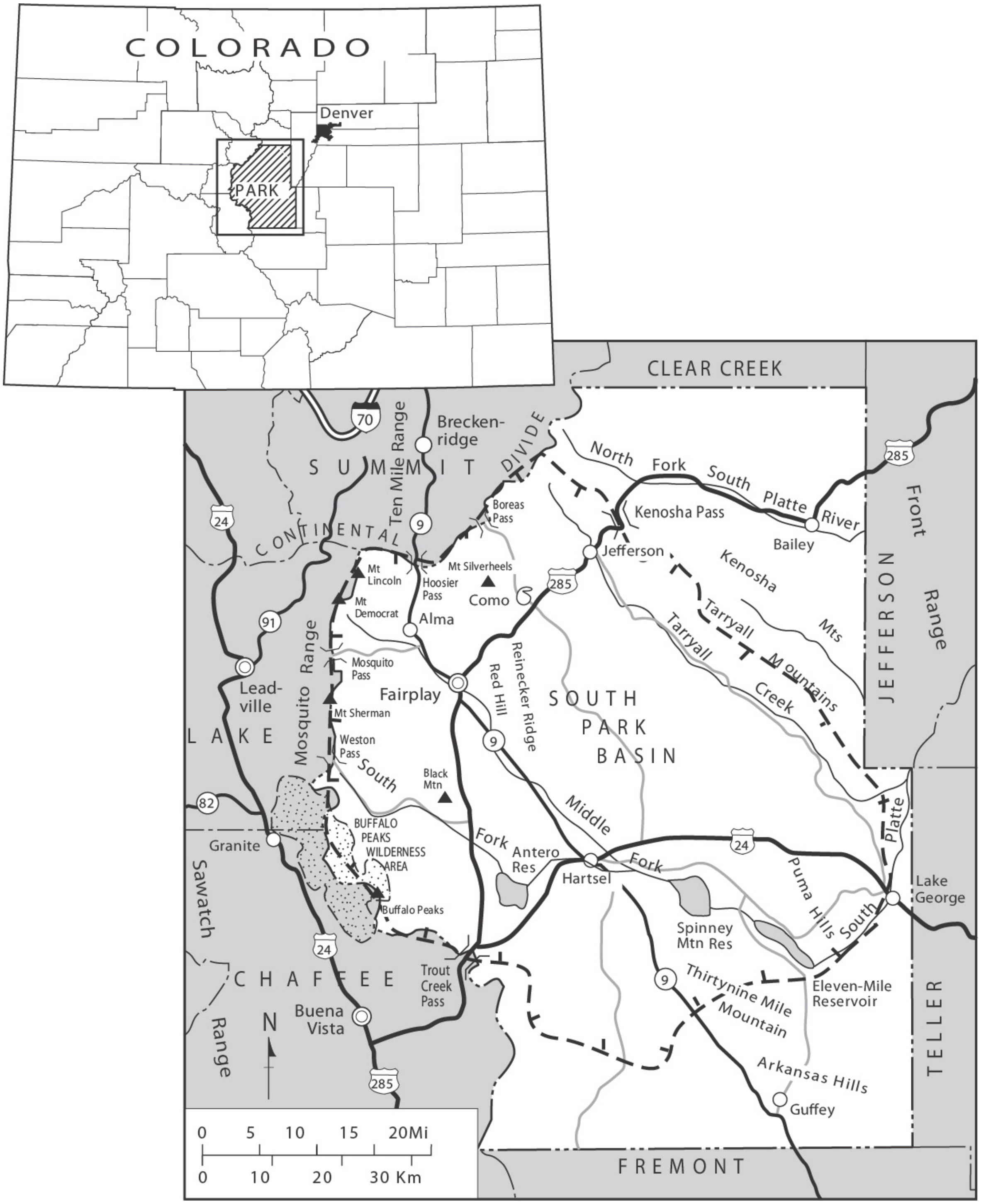


Figure 1. Regional map of the South Park groundwater quality scoping study area. The area covered by this study spans the watershed of the South Fork of the South Platte River from the Mosquito Range on the west to Tarryall Creek on the east and from the Continental Divide on the north to Thirtynine Mile Mountain on the south.

GENERAL GEOLOGY OF SOUTH PARK

REGIONAL SETTING

South Park is a topographic basin 50 miles long and 35 miles wide shaped by a long and varied history of geologic processes(Stark, and others, 1949; De Voto, 1971; Scarbrough, 2001; Ruleman, 2011). Major streams draining South Park include various forks of the South Platte River and Tarryall Creek, which have headwaters in the Mosquito Range and Boreas Pass area, respectively. These tributaries converge and exit through the Rampart Range at the south end of South Park near Lake George (Figure 1).

Generally speaking, the basin consists of eastward-dipping Paleozoic and Mesozoic sedimentary rocks preserved between uplifts of Precambrian igneous and metamorphic rocks on either side. Locally, Cretaceous and Tertiary igneous stocks, sills, and dikes intrude these rocks. Remnants of formally widespread Tertiary volcanic, lacustrine, and fluvial deposits overly the older rocks in many parts of the basin. The high ranges bordering South Park were subject to Quaternary glaciation with moraine and outwash deposits extending well into the basin.

Structurally, the basin is quite complex being dominated by the Laramide Sawatch uplift on the west and Front Range uplift on the east. Internally, the basin contains faulting and folding attributed by many to Late Cretaceous to Eocene Laramide deformation (Stark, and others, 1949; De Voto, 1971; Chapin and Cather, 1983; and Scarbrough, 2001). Deformation styles attributed to the Laramide event include thrust faulting, folding, and possible strike-slip faulting with widespread zones of deformation affecting most of the basin. The Neogene Rio Grande Rift system follows the upper Arkansas River valley just to the west, where it bisects the Laramide Sawatch uplift into the main Sawatch Range and the Mosquito Range, the latter forming the west boundary of South Park. Evidence of Neogene deformation related to the Rio Grande Rift can be found throughout South Park, as described by Ruleman and others (2011). In addition, there is evidence of ongoing local deformation related to dissolution and possible collapse of Paleozoic evaporite deposits (Kirkham and others, 2012).

MAJOR ROCK UNITS AND STRATIGRAPHY

This effort incorporates results of mapping at different scales from many sources spanning decades of work by many authors. Table 1 lists spatial data sources grouped by mapping scales. Primary sources consist of recent 1:24,000 quadrangle geologic maps produced by the CGS National Cooperative STATEMAP program and the USGS 1:100,000 30' X 60' quadrangle series. Data from older or smaller scale maps have been used to fill in where detailed mapping has not been available.

Over the years geologic mapping has expanded upon and enhanced the understanding of the origins of the many units present in the basin. Nomenclature of the geologic units found in the region has changed through this evolution in geologic interpretation. This scoping study uses the most recent nomenclature as published in the public domain, as shown in Figure 2. The following discussion groups formations by geologic settings that led to similar enough characteristics to simplify the geologic setting with respect to groundwater resources and energy resources. Figure 3 is a generalized geologic map that groups formations as units in the same manner. Figures 4 through 10 focus on these units individually and projects their extents in the subsurface where they may form aquifers buried beneath younger formations.

Table 1
Geologic Map Sources

Map Name	Authors	Scale	Year Published
Alma	Widmann and others	1:24,000	2004
Antero Reservoir	Kirkham and others	1:24,000	2012
Castle Rock Gulch	Wallace and Keller	1:24,000	2003
Como	Widmann and others	1:24,000	2005
Elkhorn	Ruleman and Bohannon	1:24,000	2008
Fairplay East	Kirkham and others	1:24,000	2006
Fairplay West	Widmann and others	1:24,000	2007
Garo	Kirkham and others	1:24,000	2007
Jefferson	Barker and Wyant	1:24,000	1976
Jones Hill	Widmann and others	1:24,000	2011
Marmot Peak	Houck and others	1:24,000	2012
Milligan Lakes	Wyant and Barker	1:24,000	1976
Sulphur Mountain	Bohannon and Ruleman	1:24,000	2009
Guffey	Wobus and Scott	1:62,500	1979
Bailey	Ruleman and others	1:100,000	2011
Park County	Scarbrough	1:100,000	2001

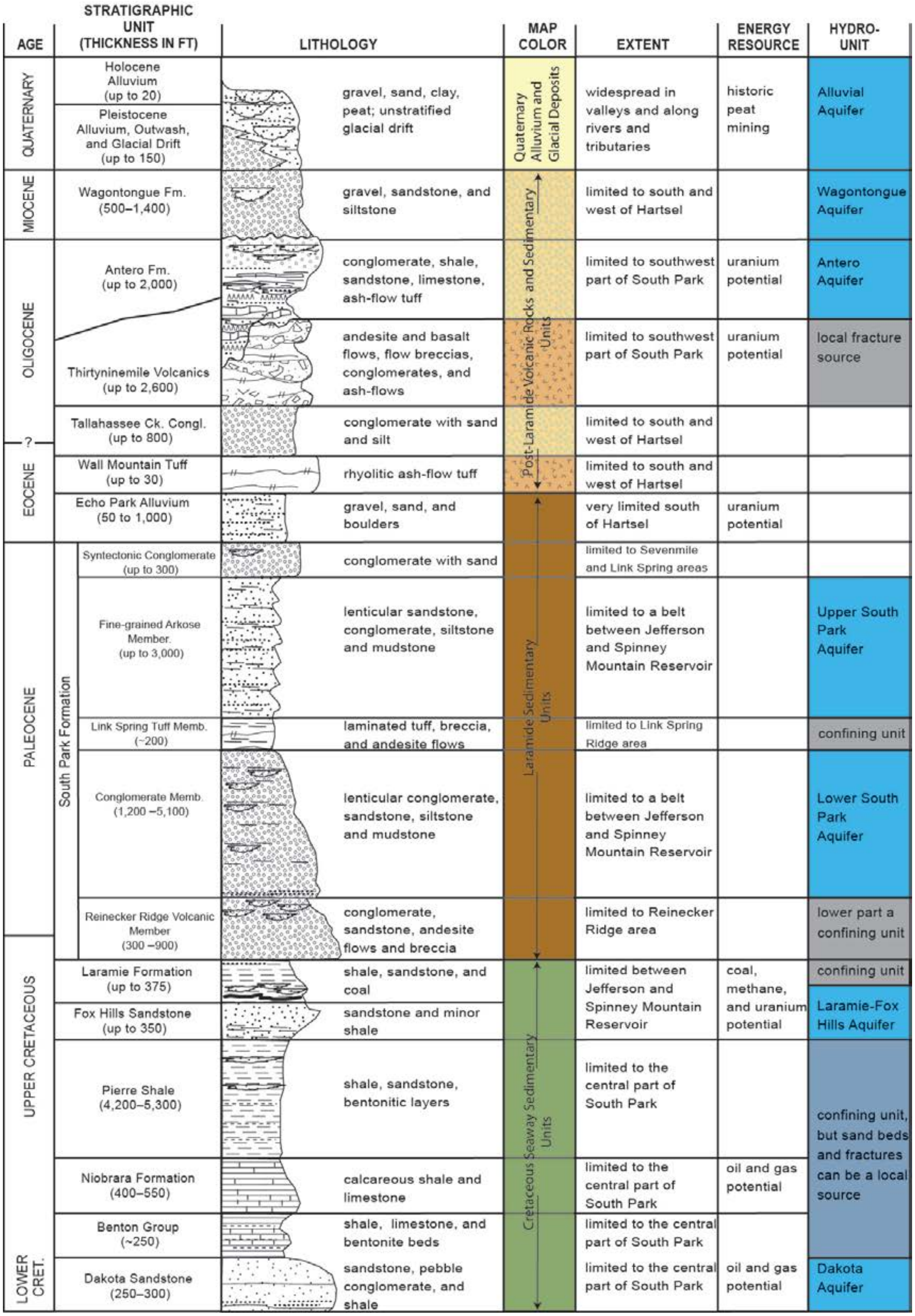


Figure 2a. Stratigraphic column showing units addressed in this study. Rock units and deposits within South Park span geologic Periods from Precambrian through Quaternary and represent widely differing environments and tectonic settings. 2a lists Quaternary through Lower Cretaceous units. Color column coincides with map units in the generalized geologic map in Figure 3.

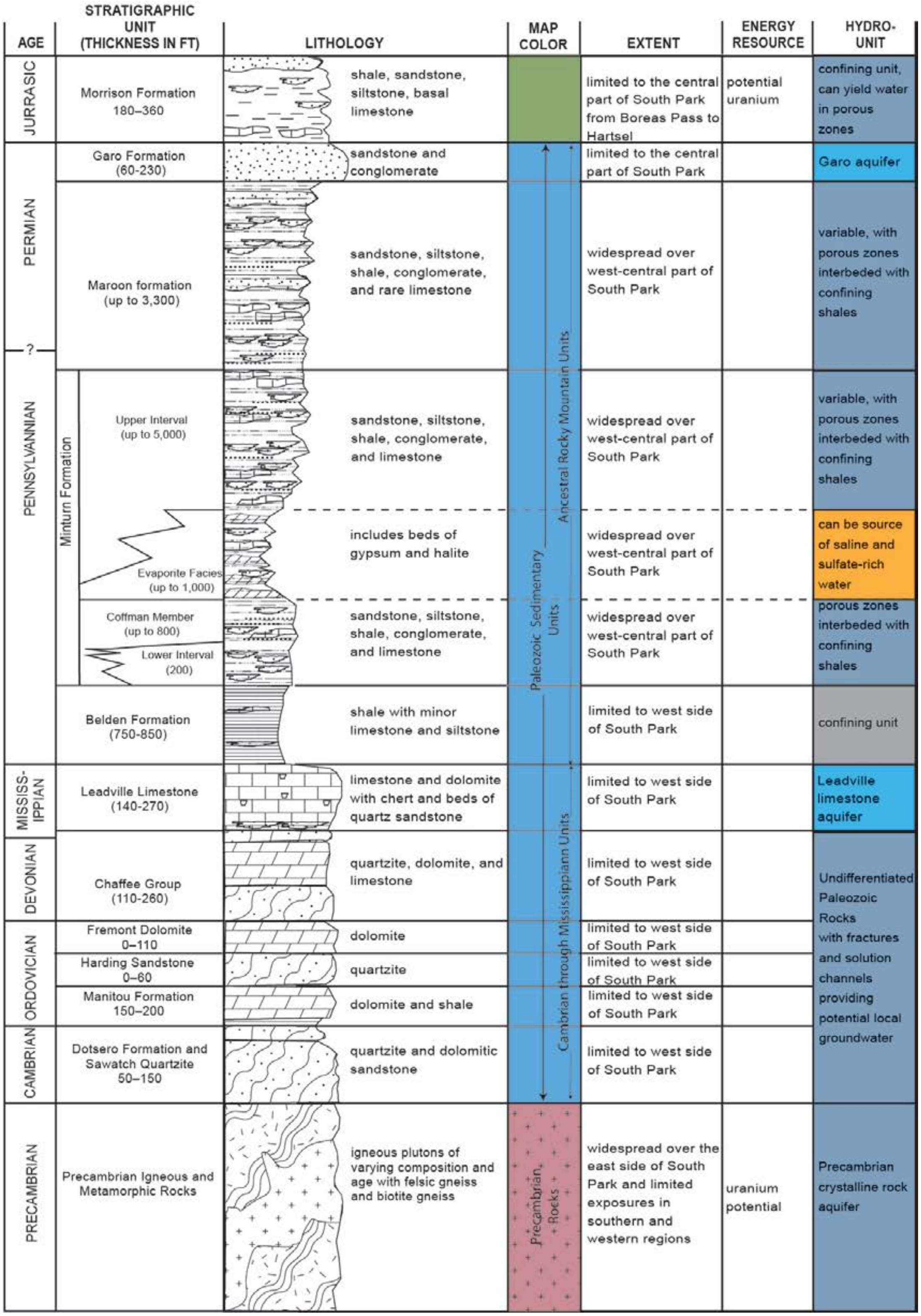
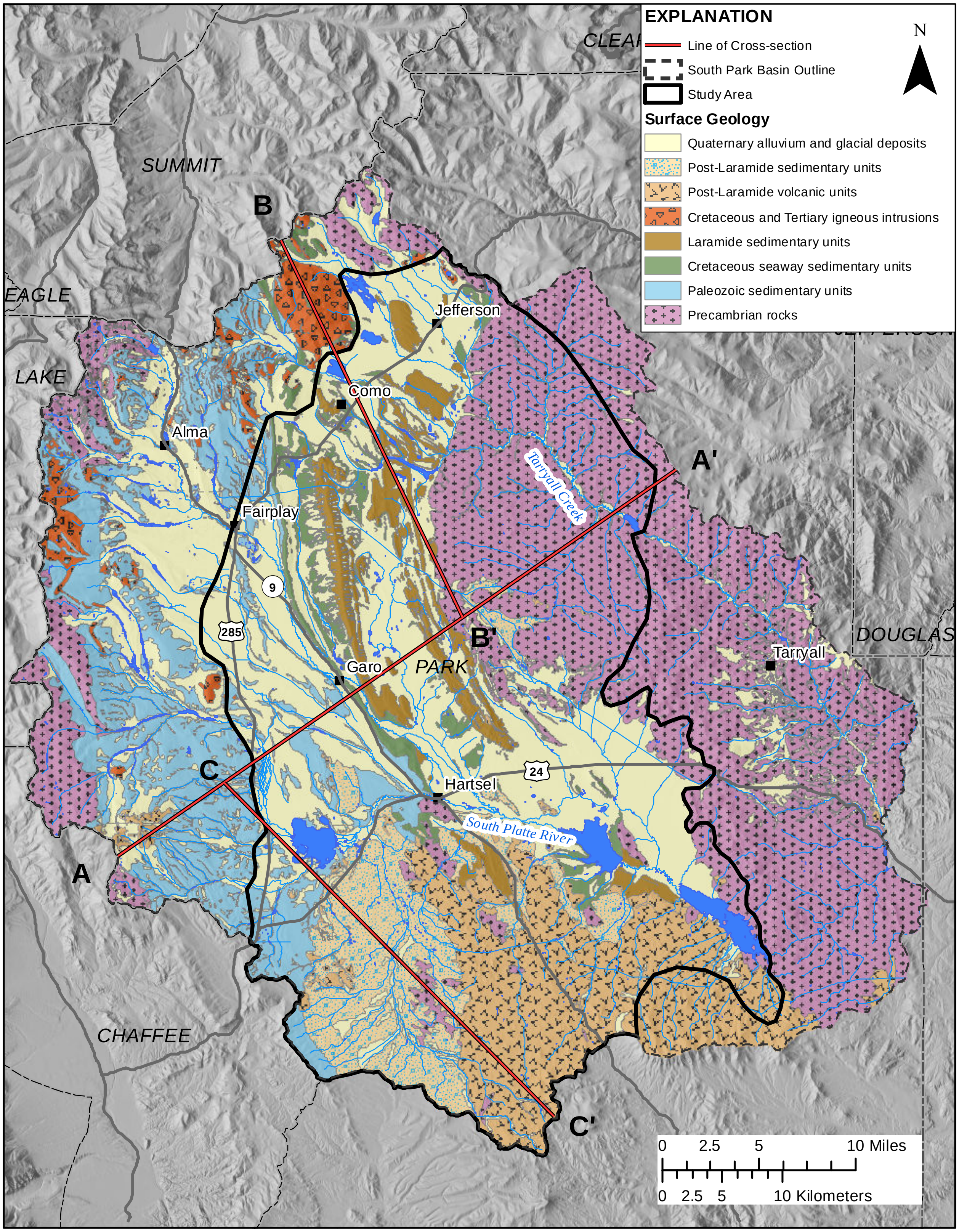


