Geologic Map of the Fort Collins 30'×60' Quadrangle, Larimer and Jackson Counties, Colorado, and Albany and Laramie Counties, Wyoming

Pamphlet to accompany
Scientific Investigations Map 3399

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph looking east from Rockhole Lake in the Rawah Wilderness down the West Branch Laramie River as it descends steeply eastward to the north-flowing upper Laramie River. High upland areas in the foreground expose granite of the Rawah batholith (XgR) with glacial till of Pinedale age (Qtp) filling the valley below. The southern end of Green Ridge, capped by a gently sloping erosion surface below the skyline, is visible just beyond the mouth of the valley. This ridge, formed by the Laramie River fault zone, separates the Laramie River drainage to the west from the Cache la Poudre River drainage to the east. South Bald Mountain is visible on the skyline to the left with Crown Point visible on the skyline to the right. The Cache la Poudre River flows east, away from view through a deep, inset canyon between these two high points below the skyline. Photograph by C.R. Ruleman, May 24, 2005.

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Acknowledgments

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Contents

Figures

Conversion Factors

International System of Units to U.S. Customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Pressure	
bar	14.5038	pounds per square inch (psi)
kilopascal (kPa)	0.01	bar
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel=42 gal)
	Mass	
metric ton (tonnes, t)	1.102	ton, short (2,000 lb)
metric ton (tonnes, t)	0.9842	ton, long (2,240 lb)

U.S. Customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Pressure	
kilopascal (kPa)	0.01	bar
	Volume	
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27)

Altitude, as used in this report, refers to distance above Mean Sea Level.

Divisions of Quaternary, Neogene, and Paleogene time used in this report[1]

Period or subperiod	Epoch		Age
Quaternary	Holocene		0–11.7 ka
	Pleistocene	late	11.7–132 ka
		middle	132–788 ka
		early	788 ka–2.588 Ma
Neogene	Pliocene		2.588–5.332 Ma
	Miocene		5.332–23.03 Ma
	Oligocene		23.03–33.9 Ma
Paleogene	Eocene		33.9–55.8 Ma
	Paleocene		55.8–65.5 Ma

[1]Ages of time boundaries are those of the U.S. Geological Survey Geologic Names Committee (2010) except those for the late-middle Pleistocene boundary and middle-early Pleistocene boundary, which are those of Richmond and Fullerton (1986). Ages are expressed in ka for kilo-annum (thousand years) and Ma for mega-annum (million years).

Geologic Map of the Fort Collins 30'×60' Quadrangle, Larimer and Jackson Counties, Colorado, and Albany and Laramie Counties, Wyoming

By Jeremiah B. Workman, James C. Cole, Ralph R. Shroba, Karl S. Kellogg, and Wayne R. Premo

Abstract

The rocks and landforms of the Fort Collins 30'×60' quadrangle reveal a particularly complete record of geologic history in the northern Front Range of Colorado. The Proterozoic basement rocks exposed in the core of the range preserve evidence of Paleoproterozoic marine sedimentation, volcanism, and regional soft-sediment deformation, followed by regional folding and gradational metamorphism. Regional and textural evidence shows that the widespread metamorphism was essentially concurrent with intrusion of the Routt Plutonic Suite, with the peak of deformation in the partially melted high-grade rocks of the suite. The metamorphic thermal pulse arrived later following the peak of deformation in the physically higher, cooler, low-grade terrane. Mesoproterozoic time was marked by intrusion of the Berthoud Plutonic Suite into crust that was structurally neutral or moderately extending in an east-northeast direction. Mylonite zones, including the Skin Gulch shear zone, formed during Mesoproterozoic time perhaps during several events.

Evidence of the late Paleozoic Anasazi uplift (Ancestral Rocky Mountains uplift) within the quadrangle is recorded by removal of Permian and older sediments and deposition of proximal Pennsylvanian and Permian strata unconformably onto the exhumed Proterozoic basement rocks. The Phanerozoic sediments indicate a steady progression of fluvial, eolian, and lacustrine environments throughout most of the Mesozoic Era which was a time of relatively slow sediment accumulation. Early Cretaceous time was marked by incursion of the Cretaceous Western Interior Seaway, a shallow-water marine embayment that persisted throughout the latter part of the Mesozoic Era. Cretaceous strata consist of abundant shale interbedded with relatively minor fine sandstone and limestone. Sedimentation rates increased significantly in the latter part of this period during downwarping related to distant crustal loading by thrusting along the western continental margin.