Figure 2b. Stratigraphic column showing units addressed in this study. Rock units and deposits within South Park span geologic Periods from Precambrian through Quaternary and represent widely differing environments and tectonic settings. 2b lists Jurassic through Precambrian units. Color column coincides with map units in the generalized geologic map in Figure 3.



Base from U.S. Geological Survey digital data, 1:100,000

Figure 3. Generalized geologic map of the South Park area

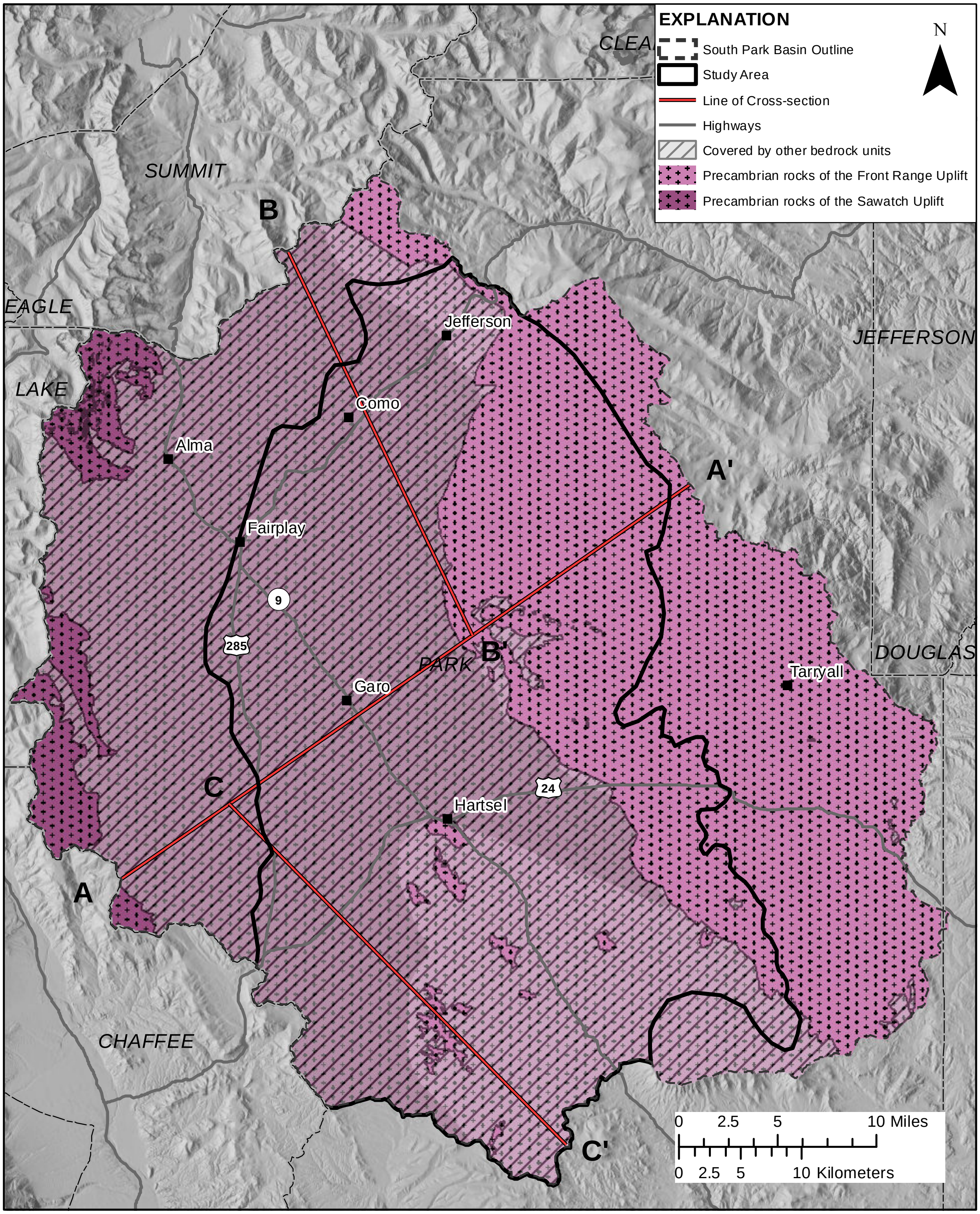


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Figure 4. Extent of Precambrian rocks in the South Park study area. Paleoproterozoic and Mesoproterozoic igneous and metamorphic rocks can be found at, or near the surface, in four areas of the South Park region including the bounding Mosquito Range on the west and Tarryall Range on the east as well as the Elkhorn upland within South Park. They also occur in isolated outcrops exposed beneath Tertiary volcanic and sedimentary cover south of Hartsel, shown as a hachured pattern in this map.

Precambrian Rocks

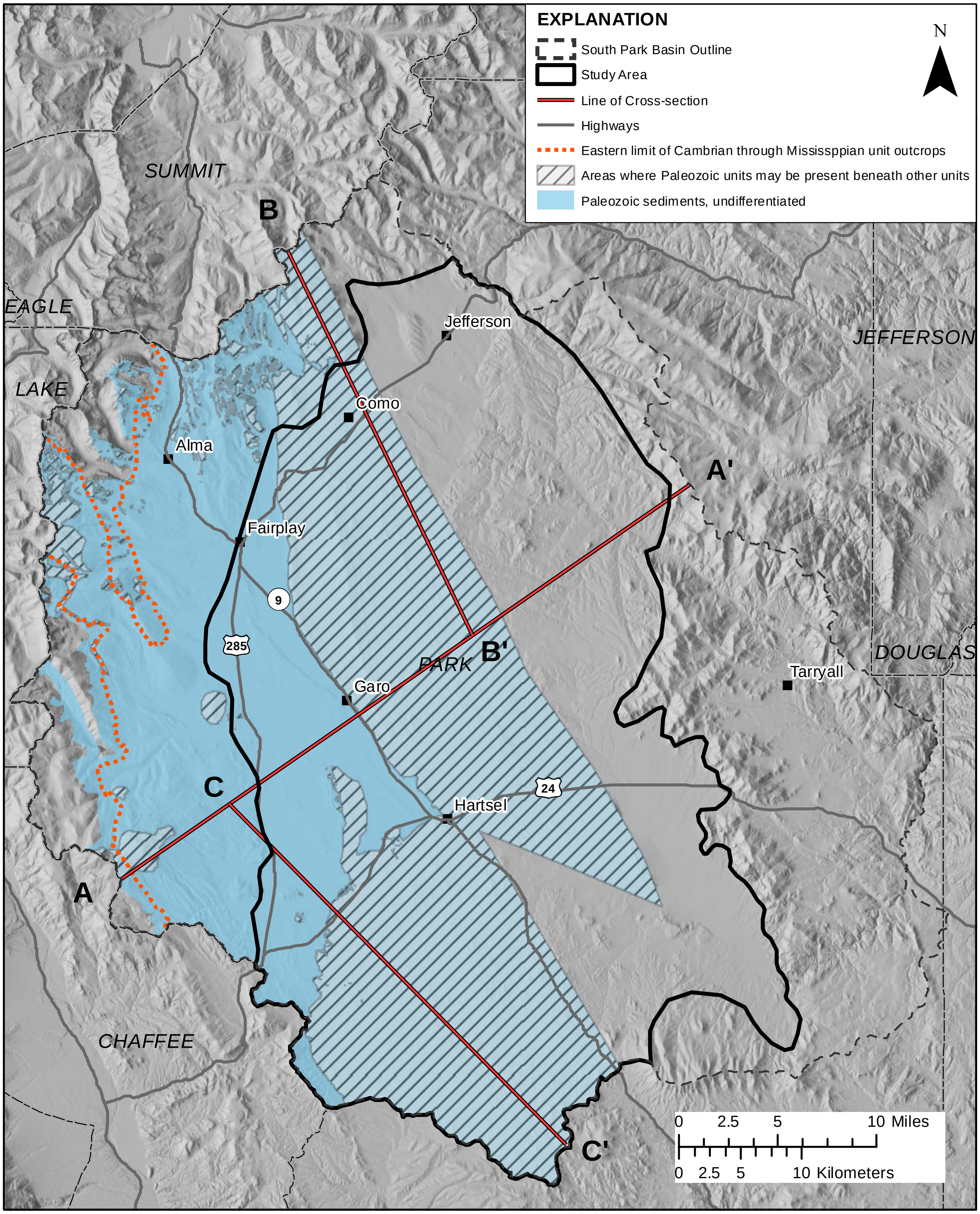
Precambrian igneous and metamorphic rocks are exposed at the surface, or can be found near the surface, in four areas in the South Park region shown in Figure 4. On the west side of the basin they form the core of the bounding Mosquito Range of the Sawatch uplift. They are widely exposed in the east-bounding Front Range uplift. Precambrian rocks also form widespread exposures in the Elkhorn upland west of Tarryall Creek (Ruleman and others, 2012), in an area considered part of South Park. Precambrian igneous rocks also appear as isolated outcrops beneath Tertiary volcanic and sedimentary cover between Hartsel and Thirtynine Mile Mountain. Elsewhere in South Park these rocks are deeply covered by younger units.

These basement rocks consist of older Paleoproterozoic(1,700 to 1,800 million year [Ma] old) biotite gneiss intruded by granite and quartz diorite. Mesoproterozoic(approximately 1,400 Ma) granite and monzogranite intrude the older units. The youngest of the Precambrian rocks found in the South Park area are the approximate 1,100 Ma granitic intrusives of the Pikes Peak Batholith exposed at the southeast end of the Tarryall Range and near Lake George.

Paleozoic Sedimentary Units

Cambrian through Mississippian Sedimentary Units

Cambrian through Mississippian sedimentary rocks underlie the western half of South Park (Figure 5). It is believed that the units extend as far east as a hypothesized buried edge of the Late Paleozoic Ancestral Front Range Uplift (De Voto, 1971; Ruleman and others, 2011). Although they are present at, or near, the surface in only a small area flanking the east side of the Mosquito Range on the west side of the study area they are discussed here collectively because they are recognized as aquifers elsewhere in the state. The units include the Cambrian Sawatch Quartzite and Dotsero Formation; Ordovician Manitou Formation, Harding Sandstone and Fremont Dolomite; Devonian Chaffee Group; and Mississippian Leadville Limestone. The basal Sawatch Quartzite overlies the Precambrian igneous and metamorphic rocks separated by a nonconformity representing a time gap of nearly 600 Ma.



Base from U.S. Geological Survey digital data, 1:100,000

Figure 5. Extent of Paleozoic sedimentary units in the South Park study area. Paleozoic sedimentary rocks extend across much of South Park. Their eastern extent is limited by the edge of the Late Paleozoic Ancestral Front Range uplift, a boundary that is not well constrained at depth. The dashed red line approximately delineates the contact between outcrops of Cambrian through Mississippian sedimentary units and the Pennsylvanian and Permian "Ancestral Rocky Mountain" sedimentary units within the Mosquito Range.

Pennsylvanian and Permian Sedimentary Units Associated with the Ancestral Rocky Mountains

Tectonic activity from Late Mississippian through Permian resulted in the development of a series of uplifts and downwarps across the region. Nesse (2007) has proposed *Anasazi Uplifts* as a term for the uplifted ranges. Erosion removed the older Paleozoic sedimentary rocks from the Precambrian metamorphic and igneous cores of the uplifts. Concurrently, clastic sediments, carbonates, and evaporite deposits accumulated in the subsiding basins (De Voto, 1971; Kirkham and others, 2007; Ruleman and others, 2011;Hauck and others, 2012; Kirkham and others, 2012). Orientations of these ancient uplifts and basins are not well constrained but are approximately defined by the distribution of the basins sediments that have survived subsequent tectonic disruption.

In South Park these accumulations of sediments are limited to the western half (Figure 5) where they consist of the Belden, Minturn, Maroon, and Garo Formations. The basal Belden Formation is predominantly fine grained marine shale with minor limestone, siltstone, and sandstone that is exposed along the western edge of South Park. It grades upward into the coarser-grained Minturn Formation which contains interbedded pebble to cobble conglomerate, sandstone, siltstone, and limestone, attesting to intensified tectonic activity of the Anazasi uplifts. The Minturn Formation also includes an evaporitic facies that contains thick beds of salt and gypsum suggesting restricted circulation and high evaporation rates within the subsiding basin (Kirkham and others, 2007). Although the extent of the evaporitic facies of the Minturn Facies is not well defined yet, this facies has particular relevance to structural and water quality aspects of this study. The Minturn Formation is exposed at or near the surface throughout much of the western portion of South Park.