With onset of the Laramide orogeny in latest Cretaceous time, mountain building resumed in this region. This deformation placed Proterozoic rock over Cretaceous and Paleocene strata along the western margin of the Front Range and Medicine Bow Mountains. The eastern margin of the range is marked by high-angle reverse faults and fault-propagation folds in the Phanerozoic strata, and by the deep syncline of the Denver-Cheyenne Basin. Dacitic to rhyodacitic porphyry dikes and plugs were emplaced during the Laramide orogeny in the Manhattan district, an historic mining area by the ghost town of Manhattan, Colo., that hosts sparse gold deposits. The Coalmont Formation on the western side of the quadrangle records erosion of the Laramide uplifts. Similar deposits transported east of the Front Range are not preserved in this quadrangle due to Neogene and younger erosion.

Post-Laramide time was marked by a prolonged period of weathering, erosion, and planation of the basement-rock surface, extending perhaps into late Oligocene or early Miocene time. Tuffaceous fluvial sediments of the White River Group record the early part of the Cenozoic geologic history across the entire area. Intrusive activity in the Never Summer Mountains south of the map area during middle Oligocene time led to eruption of basaltic, dacitic, and rhyolitic lavas and welded tuffs that blanketed the southwestern part of the map area. The upper Oligocene to Miocene North Park Formation contains clasts of this volcanic material and records erosion and fluvial deposition from the volcanic highland.

Erosion on the eastern slope of the Front Range in late Paleogene to early Neogene time produced a broad, rolling surface surrounding residual highlands and east-trending fluvial channels filled with coarse, boulder gravel. Continued degradation of the mountainous highlands led to aggradation of the Miocene and Pliocene(?) Ogallala Formation fluvial apron; this apron extends eastward from the Laramide mountain front. Low-gradient streams developed broad meandering paths across this aggraded apron. Renewed uplift of the central Rocky Mountains during Pliocene time caused these meandering streams to incise rapidly and deeply into the Proterozoic basement rocks, producing the entrenched meanders that are characteristic of the major east-flowing streams west of the mountain front today.

Significant global cooling during the Pliocene led to glaciation during the Quaternary. In the Rocky Mountain

region, the renewed uplift allowed erosion to accentuate the topographic relief across the high mountains of the map area and established the elevations necessary to trigger accumulation of persistent snow and ice. Mountain glaciers advanced and retreated during at least three glacial-interglacial cycles during the middle and late Pleistocene in this area.

Major landslide and debris flow deposits were active during the late Pleistocene to Holocene throughout the mountainous areas. Erosion continues to this day on the High Plains east of the mountain front, and progressive incision of the drainage is recorded by at least five major gravel-clad terrace and pediment surfaces along the major fluvial channels that connect to the South Platte River system.

Introduction

This report describes the geology of the Fort Collins 30'×60' quadrangle in north-central Colorado. This compilation and synthesis integrates geologic mapping and various topical studies carried out between 1960 and 1990 under the U.S. Geological Survey (USGS) study of the northeastern Front Range (Braddock and Cole, 1979; Hutchinson and Braddock, 1987), geologic mapping of Rocky Mountain National Park (Braddock and Cole, 1990), and reconnaissance geologic mapping in wilderness areas (Pearson and others, 1981, 1982). Academic studies contributed detailed geologic mapping of several areas north of the Cache la Poudre River (Walko, 1969; Burch, 1983), in the Medicine Bow Mountains and Laramie River valley (Beckwith, 1942; Kiver, 1968; Camp, 1979; Griswold, 1980), and in the northern Mummy Range (Plymate and others, 2005). Authors of this report carried out detailed geologic mapping (Kellogg, Ruleman and others, 2008; Workman, 2008; Workman and Braddock, 2010) and reconnaissance mapping in previously unmapped areas of the quadrangle and reviewed field relations across the area to arrive at an integrated understanding of the geologic history. The ages of crystallization for numerous Proterozoic igneous and metamorphic units in the quadrangle were determined using single-crystal sensitive high-resolution ion microprobe (SHRIMP) techniques. This publication further draws on topical studies in geology, hydrology, and geomorphology by numerous investigators from Federal, State, and local agencies, as well as university research published through the years.