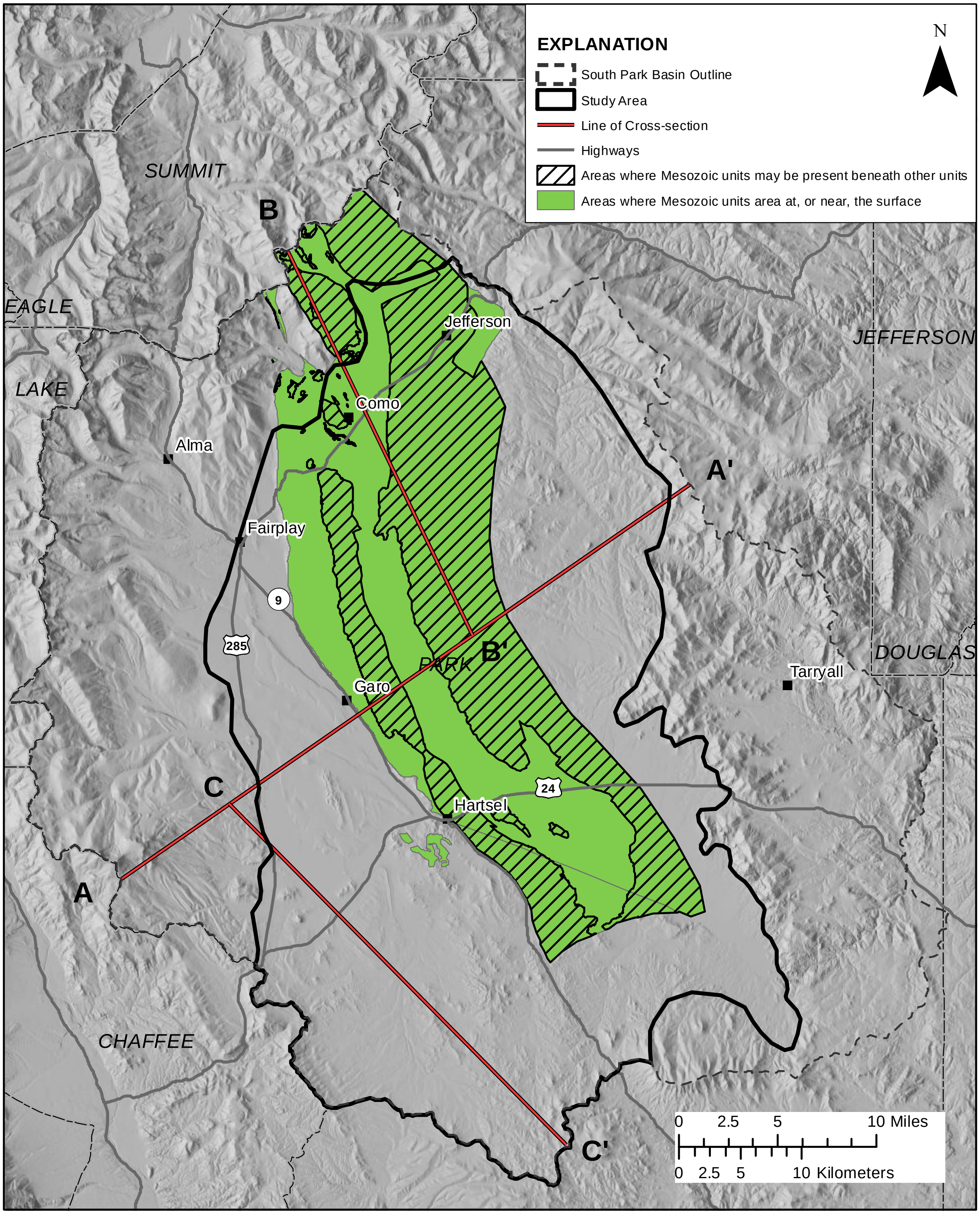
The Maroon Formation overlies and is gradational with the Minturn Formation. It closely resembles the Minturn Formation in composition but has a redder color and contains less limestone. The change reflects a transition away from a marine-dominated clastic wedge to a sub-aerial fluvial clastic wedge (De Voto, 1971; Kirkham and others, 2006). The Garo Formation consists of calcareous sandstone and conglomerate that may conformably overly the Maroon Formation (De Voto, 1971; Widmann and others, 2005). The unit forms a conspicuous hogback that separates the western part of South Park dominated by Paleozoic Rocks and the eastern part of the basin dominated by Mesozoic rocks and the Elkhorn upland. In the past, the Garo Formation and upper part of the Maroon Formation have been mapped as the Weber Formation (Stark and others, 1949) but that nomenclature is no longer used (Widmann and others, 2005).

Cretaceous Seaway Sedimentary Units

Cretaceous Seaway sedimentary units mark the encroachment and eventual retreat of the Cretaceous Interior Seaway. They are preserved in a broad arcuate belt that extends across the middle of South Park from the Continental Divide north of Como south to Hartsel (Figure 6). For the sake of simplification for this scoping study, this package of rocks includes the non-marine Jurassic Morrison Formation at its base. The Morrison Formation consists of interbedded shale, sandstone, claystone, and basal limestone (Widmann and others, 2005).

Conformably above the Morrison is the Cretaceous Dakota Formation which consists of sandstone, pebble conglomerate, and non-calcareous shale (Scarbrough, 2001) deposited along the shoreline of the advancing Interior Seaway. Volumetrically, marine shale dominates this group of sediments that accumulated over the 30 to 40 Ma period during which the Interior Seaway occupied the region. It includes, from bottom up: shale and limestone of the Benton Group; limestone and calcareous shale of the Niobrara Formation; and interbedded shale, bentonite, and minor sandstone of the Pierre Shale. The Niobrara Formation is the target of recent source bed petroleum exploration throughout the Rocky Mountain region that has prompted this scoping study.

The Pierre Shale grades upward into the Fox Hills Sandstone. The Fox Hills Sandstone was deposited in near-shore and beach environments of the retreating Interior Seaway. Eastward retreat of the Seaway caused individual overlapping sandstone bodies to climb up-section and become progressively younger to the east. The Fox Hills Sandstone is in turn overlain by, and interfingers with, non-marine Laramie Formation. This upper unit of the group consists ofoverbank shale interbedded with lenticular beds of sandstone deposited on a low-relief coastal plain following the retreat of the Interior Seaway. This formation includes coal beds near its base that were exploited in the 19th and early 20th century.



Base from U.S. Geological Survey digital data, 1:100,000

Figure 6. Extent of Mesozoic sedimentary units in the South Park study area. Cretaceous Seaway sedimentary rocks are found in an arcuate belt that crosses the middle of South Park. This group of units includes deposits of the Cretaceous Interior Seaway from the transgressional basal Dakota Formation up through the regressional Laramie Formation. It contains thick accumulations of marine shale such as the Niobrara Formation, which is the target of recent petroleum exploration. The units may extend eastward beneath younger units and overhanging fault blocks as indicated by hachured pattern units to the east. Because of its limited extent in the basin, the non-marine Jurassic Morrison Formation is included in this unit.

Laramide Sedimentary Units

Late Cretaceous, Paleogene, and Eocene sediments record the evolution of the Laramide uplift throughout the Rocky Mountain region (Chapin and Cather, 1983; Raynolds, 1997). During this period of uplift, which lasted from approximately 70 Ma to 50 Ma (Dechesne and others, 2011), a series of Precambrian basement-core blocks rose to the surface while basins subsided between and flanked the blocks. Clastic sediments shed off of the rising blocks accumulated in the intervening basins. Concurrent igneous activity contributed volcanic material to the sedimentary basin fill. Geometry and style of uplift may have evolved and changed during this prolonged period of uplift and details are still being unraveled through surface and subsurface mapping over the past 100 years and continuing today. Chapin and Cather (1983) point out that the Laramide uplift appears to have evolved through two major phases separated by a period of quiescence (Raynolds, 1997).

Although modified by later Neogene events (Ruleman, 2011), Laramide tectonism generated much of the South Park basin geologic framework as it appears today. Flanked by the Sawatch uplift to the west and the Front Range uplift to the east, an early form of the South Park basin accumulated a thick sequence of clastic sediments. These sediments have been mapped as the South Park Formation (Sawatzky, 1967) and Echo Park Alluvium (Chapin and Cather, 1983) found in a north trending belt through the center of South Park (Figure 7). The South Park Formation represents the early phase of Laramide uplift when Precambrian basement blocks first emerged and while the Echo Park Alluvium represents a later phase of renewed uplift and possible wrench faulting (Chapin and Cather, 1983).

The South Park Formation has been subdivided into six members, both formal and informal, based on compositional differences reflecting changes in source areas as Laramide tectonism evolved (Ruleman and others, 2011). At its base is the Upper Cretaceous *volcaniclastic member*(informal name), derived from local volcanic sources but very limited in extent, hence it is not shown in Figure 2. Above this is the Cretaceous to Paleocene *Reinecker Ridge Volcanic Member* (formal name) that contains flows and breccias of tracyandesite, andesite, and dacite (Widmann and others 2005). Thickness relationships indicate a source to the north (Kirkham and others, 2006). The Paleocene *conglomerate member* (informal name) is next and contains clasts of the older volcanic material mixed with clasts of limited Precambrian basement, Paleozoic rocks, and Cretaceous intrusives indicating a source from the Sawatch uplift to the west (Widmann and others, 2005; Kirkham and others, 2006). In places the conglomerate member is overlain by the Paleocene *Link Springs Tuff Member* (formal name) which consists of laminated tuff with some volcaniclastic breccia and andesitic flows (Ruleman and others, 2011). A *fine-grained arkosic member* (informal name) thins to the south and unconformably overlies the Link Springs Tuff Member in the north and the conglomerate member in the south. The arkosic content and lack of clasts of Paleozoic sedimentary rocks indicates a possible source from the Front Range uplift to the east for this later unit.

A poorly sorted, boulder-rich conglomerate believed to be derived from local Precambrian sources overlies the other South Park Formation members that Ruleman and others (2011) have informally named the s*yntectonic conglomeratic unit*. It occurs along the perimeter of the Elkhorn upland and may have been deposited as the block of Precambrian rock to the east was uplifting. Although not considered part of the South Park Formation, the Echo Park Alluvium is included in this section because of possible origins during the latest phases of the Laramide uplift. This unit is also a boulder-rich, poorly stratified alluvium limited to small areas in the southern part of South Park. Chapin and Cather (1983) believe this unit was deposited as fault-bound basins formed by regional wrench faulting at, or near, the end of the Laramide event. The relationship of the Echo Park Alluvium in the southern part of the basin to the syntectonic conglomeratic unit in the north is not clear but they may be related to the same phase of the Laramide uplift.

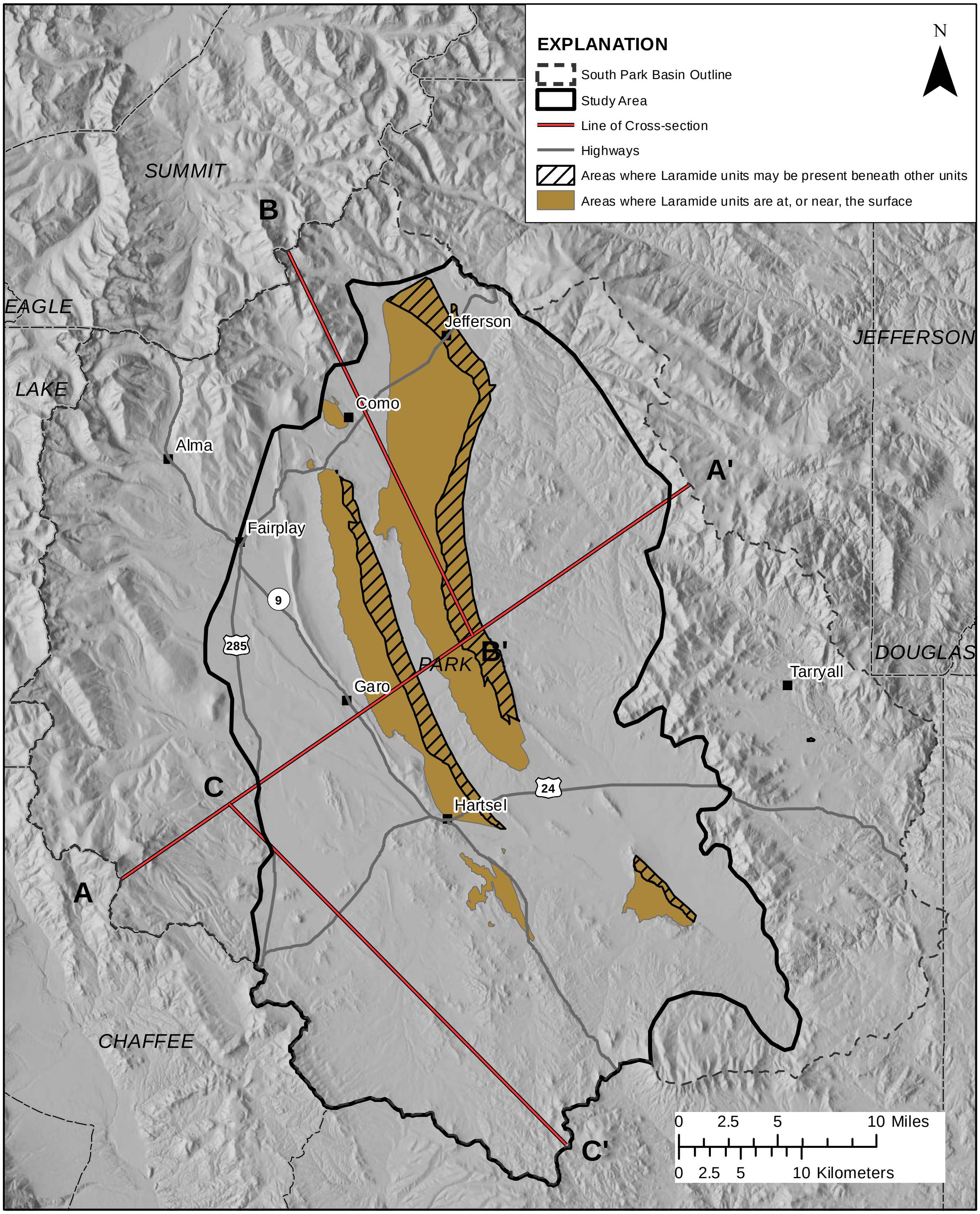


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Figure 7. Extent of Laramide sedimentary units in the South Park study area. Cretaceous and Tertiary sedimentary units associated with the Laramide uplift occur in two north-trending belts through the middle of South Park. Imbricate thrust faults separate the two distinct belts. The units may extend eastward beneath the overhanging fault blocks as indicated by hachured pattern.

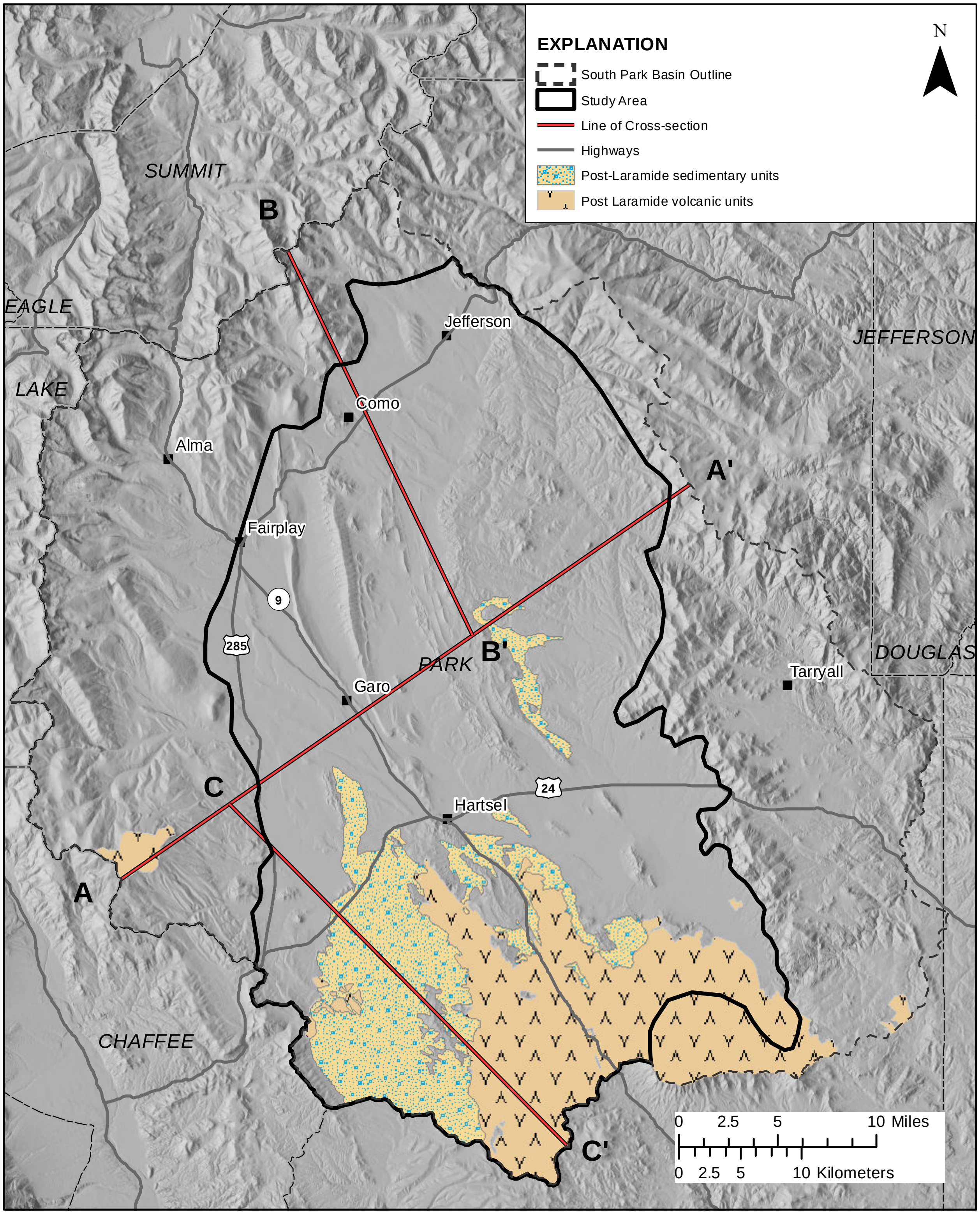

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Figure 8. Extent of Post-Laramide volcanic and sedimentary units in the South Park study area.
A series of fluvial sedimentary deposits and volcanic rocks have been preserved the southern part of South Park where they cover older formations and structures.

Post-Laramide Volcanic Rocks and Sedimentary Units

The region continued to be modified by tectonism following the Laramide uplift, although the style changed. Rock units in South Park record continued volcanism accompanied by fluvial and lacustrine sedimentation (Figure 8). The late Eocene Wall Mountain Tuff blanketed a large part of the region and was sourced from a postulated caldera northwest of Salida(Chapin and Lowell, 1979) and small remnants have been preserved scattered across much of the southern part of South Park (Scarbrough, 2001; Wallace and Keller, 2003; Ruleman and others, 2011; Kirkham and others, 2012). The Oligocene Tallahassee Creek Conglomerate consists of fluvial sediments with sizes up to boulders, containing clasts of varied composition reflecting the variety of rocks exposed in South Park by that time. This unit fills paleovalleys scattered across much of the southern part of South Park (Scarbrough, 2001; Kirkham and others, 2012).

The next phase of volcanism to affect the region was eruption of the Oligocene Thirtynine Mile volcanic field at the south end of South Park (Scarbrough, 2001). Basaltic to andesitic flows, breccias and tuffs blanket much of Southern Park County concealing older rocks and geologic structures below. The Antero Formation laps onto the Thirtynine Mile volcanic complex (Kirkham and others, 2012). This complex unit consists of fluvial sediments shed off of the eroding highland interbedded with lacustrine deposits, including limestone, formed in a restricted basin north of the volcanic field. The Miocene Wagontongue Formation is another conglomeritic unit of mixed lithologies that unconformably overlies the Antero Formation southwest of Hartsel. A more conglomeratic facies of the Wagontongue was previously mapped as the Trump Formation based on its prevalence in the southwest part of the region (Stark and others, 1949; Wallace and Keller, 2003). Recent mapping in the Hartsel area does not differentiate the two facies (Ruleman and others, 2011; Kirkham and others, 2012). This unit unconformably overlies earlier units and indicates a return to a higher energy fluvial environment possibly related to initiation of Cenozoic extensional tectonism.

Cretaceous and Tertiary Igneous Intrusions

There are a number of igneous intrusions with Late Cretaceous through Tertiary ages primarily in the northern part of the South Park region (Figure 9). Many of the mapped intrusions are of felsic to intermediate composition concentrated in the Mosquito Range and Continental Divide (Scarbrough, 2001). Sills, dikes and small stocks of similar composition can be found within South Park. Although these intrusive bodies are discontinuous and cover a very small aerial extent of the basin, they have some relevance to groundwater and water quality. Intrusive bodies can serve as conduits or barriers for groundwater flow depending on degree of alteration and fracturing. Potential alteration can also introduce mineralogy such as metal sulfides that can impact natural water quality conditions.

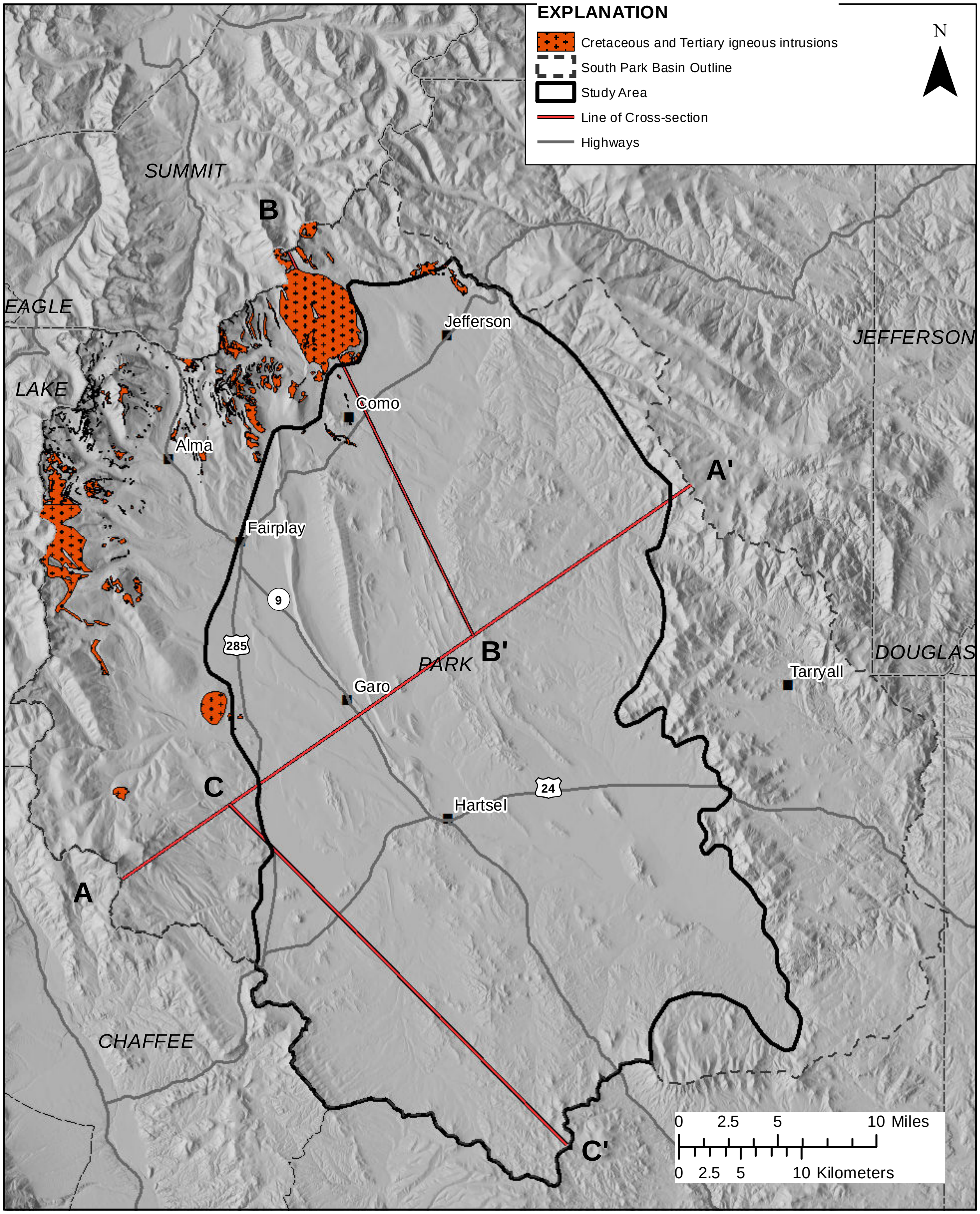

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Figure 9. Distribution of Cretaceous and Tertiary igneous intrusions in the South Park study area. Felsic to intermediate igneous bodies intrude the deformed sedimentary units along the west and northwest edges of the basin. Many of these intrusions are attributable to mineralization of this important mining district.

Quaternary Alluvium and Glacial Deposits

Quaternary deposits include extensive glacial drift and outwash deposits along with post-glacial alluvium along modern streams (Figure 10). Alpine glaciers during several stages carved the higher valleys of the Mosquito Range along the west side of South Park and Continental Divide to the north. Glacial drift left behind by these glaciers form moraine complexes at the mouths of valleys at the base of the ranges (Widmann and others, 2004 and 2007). Outwash deposits form series of terraces that extend out into the park from these moraine complexes. Mountains on the east and south sides of South Park as well as interior ridges and highlands do not display evidence of past glaciations, yet alluvial deposits do occur along streams originating from them (Ruleman and others, 2011).

The manner in which these many Quaternary deposits have been mapped has varied between geologists over time. Classification schemes and nomenclature as well as interpretations of relationships with alluvial deposits in areas not directly affected by glacial sedimentation have changed over time. For the purposes of this scoping study, Quaternary deposits in South Park generally fall into three main age groups, older, intermediate and younger Pleistocene, followed by Holocene. Older deposits form relatively thin veneers on terraces that stair-step down, from oldest to youngest, to modern stream courses. Modern streams and corresponding flood plains follow bands of the youngest Holocene and late Pleistocene deposits.

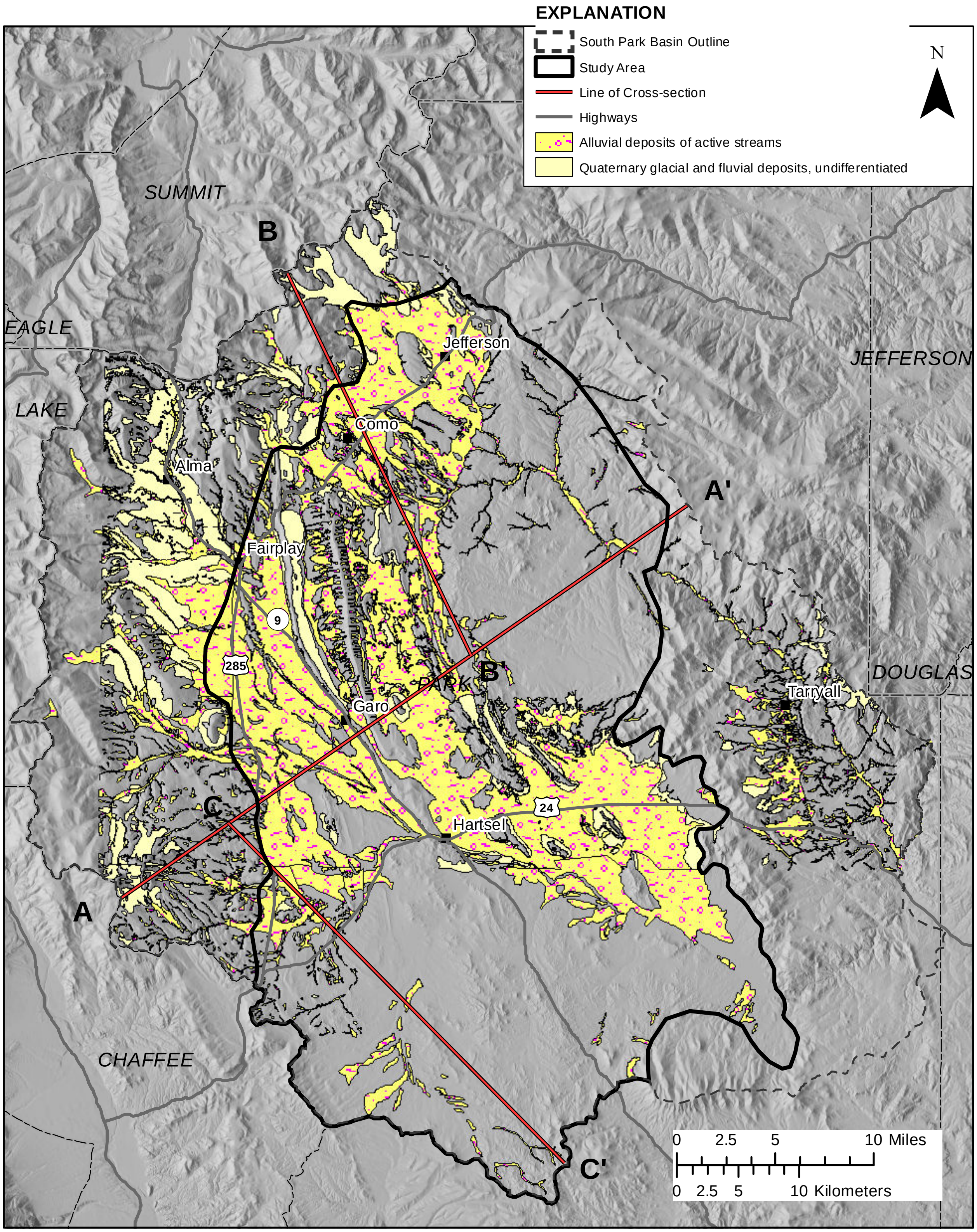

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Figure10. Extent of Quaternary alluvium and glacial deposits in the South Park study area. Unconsolidated Quaternary and Holocene deposits blanket much of the area and include glacial drift and outwash along with deposits of alluvium associated with the modern streams.

STRUCTURAL GEOLOGY

The structural setting of South Park is quite complex owing to its long and varied evolution. Simply viewed, the basin can be described as an east-dipping block between two Laramide uplifts (Figure 11). The Elkhorn Fault system forms the east boundary of the tilted block where it drops against the uplifted Front Range. Internally, this block has been deformed by folding and faulting with the structural grain exhibiting a prevailing northwest trend. Many faults and folds have been mapped by workers in South Park over the years (Figure 12). Interpretations of individual structures have varied from author to author and over time. Consequently, there is poor nomenclature consistency and match between maps and for various fold and fault systems. For example, earlier mapping (Stark and others 1949; DeVoto, 1979) show a number of large-scale folds throughout the basin as shown in Figure 12. More recent mapping efforts indicate the structural zones as faults with associated changes in attitudes (Widmann and others 2005; Ruleman and others 2011). The variety in interpretations of structures is in part due to poor exposures that prevent following individual features across the landscape. It also reflects the complexity of the region and the fact that a unifying model for deformation through the multiple phases of tectonism may not yet have been devised to facilitate mapping of the features. The following discussion provides a brief summary of the evolution of the basin and describes principal features that appear to be relevant to regional groundwater conditions.

Figure 11. Regional Cross-sections through South Park. These cross-sections illustrate changes in distribution of each of the major rock types across South Park. The simple view is of an east dipping block between two Precambrian-cored uplifts, the Sawatch Range on the West and the Front Range on the east. Internally, the structures are quite complex dominated by a series of east-dipping reverse and thrust faults east-side over west.

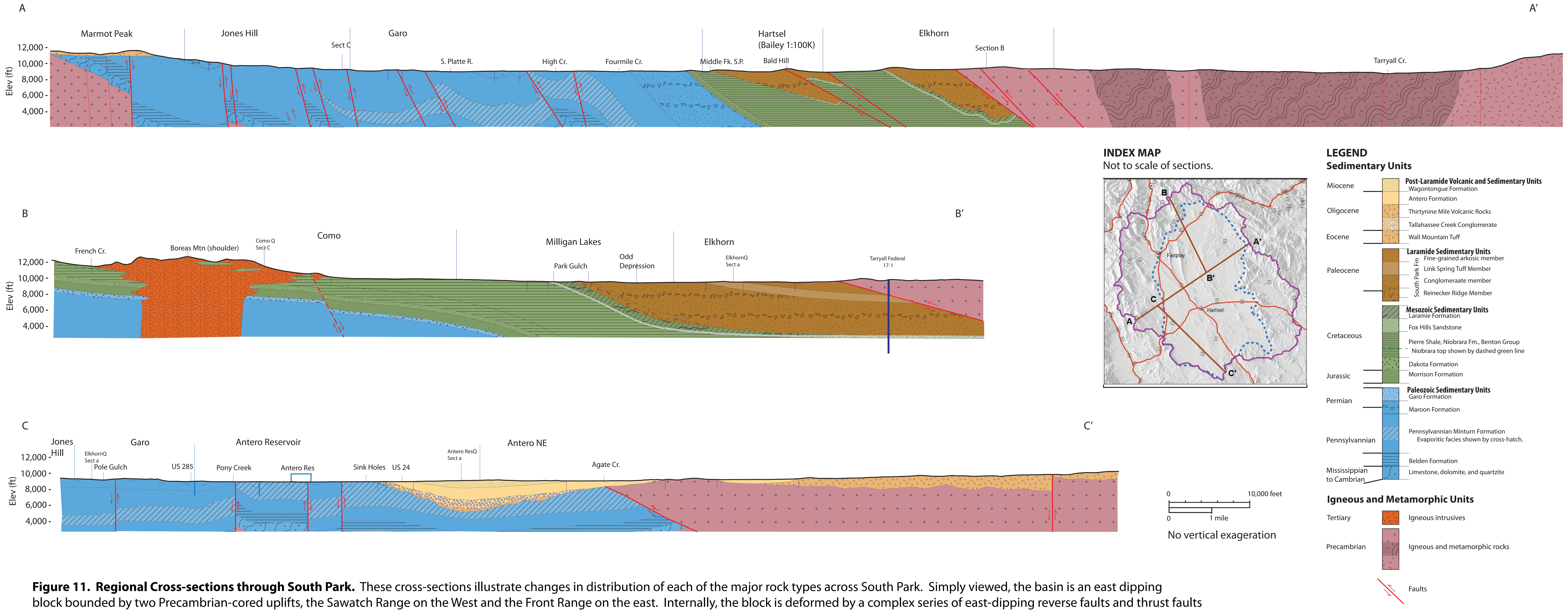

Figure 11. Regional Cross-sections through South Park. These cross-sections illustrate changes in distribution of each of the major rock types across South Park. Simply viewed, the basin is an east dipping block bounded by two Precambrian-cored uplifts, the Sawatch Range on the West and the Front Range on the east. Internally, the block is deformed by a complex series of east-dipping reverse faults and thrust faults exhibiting east over west displacements cross-cut by normal and strike-slip faults. Where present, evaporitic facies within the Pennsylvanian sedimentary units bay be further deformed by flow and dissolution.