The purpose of this report is to summarize the geologic framework of a significant portion of the northern Colorado mountain terrain in support of updated mineral-resource assessments, particularly in lands administered by the U.S. Forest Service.

The geographic information system (GIS) data and related data files are available as a USGS data release in ScienceBase at https://doi.org/10.5066/F7G44PHV or https://www.sciencebase.gov/catalog/item/5a26d96ae4b03852baf7f16d (Workman and others, 2018).

Geography and Geomorphology

The Fort Collins 30'×60' quadrangle encompasses an area of 5,040 square kilometers (km^2), extends 93 kilometers (km) east-west and 57 km north-south, and includes parts of Jackson and Larimer Counties, Colorado, as well as a very thin sliver of the southernmost parts of Albany and Laramie Counties, Wyoming (fig. 1).

Most of the quadrangle is mountainous and much of the central terrain is rugged. The regional term Front Range is applied to the mountain uplift west of the Colorado Piedmont as far as the Laramie River valley in northern Colorado (fig. 2). The term Mummy Range applies to the highest parts of the Front Range south of the Cache la Poudre River, whereas the term Laramie Mountains refers to that part of the Front Range north of the river as shown on USGS topographic maps in the region (figs. 3 and 4*A*).

Elevations range between about 1,500 meters (m) in the Cache la Poudre valley in the southeastern part of the quadrangle to over 3,850 m in the northern Mummy Range and nearly 4,000 m in the Medicine Bow Mountains. Most elevations in the Laramie Mountains are between 2,300 m and 3,050 m. The Laramie River valley lies at about 2,500 m at its widest part and declines gently to the northwest. The southern margin of the Laramie Basin along the western part of the northern border of the Fort Collins quadrangle lies at about 2,300 m elevation.

In the Fort Collins 30'×60' quadrangle, approximately one-half of the area lies within the Roosevelt National Forest, another five percent within the northern part of Rocky Mountain National Park, and another five percent in the southwest corner lies within the Colorado State Forest State Park. Wilderness areas are designated in some of the more remote, high alpine areas (both Forest Service and National Park lands), including the Neota and Comanche Peak Wilderness areas in the Front Range (Pearson and others, 1981) and the Rawah Wilderness Area in the Medicine Bow Mountains (Pearson and others, 1982). Most of the inner valley of the main Cache la Poudre River and the South Fork Cache la Poudre River are designated as Wild and Scenic Rivers, and about 26 km^2 or about 10 square miles [mi^2])surrounding the confluence of these streams is designated the Cache la Poudre Wilderness.

Colorado State parks and wildlife areas encompass a few percent of the Fort Collins quadrangle. The Cherokee Park State Wildlife Area covers more than 52 km^2 (20 mi^2) along the North Fork Cache la Poudre River and Trail Creek, and about 13 km^2 (5 mi^2) surrounding the deep canyon of Lone Pine Creek are designated the Lone Pine State Wildlife Area. In the foothills area west of Fort Collins, Horsetooth Reservoir State Park includes the reservoir facility and several square miles of adjacent mountain land.

The eastern one-fifth of the Fort Collins quadrangle lies on the Colorado Piedmont below about 1,800 m elevation and includes the developed city center of Fort Collins, surrounding suburban areas, and farmland. The population of Fort Collins is just over 160,000, and the combined