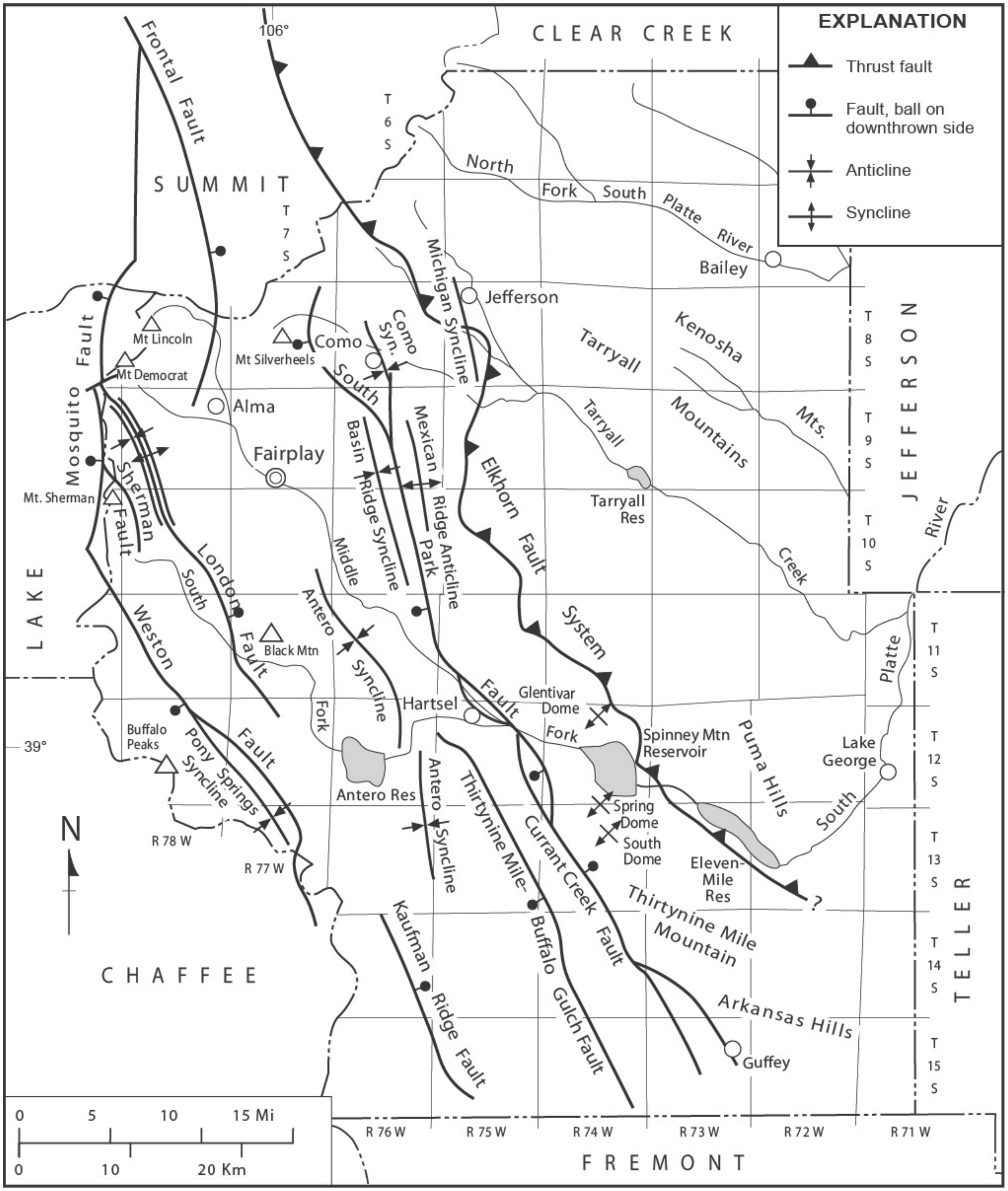

Figure 12. Map of principal structural features in the South Park area. This map, adapted from Scarbrough, 2001, shows the many major folds and fault systems in South Park recognized by previous authors. A series of predominantly northwest-trending faults and folds traverse the area creating a complex structural grain.

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Structural Evolution of South Park

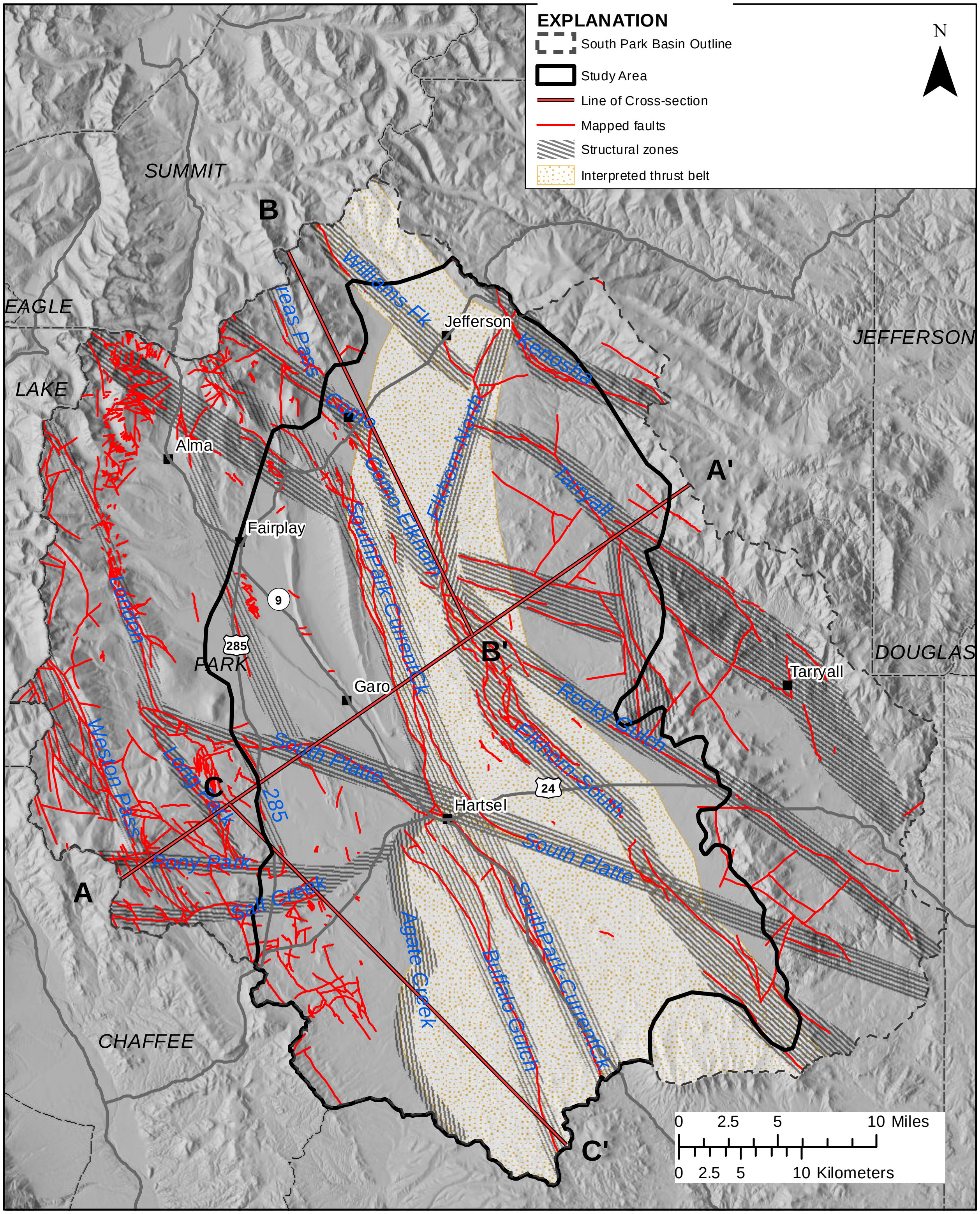
South Park has undergone a long and complex structural evolution. Phases of this evolution most relevant to groundwater resources and water quality reach back to the Pennsylvanian-Permian Anazasi uplifts and development of the Minturn-Maroon trough (DeVoto, 1979; Ruleman and others, 2011). This trough extended in a north-northwest direction through the region and accommodated deposition of the Minturn and Maroon Formations. Bounding features of the uplifts are not well constrained; however, some authors (DeVoto, 1971; others; Ruleman, 2011) have proposed that a concealed fault with a trend and location similar to the South Park Fault (Figure 12) may have formed the west edge of the ancestral Rocky Mountain uplift, and the east edge of the Minturn trough. Distribution of the evaporiticfacies in the Minturn Formation suggests that that fault may not have been the edge during its deposition. This leads to the question about timing of movement on a fault at depth bounding the trough. Widmann and others (2004; 2005) argue that the Pennsylvanian sediments may have lapped on to the eastern highland. The apparent abrupt termination of the evaporitefacies shown by Devoto (1979) and Kirkham (2012) suggest a more complicated structural history at the edge that may include multiple phases of uplift along different fault systems separating the ancient uplift and trough.

Following the Anazasi uplift phase, the region underwent erosion to a generally flat sub-aerial landscape from Permian through Jurassic times accompanied by deposition of the Garo and Morrison Formations. The next important phase of structural evolution began during the Cretaceous Period marked by a broad regional downwarp that accommodated the Western Interior Seaway. Marine sediments blanketed the entire Rocky Mountain region for a period of over 30 to 40 Ma (Cobban, 1993; Cobban and others, 2006). This thick accumulation of organic-rich sediments includes many sandstone, shale, and limestone units from the Dakota Formation up through the Fox Hills Sandstone (Figure 2).

The next phase of tectonism began in the Late Cretaceous with initiation of the Laramide uplift. In its early stages, this phase of tectonism may have been the result of east to northeast directed compression (Chapin and Cather, 1983). An early hint of this phase was retreat of the Interior Seaway and deposition of the Fox Hills shoreline. Eventually, basement-cored uplifts rose to be stripped of older Paleozoic and Mesozoic sedimentary cover exposing their Precambrian basement cores (Raynolds, 1997). Locally this was accompanied by volcanism. This sequence of uplift and denudation is recorded in the sediments preserved in the basins between uplifts. Fine-grained sediments dominate the Laramie Formation, which may represent denudation of the thick sequence of Cretaceous Interior Seaway sediments. Next, the South Park Formation records progressive stripping of volcanic rocks and Paleozoic sediments down to the Precambrian igneous and metamorphic rocks were exposed. The presence of clasts of Paleozoic sediments in the Conglomeritic member of the South Park Formation indicates a western source (Widmann and others, 2005; Kirkham and others, 2006). In contrast, the granitic composition of the upper Fine-grained arkosic member indicates an eastern source. This compositional contrast suggests that the Sawatch uplift, which contained Paleozoic sediments, preceded the Front Range uplift, which had already been stripped of that very same Paleozoic cover during the Pennsylvanian Anazasi uplift. The unconformity at the base of the South Park Formation, which indicates erosion of more section to the west and preservation on the east (Figure 11) provides further evidence of earlier uplift on the west side. Another piece of evidence of later timing of the Front Range uplift is westward verging deformation of the older South Park Formation by the Front Range uplift.

Chapin and Cather (1983) have proposed that the later stages of the Laramide event reflect a change to a more northerly directed compressive stress. The style of deformation may have changed from one dominated by westward verging folding and faulting to one of right-lateral wrench faulting. This later phase may have been characterized by the growth of smaller fault-bound basins that accommodated the Echo Park Alluvium.

The most recent phase of tectonism affecting the region has been development of the Rio Grande system which extends up through Central New Mexico into Colorado. Development of this system represents transition to an extensional stress environment which overprinted older structural features. The main part of this rift system passes through the upper Arkansas Valley just to the west where it separates the former Sawatch uplift into the modern Sawatch Range and the Mosquito Range. A number of faults in South Park display evidence of movement related to this phase of tectonism (Ruleman and others, 2011). Indeed, the topographic expression of the Tarryall Range rising above the Elkhorn upland, both parts of the former Laramide Front Range uplift, may be attributed to Late Tertiary movement along faults parallel to Tarryall Creek.



Base from U.S. Geological Survey digital data, 1:100,000

Figure13. Map of structural zones in the South Park area. Recent mapping efforts have identified many faults within South Park. Although the pattern can be complex, it is possible to group faults into zones where a greater number with similar trends have been mapped.

Primary Laramide Structural Features

Figure 13 is a generalized map that shows the major fault systems as bands of deformation rather than distinct linear traces. Most faults and folds in South Park have been attributed to Laramide deformation, although many, such as the South Park Fault zone, may have origins from earlier tectonism(DeVoto, 1979).

The Eklhorn Fault zone dominates the structural terrain where it forms the eastern boundary separating the Precambrian Front Range uplift to the east from the tilted sedimentary block to the west. Its follows a sinuous trace that has supported the interpretation of it as a low angle thrust fault (Stark and others, 1949; Sawatzky, 1964; Barker and Wyant, 1976; Wyant and Barker, 1976; Bryant and others, 1981; Ruleman and Bohannon, 2008; Ruleman and others, 2011). It has been suggested that it continues north to connect with the Williams Fork Thrust fault north of the Continental Divide (Kellogg and others, 2008) To the south it may connect with a mapped thrust fault at Spinney Mountain (Sawatsky, 1967). The Elkhorn Fault system is difficult to follow further to the southeast where it crosses into the area covered by Tertiary volcanic and sedimentary units.

In 1992 Hunt drilled the No. 17-1 Tarryall Federal to a depth of 12, 768 ft. through the Precambrian hanging wall of the Elkhorn Fault (Steyaert and Wandrey, 1997). The well penetrated South Park Formation at a reported depth of 1900 feet before drilling into the Upper Cretaceous marine section. The depth of the reported fault at the distance to the outcrop of the fault gives an angle of approximately 35°. Durrani (1980) argues that the southern trace near Hartsel is a high angle reverse fault and Ruleman and others (2011) provide evidence that the northern segment near Jefferson is a normal fault. This fault may very well be very complicated displaying changing geometry along its trace as a result of its long complex history of movement.

The South Park Fault system is another Laramide fault system just west of the Elkhorn that deforms the Cretaceous sediments from Dakota up through Paleocene South Park Formation. It consists of several splays in the central part of South Park that may all be part of the same zone of deformation or separate thrusts (Sterne, 2006). As with the Elkhorn Fault, this fault places the east side up above the west side. It is difficult to extend this zone as a discrete fault north in the direction of Boreas Pass. To the south it may connect with the Current Creek Fault system that deforms the Tertiary volcanic and sedimentary units (Scarbrough, 2001). Sense of displacement in younger rocks to the south is opposite of that observe to the north in older rocks that may reflect reactivation of the Laramide feature within the different extensional environment.

Two other fault systems on the west side of the basin have been considered major features bounding the basin believed to have Laramide origins. The London Fault at the northern end of

South Park has also been mapped as an east-dipping reverse fault that places the east side above the west (Widmann and others, 2007). The zone of deformation that this fault follows continues to the southwest to include the 285 fault mapped by Kirkham and others (2012). In this area Kirkham has mapped many of the faults as strike slip faults with left lateral displacement prevalent. The Weston Fault zone is the furthest west feature in the South Park study area that shares characteristics with the London Fault zone. It too places the east side up relative to the west. Sterne (2006) interprets this to be yet another east-dipping thrust fault.

Other structural zones shown in Figure 13 may play important roles in the structural evolution of the Basin. These include the Agate Creek zone west of Hartsel, the South Platte zone that passes beneath Hartsel, and the Tarryall zone at the east side of the Basin. The Agate Creek zone bounds the west side of the structural block often referred to as the Hartsel Ridge. It also forms the eastern boundary of the extent of the Minturn-Maroon sediments in the southern part of the Basin. It has been shown as a high-angle feature by previous authors (DeVoto, 1979) however it's sinuous trace and the apparent eastward thickening of Minturn evaporitefacies adjacent to it (Kirkham and others, 2012) suggest a lower angle reverse fault or thrust. The South Platte zone is a northwest trending zone that separates the Elkhorn highlands from Hartsel Ridge that has not received wide recognition, yet it appears to affect patterns of distribution of many units. There is an apparent right lateral offset of uplifted Precambrian rocks across this zone from the Elkhorn highland to the Hartsel Ridge. Paleozoic and Mesozoic sediments are rare or absent on the south side as are the synorogenic sediments of the South Park Formation. The Oligocene Thirtynine Mile volcanic field is restricted to the south side. Lastly, Quaternary fluvial sediments appear to be deflected to the southeast along this zone.

The Tarryall zone follows the topographic scarp between the elevated Tarryall Range on the east and the subdued Elkhorn highlands to the west. The zone lies entirely within Precambrian igneous and metamorphic rocks of the Front Range uplift.

<u>Post-Laramide and Neogene Structures</u>

Ruleman and others (2011) and Houck and others (2012) have identified many features and relationships within South Park the suggest post-Laramide deformation. Ruleman (personal communication) believes that much of the topographic relief the defines the South Park physiographic basin may owe its origin to Late Tertiary tectonism. The most prominent is the series of faults that separate the Tarryall Range from the Elkhorn uplands.

Evaporitic Tectonism

Houck and others (2012) and Kirkham and others (2007; 2012) have identified features in the southwest part of South Park that may owe their origin to dissolution and flowage of evaporitic minerals within the Minturn Formation. Evaporitic tectonism has been recognized in other parts of the state where the similar strata are present (Kirkham and others, 2001) and this may be another example of this type of deformation style. While evaporites have long been known to be a part of the Pennsylvanian section, their role in the structural evolution of South Park may not be well understood yet. Differential movement in the evaporitic facies, diapiric flow, and collapse may all modify the Laramide and post-Laramide features where these sediments are present at depth. Much of the apparent discontinuity in structural features in the western part of the basin may be attributable to modification or overprinting by evaporitic tectonism.

GROUNDWATER IN SOUTH PARK

This section describes the various aquifers present in the South Park area following the framework outlined in the previous general geologic description. With the exception of the section titled "Structural Elements of Groundwater Flow", content is adapted from Arnold (2013).

Descriptions of the aquifers are general given that data are sparse for this area. This scoping study focuses on potential impacts related to oil and gas potential in the Cretaceous marine shale section. Accordingly, this discussion addresses the area and aquifers within a study area subset of within the greater South Park basin (Figure 14). This subset spans areas where the Cretaceous marine shale section is present near the surface or is interpreted to extend beneath the Elkhorn Fault.

To assess the current distribution of water wells and use of groundwater in South Park, the well application database of the Colorado Division of Water Resources (CDWR, 2012) was reviewed for data concerning well location, depth, screen interval, and primary water use. To minimize the inclusion of wells from the database that were not constructed or have been abandoned, only wells having a current status of "Well Constructed" were included in the analysis. No additional criteria were used to filter the data. General hydrogeologic units, rather than specific aquifers, were used to group wells in the analysis because of uncertainties associated with the identification of aquifers in which the wells are screened.

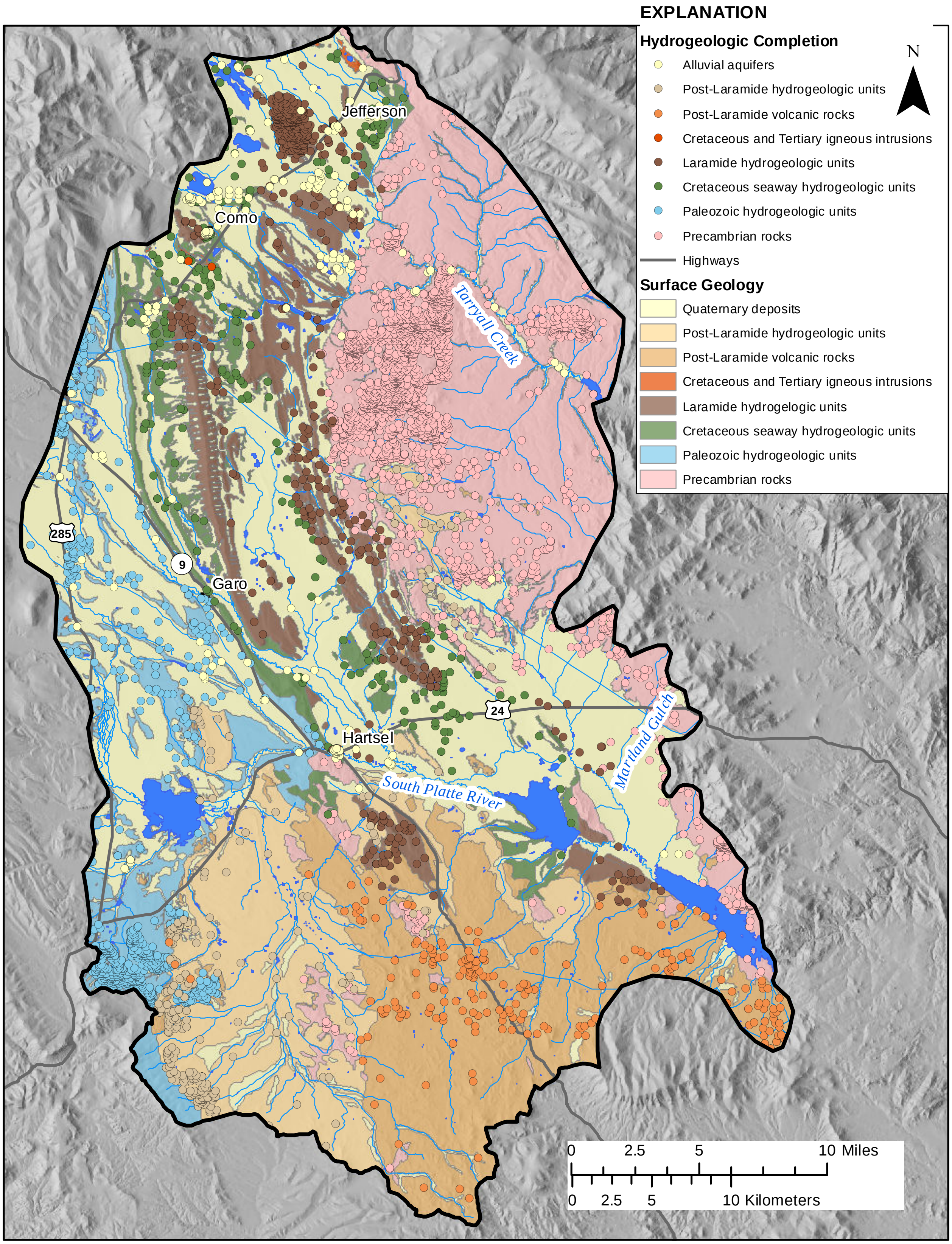
Wells were grouped according to the following general hydrogeologic units:

- (1) Alluvial aquifers
- (2) Sedimentary bedrock aquifers and confining units
  - (a) Post-Laramide hydrogeologic units
  - (b) Cretaceous and Tertiary hydrogeologic units associated with the Laramide uplift, hereafter referred to as "Laramide hydrogeologic units"
  - (c) Cretaceous hydrogeologic units associated with the Western Interior Seaway, hereafter referred to as "Cretaceous seaway hydrogeologic units"
  - (d) Paleozoic hydrogeologic units
- (3) Crystalline-rock aquifers
  - (a) Post-Laramide volcanic rocks
  - (b) Cretaceous and Tertiary igneous intrusions
  - (c) Precambrian igneous and metamorphic rocks

The distribution of wells classified by their estimated hydrogeologic completion intervals is included in Figure 14. Well location and depth relative to surficial geology described in the previous section were used to create initial estimates of hydrogeologic units in the completion intervals for each well. Wells less than or equal to 50 feet deep in areas covered by alluvium were assumed to be completed in alluvium. Wells greater than 50 feet deep in areas covered by alluvium were assumed to be completed in the hydrogeologic unit estimated to underlie the alluvium. Lithologic logs describing materials encountered during drilling were examined for many wells near the margins of hydrogeologic units and for deeper wells away from margins to verify hydrogeologic completions identified by the initial estimate. In cases where lithologic logs provided evidence contrary to the initial estimate, the hydrogeologic completion was modified to reflect the lithologic log.

Using the methods described above, there were 4,163 water wells inventoried in the South Park study area as of December 19, 2012. Of these wells, about 5 percent (216 wells) appear to be completed in alluvial aquifers (Figure 15A), 6 percent (239 wells) in post-Laramide hydrogeologic units, 14 percent (587 wells) in Laramide hydrogeologic units, 7 percent (286 wells) in Cretaceous seaway hydrogeologic units, 16 percent (649 wells) in Paleozoic hydrogeologic units, 5 percent (206 wells) in post-Laramide volcanic rocks, 2 wells in Cretaceous and Tertiary igneous intrusions, and 47 percent (1,978 wells) in Precambrian igneous and metamorphic rocks.

About 89 percent (3,719 wells) of wells in the South Park study area are permitted for domestic use or household use only (Figure 15B), 5 percent (190 wells) are permitted for monitoring, 4 percent (156 wells) are permitted for watering livestock, 1 percent (62 wells) are permitted for commercial purposes, and the remaining 1 percent have municipal (3 wells), irrigation (1 well), geothermal (1 well), evaporative (1 well), fire (1 well), or other unspecified uses (15 wells), or they have no use indicated (14 wells).



Base from U.S. Geological Survey digital data, 1:100,000
Wells modified from Colorado Division of Water Resources, 2012
Modified from Arnold (2013)

Figure 14. Areal distribution and hydrogeologic completion interval of constructed water wells in the South Park study area. Permitted water wells are found throughout the South Park study area. Areas with dense clusters reflect rural development patterns. The distribution by completion generally follows outcrop patterns with the exception of wells that tap deeper hydrogeologic units than is at the surface.

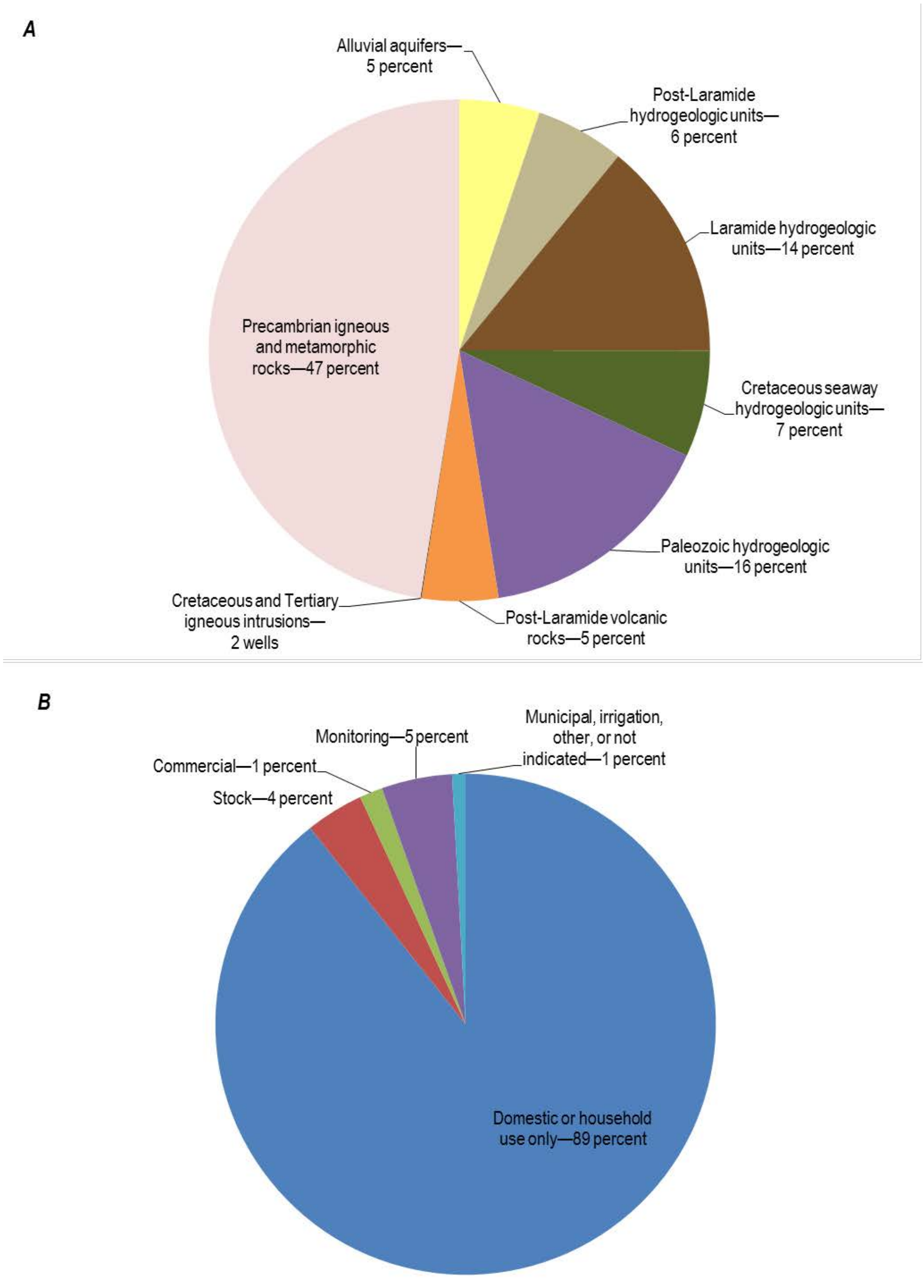


Figure 15. Distribution of wells in the South Park study area by hydrogeologic completion interval and permitted water use. Pie charts illustrate overall permitted well distributions in the study area; chart *A* shows wells by hydrogeologic completion interval and chart *B* shows wells by permitted primary water use. Percentages are approximate due to rounding using December 2012 permit data from CDWR (2012).

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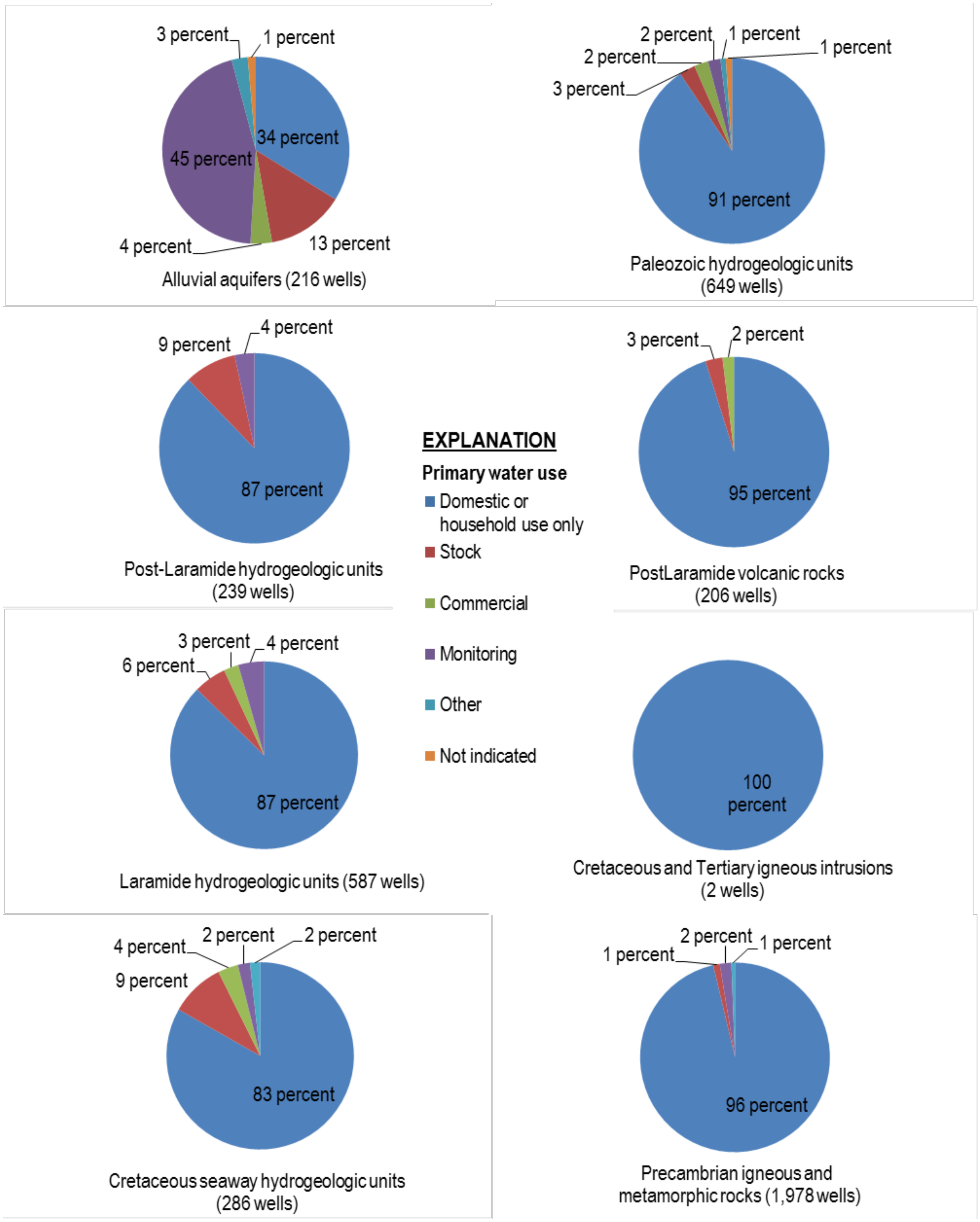

Figure 16. Distribution of wells in South Park hydrogeologic units by permitted primary water use. Pie charts illustrate distribution of permitted well use by completed hydrogeologic unit. Percentages are approximate due to rounding using December 2012 permit data from CDWR (2012).

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ALLUVIAL AQUIFERS

Quaternary alluvial deposits along the modern streams and glacial deposits form perhaps the most widespread aquifer system in the South Park area. Where present, this system is the most accessible source of groundwater with its shallow depth and relative ease in well drilling and construction.

Alluvial aquifers are composed of sand and gravel deposits associated with modern stream systems. As such the aquifer forms a network of narrow belts along streams yet with wide aerial distribution. Lithologic logs of several wells penetrating alluvium indicate the alluvium generally is less than 50 feet thick and is variably saturated. Water level measurements reported for completed wells range from 1 to 32 feet below land surface.