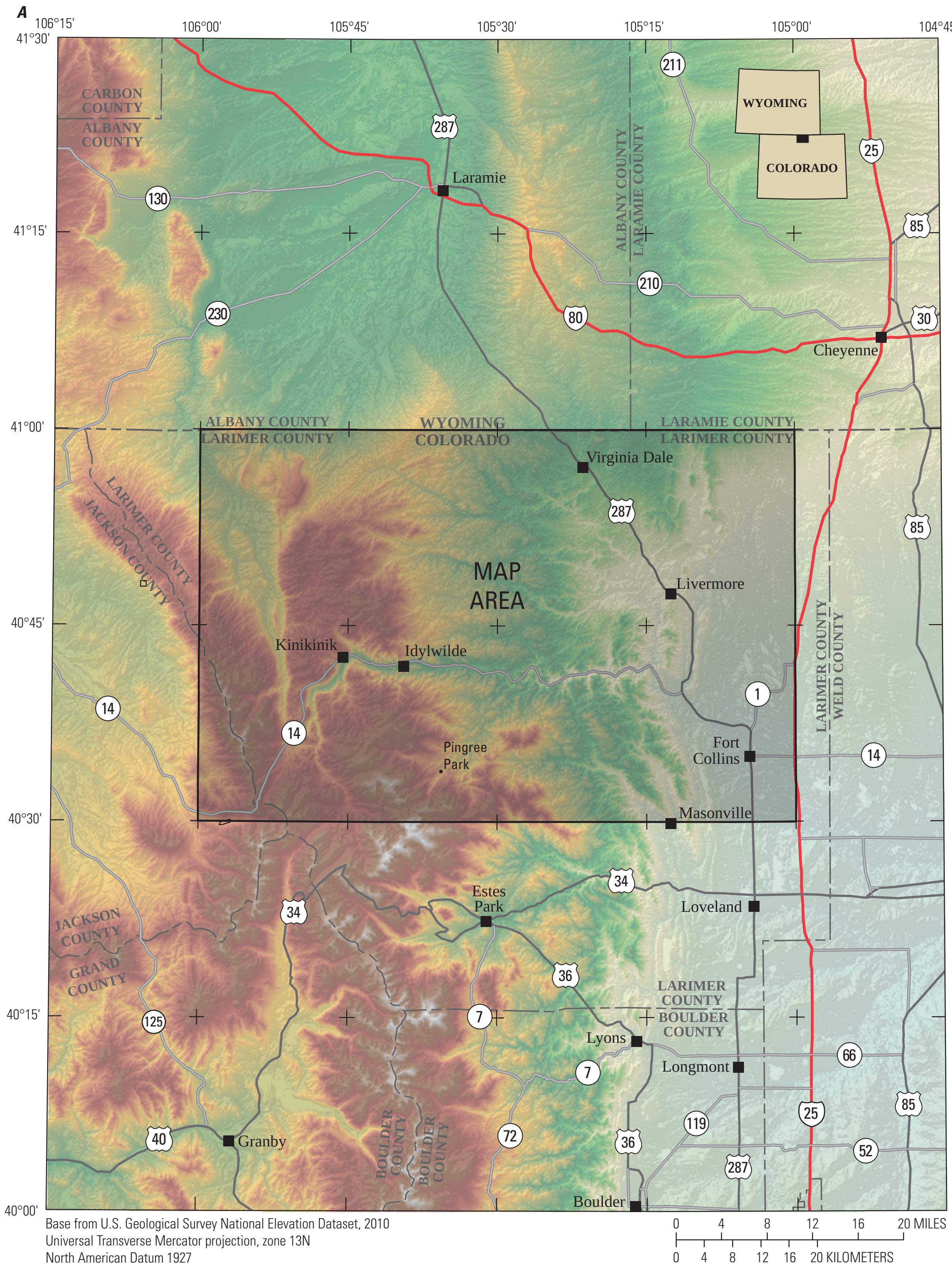


Figure 1 (continued on following page). *A*. Geographic setting of the Fort Collins 30'×60' quadrangle. *B*. Simplified boundaries and areas of some of the Federal and State lands found in the Fort Collins, Colorado, map area.