About 45 percent of the 216 wells estimated to be completed in alluvial deposits are used for monitoring (Figure 16), 34 percent are permitted for domestic use or household use only, 13 percent are permitted for watering livestock, 4 percent are permitted for commercial purposes, 3 percent are permitted for other purposes, and 1 percent has no use indicated. Monitoring wells are concentrated in the northern part of South Park along the drainages of Tarryall Creek and its tributaries (Figure 14).

SEDIMENTARY BEDROCK AQUIFERS AND CONFINING UNITS

For the purpose of this study, sedimentary bedrock aquifers and confining units are subdivided into four general hydrogeologic units on the basis of geologic age and similar tectonic setting—(1) Post-Laramide hydrogeologic units, (2) Laramide hydrogeologic units, (3) Cretaceous seaway hydrogeologic units, and (4) Paleozoic hydrogeologic units.

<u>Post-Laramide Hydrogeologic Units</u>

Post-Laramide hydrogeologic units in the South Park study area consist of the Antero and Wagontongue aquifers. About 87 percent of the 239 wells estimated to be completed in post-Laramide hydrogeologic units are permitted for domestic use or household use only (Figure 16), 9 percent are permitted for watering livestock, 4 percent are permitted for monitoring, and 1 well is permitted for other purposes.

<u>Laramide Hydrogeologic Units</u>

Laramide hydrogeologic units consist primarily of various sedimentary members that collectively comprise the South Park aquifer and its confining units. Locally, Laramide hydrogeologic units also include the Echo Park Alluvium. About 87 percent of the 587 wells estimated to be completed in Laramide hydrogeologic units are permitted for domestic use or household use only (Figure 16), 6 percent are permitted for watering livestock, 4 percent are permitted for monitoring, 3 percent are permitted for commercial purposes, and 1 well is permitted for other purposes.

Cretaceous Seaway Hydrogeologic Units

Cretaceous seaway hydrogeologic units are grouped by this study to include the Morrison Formation, Dakota aquifer, Benton Group, Niobrara Formation, Pierre Shale, Laramie-Fox Hills aquifer, and Laramie Formation. About 83 percent of the 286 wells estimated to be completed in Cretaceous seaway hydrogeologic units are permitted for domestic use or household use only (Figure 16), 9 percent are permitted for watering livestock, 4 percent are permitted for commercial purposes, 2 percent are permitted for monitoring, and the remaining 2 percent are permitted for other purposes.

Paleozoic Hydrogeologic Units

Paleozoic hydrogeologic units in South Park include water-yielding Cambrian through Mississippian rocks, the Minturn-Maroon aquifer, and the Garo aquifer. Sedimentary units comprising the Cambrian through Mississippian rocks are the Sawatch Quartzite, Dotsero Formation, Manitou Formation, Harding Sandstone, Fremont Dolomite, Chaffee Group, and Leadville Limestone. About 91 percent of the 649 wells estimated to be completed in Paleozoic hydrogeologic units are permitted for domestic use or household use only (Figure 16), 3 percent are used for watering livestock, 2 percent are used for commercial purposes, 2 percent are used for monitoring, 1 percent is used for other purposes, and 1 percent has no use indicated.

CRYSTALLINE ROCK AQUIFERS

Crystalline-rock aquifers in the South Park study area can be subdivided into three general hydrogeologic units on the basis of geologic age and rock type—(1) Post-Laramide volcanic rocks, (2) Cretaceous and Tertiary igneous intrusions, and (3) Precambrian igneous and metamorphic rocks.

Post-Laramide Volcanic Rocks

About 95 percent of the 206 wells estimated to be completed post-Laramide volcanic rocks are permitted for domestic use or household use only (Figure 16), 3 percent are used for watering livestock, and the remaining 2 percent of wells are used for commercial purposes.

Cretaceous and Tertiary Igneous Intrusions

Only two wells appear to be completed in Cretaceous and Tertiary igneous intrusions in the South Park study area. Both wells are near Como (Figure 14) and are permitted for domestic use or household use only (Figure 16).

Precambrian Igneous and Metamorphic Rocks

About 96 percent of the 1,978 wells estimated to be completed Precambrian igneous and metamorphic rocks are permitted for domestic use or household use only (Figure 16), 2 percent are used for monitoring, 1 percent is used for watering livestock, 1 percent is used for other purposes, and 4 wells have no use indicated.

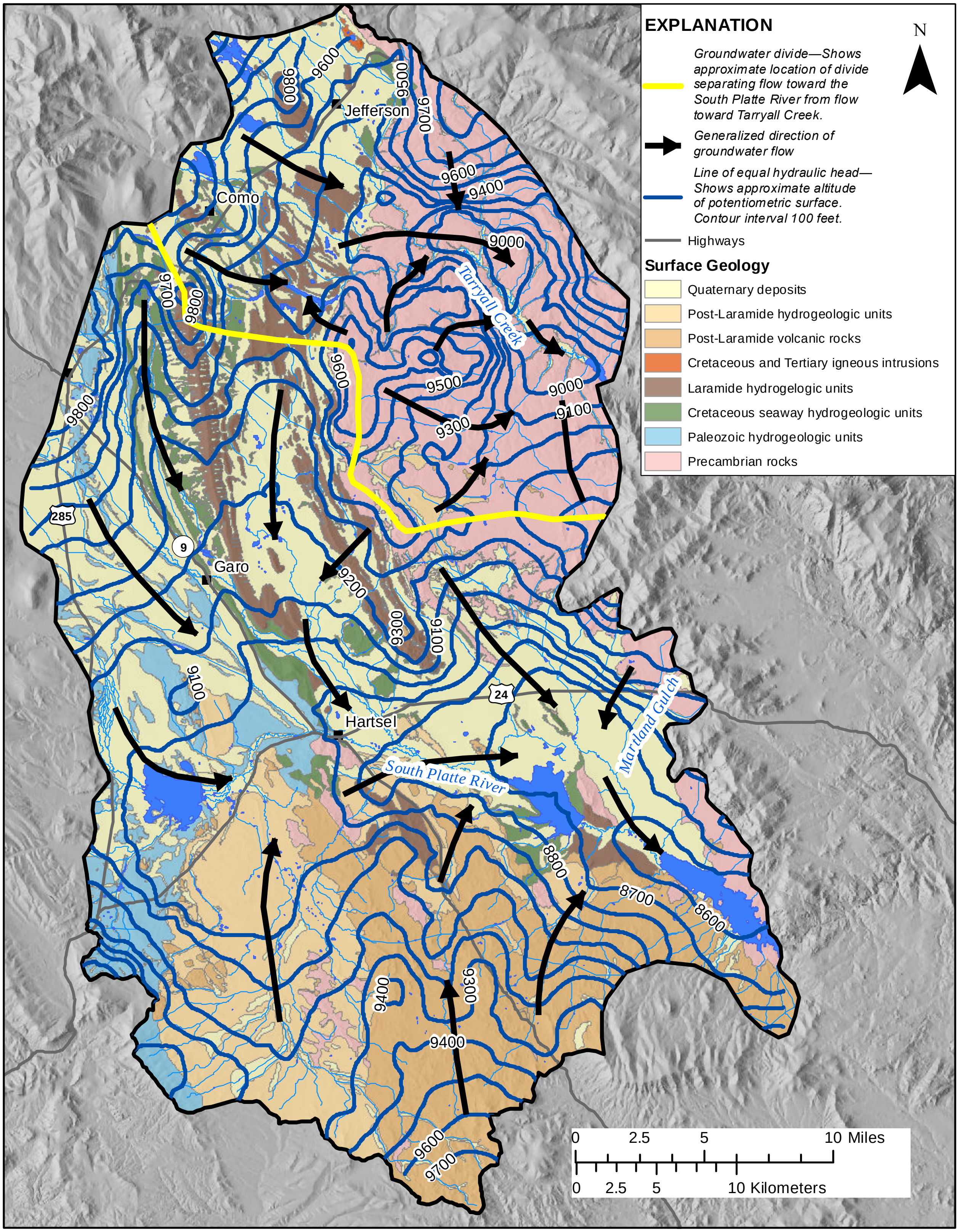
GROUNDWATER FLOW

Water-level Conditions and Direction of Groundwater Flow

To assess water-level conditions and directions of groundwater flow in South Park, a map showing the generalized potentiometric surface of sedimentary bedrock and crystalline-rock aquifers in South Park (Figure 17) was created using water-level data in the CDWR well-applications database (Colorado Division of Water Resources, 2012). Alluvium was not included in the analysis because it occurs as a relatively thin layer of sediment overlying sedimentary bedrock and crystalline rocks and potentially has substantially different water levels than in the underlying units. The map incorporates water-level data from different hydrogeologic units, and because nearly all wells appear to be completed in the uppermost hydrogeologic unit at a given location (except where alluvium is present), the map represents the composite potentiometric surface of the uppermost hydrogeologic units basin-wide. Because the water-level data represent various aquifers, measurement dates, depth intervals within aquifers, and hydrologic conditions, the resulting potentiometric map should be considered representative of general water-level conditions in South Park rather than precise water-level conditions for a specific location or time.

The altitude of the water level in each well used to create the potentiometric-surface map was determined by interpolating the land-surface altitude derived from the USGS National Elevation Data Set (NED) with 10-meter resolution (U.S. Geological Survey, 2011) to each well location and subtracting depth to water indicated by the STATIC_LVL field in the database to obtain a water-level altitude for each well location. Water-level altitudes were then interpolated by using kriging (circular semivariogram model) with the Spatial Analyst tool in ArcGIS 10.0 (Environmental Systems Research Inc., 1999–2010) and contours were drawn to graphically represent the potentiometric surface. Kriging was used to interpolate water-level data in order to generate a geostatistical fit to potentially inconsistent values at a local scale. Prior to kriging, construction reports were reviewed for wells having STATIC_LVL greater than the well depth, and corrections were made to the water-level data where errors were found. Wells having a value of zero for STATIC_LVL were excluded from analysis to avoid misrepresenting null values as valid water levels. Resulting contours were smoothed using a maximum offset of 30 meters (about 98.4 feet).

The potentiometric surface shown in Figure 17 generally reflects the topography of the ground surface with highest altitudes along the margins of the South Park basin and beneath upland areas and ridges. Groundwater flows generally from the topographically high areas toward the stream valleys and tributaries of the South Platte River and Tarryall Creek. A groundwater divide (Figure 17) that separates the direction of groundwater flow toward the South Platte River from flow toward Tarryall Creek is located approximately along the topographic divide between the two drainage basins. Groundwater south and west of the divide flows toward the South Platte River and its tributaries, whereas groundwater north and east of the divide flows toward the stream valley of Tarryall Creek. Because few wells were found to penetrate through the uppermost sedimentary bedrock or crystalline-rock hydrogeologic unit into underlying units, comparisons of water levels in vertically adjacent units was limited and vertical gradients among hydrogeologic units could not be properly evaluated. Although water-level data for the alluvial aquifer are sparse or lacking for substantial parts of the South Park basin, available data indicate groundwater flow directions in the alluvium, where saturated, generally are similar to those in the underlying hydrogeologic units.



Base from U.S. Geological Survey digital data, 1:100,000
Wells modified from Colorado Division of Water Resources, 2012
Modified from Arnold (2013)

Figure 17. Potentiometric surface and generalized direction of groundwater flow in South Park. The potentiometric surface is estimated from groundwater-levels in sedimentary bedrock and crystalline-rock aquifers and generally follows surface topography. It is based on water-level data from the Colorado Division of Water Resources permit files (CDWR, 2012).

Aquifer Recharge and Discharge

Recharge to aquifers in the South Park basin can occur through areal infiltration of precipitation, return flow from irrigation and individual sewage disposal systems, seepage from surface water features such as streams and reservoirs, and subsurface flow from adjacent hydrogeologic units or mountain blocks. Groundwater discharge from aquifers in the basin can occur as outflow to streams or reservoirs; outflow to springs, seeps, and wetlands; evapotranspiration; subsurface flow to adjacent hydrogeologic units; subsurface outflow at downgradient areas of the basin; and pumping. Groundwater modeling by Ball (2012) indicated that more than 92 percent of inflow to the South Park basin (including the eastern slopes of the Mosquito Range) comes from areal recharge in topographically high areas along the basin margins and 8 percent comes from losing streams. The modeling also indicated that 50 percent of outflow from the basin occurs as discharge to streams, 45 percent occurs as surface seepage or evapotranspiration, and 4 percent leaves the basin as groundwater flow along its eastern side, primarily through alluvial aquifers in the valleys of the South Platte River and Tarryall Creek. Groundwater discharge from the basin by pumping was not simulated. Within the basin, subsurface flow from high-elevation mountain blocks at the margins of the basin (particularly the Mosquito Range on the western margin) to sedimentary bedrock aquifers at lower elevations was an important component of groundwater flow in the model. Groundwater modeling specifically of the Laramide South Park aquifer by Jehn Water Consultants, Inc. (1997) simulated natural recharge to the aquifer as ranging from about 0.18 to 0.88 inch per year. Similarly, natural recharge to an area of Precambrian igneous and metamorphic rocks in South Park was simulated as 0.22–0.88 inch per year. Chlorofluorocarbon data collected from selected wells by Miller and Ortiz (2007) indicated apparent groundwater recharge dates in Park County, including the South Park study area, ranged from the mid-1940’s to modern water (2004) . Wells completed in sedimentary bedrock aquifers tended to have older waters than wells completed in alluvium, Precambrian igneous and metamorphic rocks, and post-Laramide volcanic rocks. Many of the wells sampled were believed to likely have a mixture of water from several parts of the aquifer system that may have different recharge areas, flow paths, and groundwater recharge dates.

Structural Elements and Groundwater Flow

Fault Systems

Attention has been given to the possibility of faults, or fault systems, playing an important roll in groundwater flow systems (Jehn Water Consultants, Inc, 1997; Ball, 2012), yet there is little data to provide conclusive determinations. Depending on physical geometry and characteristics, faults may juxtapose hydrologic units with varying hydrologic properties. They have been described as either barriers or pathways, or both, to groundwater flow.

Site-specific investigations by Ball (2012) showed the Elkhorn Fault acts as both a barrier and a pathway and can affect groundwater flow locally, but less so regionally. This feature juxtaposes the Precambrian crystalline rock hydrogeologic unit against a bedrock sedimentary hydrogeologic unit. Field investigations combining geophysics with borehole drilling and water level data indicated that the zone consists of a fault core barrier surrounded by a permeable damage zone. Groundwater modeling suggests that, locally, the fault can channel flow through its permeable zone and can mound flow when flow is perpendicular to the fault. On a regional scale modeling suggests that faults have little impact to groundwater flow.

Other evidence within South Park suggests that faults may act as significant conduits to local flow. Ruleman (personal communication) reports that springs in the Basin are very often located close to mapped faults. Jehn Water Consultants, Inc (1997) cites salt deposits near Garcia Gulch and Seven Mile Gulch south of Como that they attribute to evaporation of discharging groundwater. Although the exact locations of these deposits have not been provided, they appear to be within the faulted and folded zone between the Elkhorn and South Park fault systems. This suggests a possible connection with deeper systems that may include the Minturn formation evaporite facies. This possibility deserves further investigation.

Implications of Minturn formation Evaporite Facies on Groundwater Flow

Very little is known about possible influences on the evaporite facies of the Minturn formation on groundwater flow. Most of the area where this unit is located lies at the west side of the study area, however, the eastward extent beneath other units is not well constrained. In the area where it is present at, or near the surface, structural deformation appears to be quite complex, possibly owing to diapiric flow and dissolution (Kirkham and others, 2012). The complex structural framework may have significant impacts on local flow conditions. Obviously, groundwater flow within this unit has the potential of direct contact with soluble salt minerals that will impact water quality.

Content for this section is adapted from Arnold (2013).

POTENTIAL FOR ENERGY DEVELOPMENT

Oil and Gas Development

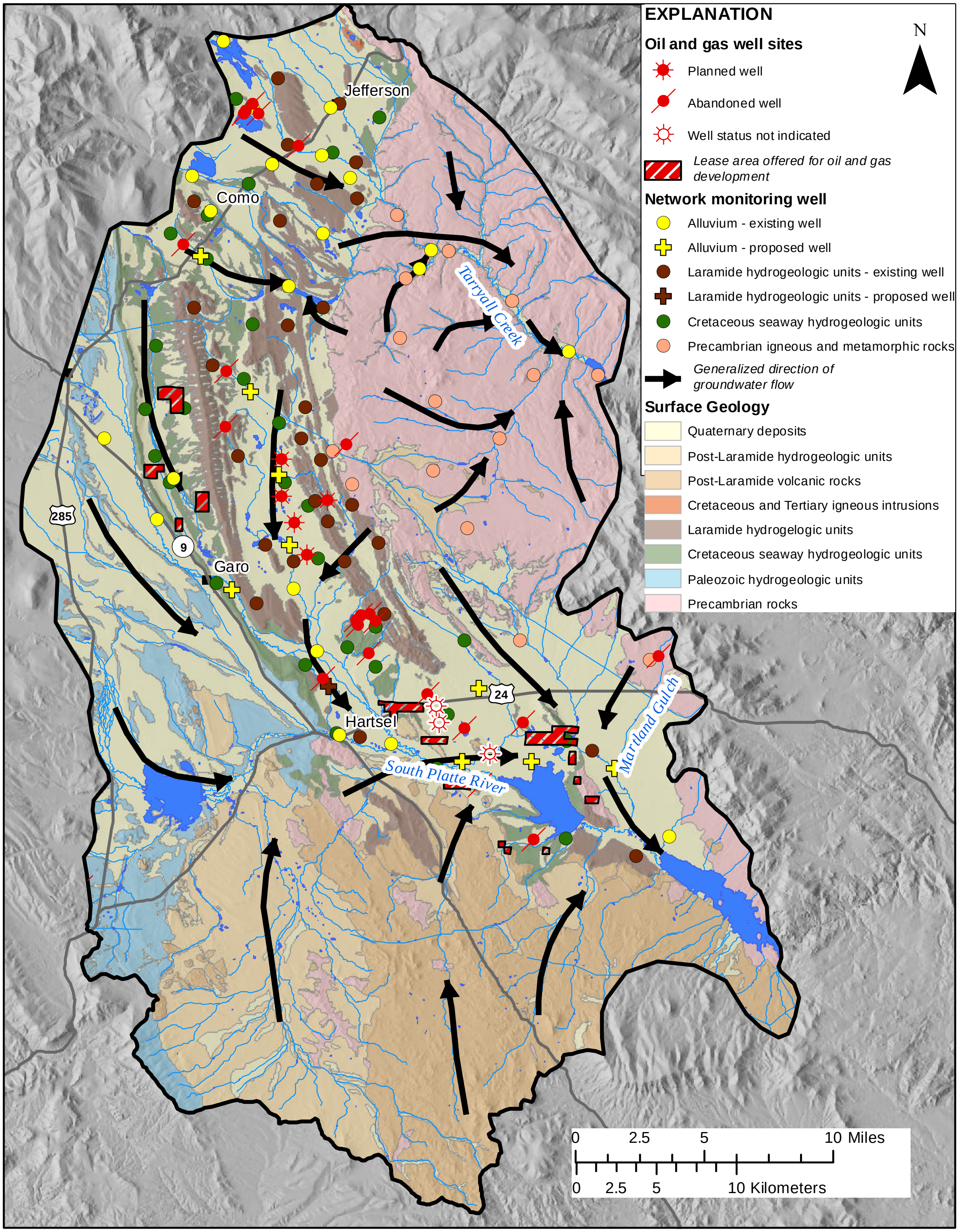
Thirty sites in the South Park study area have been permitted for drilling oil and gas wells as of November 2010. Twenty-two of the well sites have been abandoned and are not in use, five sites are planned for development and have not yet been drilled, and three sites have no status indicated. In addition to permitted wells, 15 locations covering a total area of about 2,923 acres were offered for lease by the U.S. Bureau of Land Management in February 2013 for oil and gas development in the South Park study area (Bureau of Land Management, 2013; Figure 18). These sites all lie within the area underlain by the Mesozoic sedimentary units (Figure 18).

VULNERABLE AQUIFERS

The vulnerability of aquifers to oil and gas development in South Park depends on several conditions, including the aquifer's location relative to oil and gas development sites, hydraulic conductivity of aquifers and confining units, and direction of groundwater flow. Aquifers penetrated by oil and gas wells or located in hydrogeologic units in direct contact with surface operations of oil and gas development are most vulnerable to potential water-quality effects. Aquifers having high hydraulic conductivity are more vulnerable to the effects of oil and gas development than those having low hydraulic conductivity because of their greater ability to transport chemical constituents over relatively long distances. Aquifers or parts of aquifers located downgradient from oil and gas development sites are more vulnerable to the effects of development than those that are upgradient because groundwater transports chemical constituents in a downgradient direction.

The potentiometric surface mapped by this study and hydrogeologic data available in published literature and consultant reports were used to assess the vulnerability of aquifers to oil and gas development in the South Park study area. As shown in Figure 18, oil and gas wells and lease areas offered for oil and gas development primarily are located where alluvium, Laramide hydrogeologic units, Cretaceous seaway hydrogeologic units, and Precambrian igneous and metamorphic rocks are present at the land surface. In addition, groundwater in these units occurs downgradient from areas of proposed oil and gas development. As such, these units likely are the most vulnerable to the potential effects of oil and gas development in South Park. However, the vulnerability of alluvium is limited where it has little or no saturated thickness. Because of its generally permeable, coarse-grained composition and large extent, the primary aquifer within Laramide hydrogeologic units potentially vulnerable to the effects of oil and gas development is the

South Park aquifer. Potentially vulnerable aquifers within Cretaceous seaway hydrogeologic units include the Dakota and Laramie-Fox Hills aquifers, as well as permeable sandstone layers within the Morrison Formation, Benton Group, Niobrara Formation, and Pierre Shale. Groundwater in Paleozoic hydrogeologic units and post-Laramide volcanic rocks generally is upgradient from current oil and gas sites and geologic units targeted for development. Therefore, aquifers within Paleozoic hydrogeologic units and post-Laramide volcanic rocks likely have relatively low vulnerability to the potential effects of oil and gas development compared to aquifers in Laramide and Cretaceous seaway hydrogeologic units. Groundwater in Precambrian igneous and metamorphic rocks generally is upgradient from oil and gas sites, except along the stream valleys of Tarryall Creek and Martland Gulch (Figure 18). Consequently, this groundwater is unlikely to be vulnerable to the potential effects of oil and gas development except in these areas. Groundwater in post-Laramide hydrogeologic units and Cretaceous and Tertiary intrusions occurs in only very limited areas downgradient from oil and gas sites. Potentially vulnerable aquifers in post-Laramide hydrogeologic units are the Antero and Wagontongue aquifers.



Base from U.S. Geological Survey digital data, 1:100,000
Wells modified from Colorado Division of Water Resources, 2012
Modified from Arnold (2013)

Figure 18. Location of oil and gas wells, lease areas offered for oil and gas development, and network wells for monitoring water quality. Target aquifers include alluvial aquifers, Laramide hydrogeologic units, Cretaceous seaway hydrogeologic units, and Precambrian igneous and metamorphic rocks in the central part of South Park.

Content for this section is adapted from Arnold (2013).

PRIORITY AQUIFERS

Well networks were developed for monitoring groundwater throughout the South Park basin for changes in quality related to oil and gas development in each of four priority hydrogeologic units selected on the basis of their potential vulnerability and degree of use. Well networks were designed for monitoring groundwater in (1) alluvium, (2) Laramide hydrogeologic units, (3) Cretaceous seaway hydrogeologic units, and (4) Precambrian igneous and metamorphic rocks. Monitoring-well networks were not designed for post-Laramide hydrogeologic units, Paleozoic hydrogeologic units, post-Laramide volcanic rocks, and Cretaceous and Tertiary igneous intrusions because these units generally are upgradient from oil and gas development sites.

MONITORING-WELL NETWORK DESIGN

With the exception of the well network for Precambrian igneous and metamorphic rocks, well networks were designed using 30 wells completed in each hydrogeologic unit to provide broad areal coverage for characterizing water-quality conditions in areas of current or potential oil and gas development. Because of the relatively small area of Precambrian igneous and metamorphic rocks downgradient from oil and gas development sites, the well network for these rocks includes only 15 wells. Existing wells were used in the networks wherever possible to minimize the number of new wells to be drilled for monitoring. Where existing wells were not located within about 2 miles downgradient from areas of oil and gas development or do not have suitable construction for monitoring groundwater quality, locations for new wells generally are proposed. Well networks include wells from the existing monitoring network used by CUSP wherever possible to provide continuity with previous sampling efforts undertaken by CUSP. Well networks were designed to monitor groundwater conditions primarily downgradient from areas of current or potential oil and gas development. However, some wells upgradient from areas of oil and gas development also are included in the network to provide for comparison to any changes potentially observed in downgradient wells. Wells also were selected to represent a range of depths within each hydrogeologic unit to monitor water quality throughout the vertical extent of each unit. Well records on file with the CDWR were reviewed to determine the suitability of existing water wells for use in the networks. Existing wells without construction information or a lithologic log were excluded from the networks except for some alluvial wells less than 40 feet deep located where alternative wells having construction or lithologic information were lacking. Where possible, wells having screen intervals longer than 40 feet also were excluded from consideration unless the well had been part of the network previously sampled by CUSP. Well networks developed for each of the four priority hydrogeologic units are shown in Figure 18. Existing wells were considered to provide sufficient coverage for monitoring water quality in Cretaceous seaway hydrogeologic units and Precambrian igneous and metamorphic rocks. One new well is proposed for monitoring water quality in Laramide hydrogeologic units (South Park aquifer), and nine new wells are proposed for monitoring water quality in alluvial aquifers. A listing of existing wells included in the networks and locations of proposed wells is provided as Appendix A.

DATA GAPS AND RECOMMENDATIONS FOR FUTURE WORK

Review of available existing hydrogeologic data for the South Park basin identified several data gaps where new or additional information is needed to improve evaluation of groundwater resources in the basin. First, collection and analysis of groundwater samples for water quality from the network wells presented in this report would provide for assessment of water-quality conditions in South Park prior to extensive oil and gas development in the basin. Ongoing collection and analysis of samples for water quality would provide for long-term monitoring of water-quality conditions. Better structural definition of sedimentary bedrock aquifers and confining units at depth in the South Park basin is needed to accurately characterize the location, depth, and geometry of water-bearing units and their relation to adjacent units. Better definition of the surface of the crystalline-rock basement below sedimentary bedrock units in the basin would provide useful information for characterizing the vertical extent of groundwater resources in the sedimentary bedrock units overlying basement rocks. Data concerning hydraulic conductivity and storage properties of hydrogeologic units in the basin are sparse, and additional data from aquifer tests, specific-capacity tests, lab analysis of core samples, or other methods are needed to improve characterization of these hydrologic properties and facilitate understanding of groundwater-flow patterns and responses to hydrologic stresses such as pumping or climate change. Regular water-level measurements using an established well network would provide useful information for monitoring temporal changes to groundwater resources in the basin and provide additional information on directions of groundwater flow for interpreting water-quality data collected at monitoring-well locations. Studies to quantify the exchange of water between surface-water features, such as streams and reservoirs, and underlying aquifers are needed to improve understanding of groundwater-surface water fluxes in the basin and the potential for water-quality constituents in groundwater to enter streams or reservoirs. Lastly, development of a water budget and construction of a numerical groundwater flow model that incorporates pumping and other data (existing and new) could be used to improve management and monitoring of groundwater resources in the South Park basin and form the basis for assessing groundwater flow paths and transport of water-quality constituents near sites of oil and gas development.

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APPENDIX A

Listing of Wells in the Monitoring Network

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Appendix. Permit number, use, well depth, and hydrogeologic completion of network wells for monitoring water quality in South Park.

[DDMMSS, degrees, minutes, seconds; ft, feet]

Permit number[1]	Use[1]	Well depth[1] (ft)	Hydrogeologic completion[3]
128038	Stock	30	Alluvium
126297A	Commercial	33	Alluvium
24594	Stock	25	Alluvium
129140	Stock	40	Alluvium
104115A	Domestic	31	Alluvium
175084	Domestic	28	Alluvium
46102MH	Monitoring	20	Alluvium
212371	Monitoring	15	Alluvium
258550	Monitoring	15	Alluvium
42340MH	Monitoring	14	Alluvium
47427MH	Monitoring	8	Alluvium
41421MH	Monitoring	11	Alluvium
233892	Monitoring	28	Alluvium
47162	Domestic	35	Alluvium
250230	Other	15	Alluvium
60560A	Domestic	50	Alluvium
25857	Domestic	38	Alluvium
22174	Domestic	18	Alluvium
79965	Domestic	19	Alluvium
11WCB	--	27	Alluvium
270636	Domestic	60	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
Proposed	Monitoring	--	Alluvium
256243	Domestic	160	Laramide hydrogeologic units
151093	Stock	98	Laramide hydrogeologic units
222268	Household use only	340	Laramide hydrogeologic units
149877	Domestic	323	Laramide hydrogeologic units
127704	Domestic	65	Laramide hydrogeologic units
120722	Household use only	140	Laramide hydrogeologic units
100023	Stock	83	Laramide hydrogeologic units
211524	Domestic	245	Laramide hydrogeologic units
165702	Household use only	400	Laramide hydrogeologic units
186742	Domestic	150	Laramide hydrogeologic units

Permit number[1]	Use[1]	Well depth[1] (ft)	Hydrogeologic completion[3]
155302	Domestic	240	Laramide hydrogeologic units
132121A	Stock	100	Laramide hydrogeologic units
131737	Domestic	115	Laramide hydrogeologic units
276848	Domestic	125	Laramide hydrogeologic units
139487	Domestic	125	Laramide hydrogeologic units
27401	Domestic	90	Laramide hydrogeologic units
246902	Domestic	360	Laramide hydrogeologic units
25875	Domestic	90	Laramide hydrogeologic units
117221	Household use only	140	Laramide hydrogeologic units
224449	Domestic	140	Laramide hydrogeologic units
287013	Stock	203	Laramide hydrogeologic units
219414	Domestic	280	Laramide hydrogeologic units
48937A	Domestic	160	Laramide hydrogeologic units
19002A	Stock	240	Laramide hydrogeologic units
240829	Domestic	200	Laramide hydrogeologic units
159222A	Commercial	125	Laramide hydrogeologic units
25906F	Household use only	220	Laramide hydrogeologic units
261290	Domestic	175	Laramide hydrogeologic units
151076	Domestic	180	Laramide hydrogeologic units
Proposed	Monitoring	--	Laramide hydrogeologic units
149041	Other	60	Cretaceous seaway hydrogeologic units
58592F	Household use only	450	Cretaceous seaway hydrogeologic units
222372	Commercial	120	Cretaceous seaway hydrogeologic units
231892	Domestic	280	Cretaceous seaway hydrogeologic units
202391	Household use only	320	Cretaceous seaway hydrogeologic units
249983A	Domestic	385	Cretaceous seaway hydrogeologic units
288879	Domestic	120	Cretaceous seaway hydrogeologic units
191704	Household use only	180	Cretaceous seaway hydrogeologic units
234902	Domestic	320	Cretaceous seaway hydrogeologic units
283841	Household use only	320	Cretaceous seaway hydrogeologic units
286620	Stock	160	Cretaceous seaway hydrogeologic units
213678	Domestic	246	Cretaceous seaway hydrogeologic units
285492	Domestic	345	Cretaceous seaway hydrogeologic units
22077F	Municipal	752	Cretaceous seaway hydrogeologic units
271984	Stock	174	Cretaceous seaway hydrogeologic units
203769	Domestic	200	Cretaceous seaway hydrogeologic units
278031	Domestic	380	Cretaceous seaway hydrogeologic units
240826	Household use only	360	Cretaceous seaway hydrogeologic units
240250	Domestic	160	Cretaceous seaway hydrogeologic units
280323	Domestic	402	Cretaceous seaway hydrogeologic units
202393	Domestic	200	Cretaceous seaway hydrogeologic units
254182	Domestic	100	Cretaceous seaway hydrogeologic units
194832	Household use only	200	Cretaceous seaway hydrogeologic units
84584	Domestic	165	Cretaceous seaway hydrogeologic units
270671	Domestic	340	Cretaceous seaway hydrogeologic units

Permit number[1]	Use[1]	Well depth[1] (ft)	Hydrogeologic completion[3]
276389	Domestic	240	Cretaceous seaway hydrogeologic units
60559A	Domestic	80	Cretaceous seaway hydrogeologic units
60558A	Stock	185	Cretaceous seaway hydrogeologic units
189205	Commercial	60	Cretaceous seaway hydrogeologic units
267892	Stock	95	Cretaceous seaway hydrogeologic units
284163	Household use only	180	Precambrian igneous and metamorphic rocks
64929	Household use only	120	Precambrian igneous and metamorphic rocks
282886	Household use only	220	Precambrian igneous and metamorphic rocks
121147	Domestic	100	Precambrian igneous and metamorphic rocks
201325	Household use only	285	Precambrian igneous and metamorphic rocks
25469	Domestic	87	Precambrian igneous and metamorphic rocks
17985	Domestic	97	Precambrian igneous and metamorphic rocks
49629F	Household use only	650	Precambrian igneous and metamorphic rocks
253559	Stock	100	Precambrian igneous and metamorphic rocks
65841F	Household use only	580	Precambrian igneous and metamorphic rocks
41807F	Household use only	120	Precambrian igneous and metamorphic rocks
174555	Household use only	232	Precambrian igneous and metamorphic rocks
211581	Domestic	500	Precambrian igneous and metamorphic rocks
214091	Household use only	200	Precambrian igneous and metamorphic rocks
129979	Domestic	215	Precambrian igneous and metamorphic rocks

[1]Data from Colorado Division of Water Resources (2012).

[2]North American Datum of 1983.

[3]Hydrogeologic completion estimated by this study.