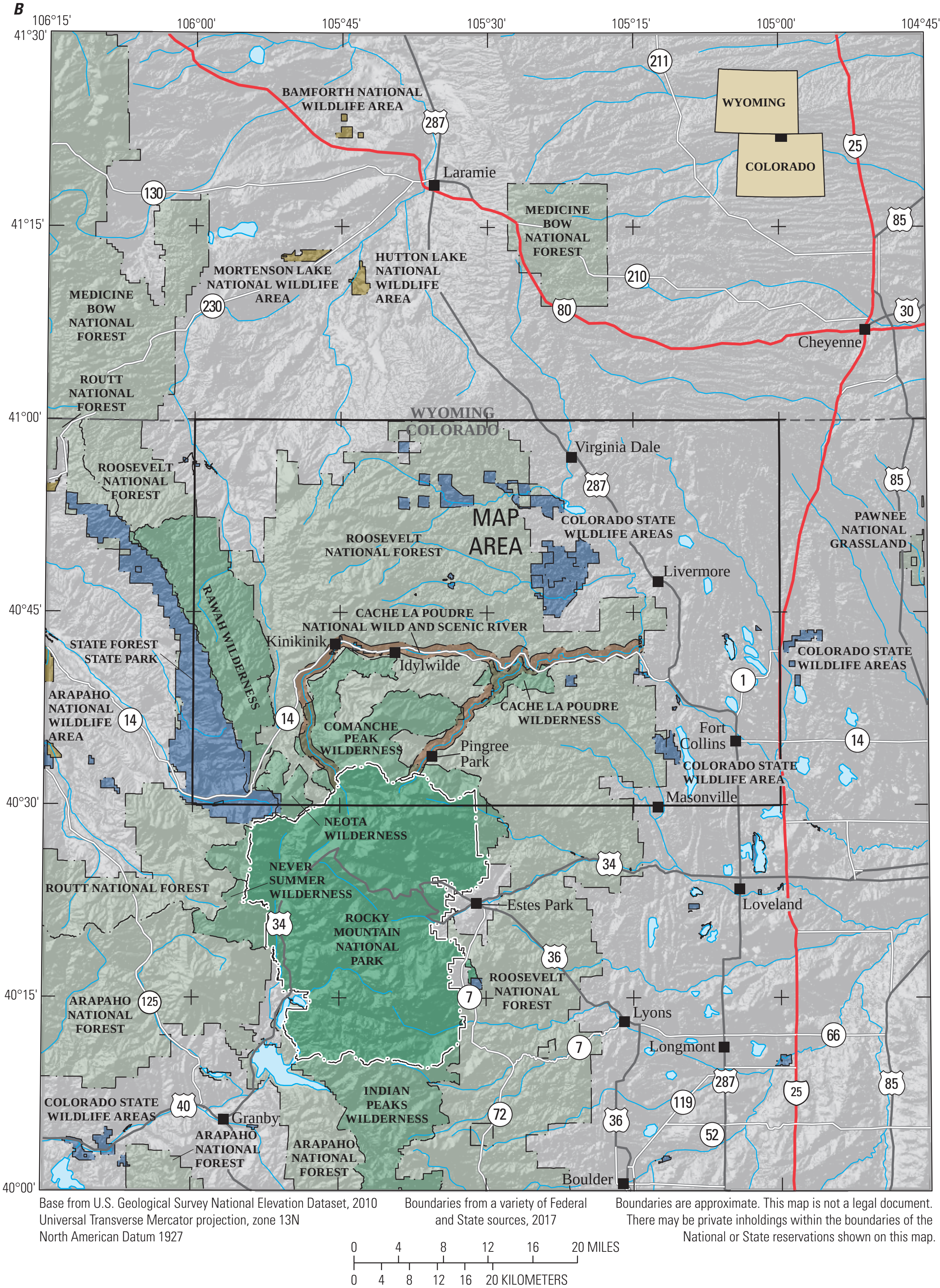


Figure 1. *A*. Geographic setting of the Fort Collins 30'×60' quadrangle. *B*. Simplified boundaries and areas of some of the Federal and State lands found in the Fort Collins, Colorado, map area.—Continued

population of Larimer County is estimated at being slightly over 333,000 (2015 estimates from 2010 U.S. Census Bureau, accessed Aug. 2, 2016, at http://www.census.gov/quickfacts/table/PST045215/0827425,08) concentrated primarily in the Piedmont region which contrasts significantly with the sparsely populated areas in the mountainous central and western regions.

Highway access in the area is provided primarily by U.S. Route 287 and State Highway 14. Route 287 passes north-south through Fort Collins and then goes northwestward through the small historic town of Virginia Dale, Colo., toward Laramie, Wyoming. Colorado State Highway 14 is an east-west road that starts in the east off of Interstate 76, goes westward to Fort Collins where it runs concurrently with Route 287 for about 3 km (8 mi) north of the city. It then turns westward again and follows the canyon of the Cache la Poudre River to Cameron Pass, and then continues beyond the quadrangle to Walden, Colorado. Most other mountain areas are connected by a network of paved and unpaved roads, some of which are maintained year-round.

The Fort Collins quadrangle spans the north end of the Colorado Front Range uplift of the Southern Rocky Mountains (Eaton, 1986) and includes part of the northwesternmost Colorado Piedmont geographic province to the east (Fenneman, 1931). The Medicine Bow Mountains along the westernmost part of the quadrangle form a discrete structural uplift west of the Laramie River. The southwestern edge of the Laramie Basin extends into the northwest corner of the quadrangle. The eastern edge of the North Park Basin extends into the southwest corner of the quadrangle (fig. 2).

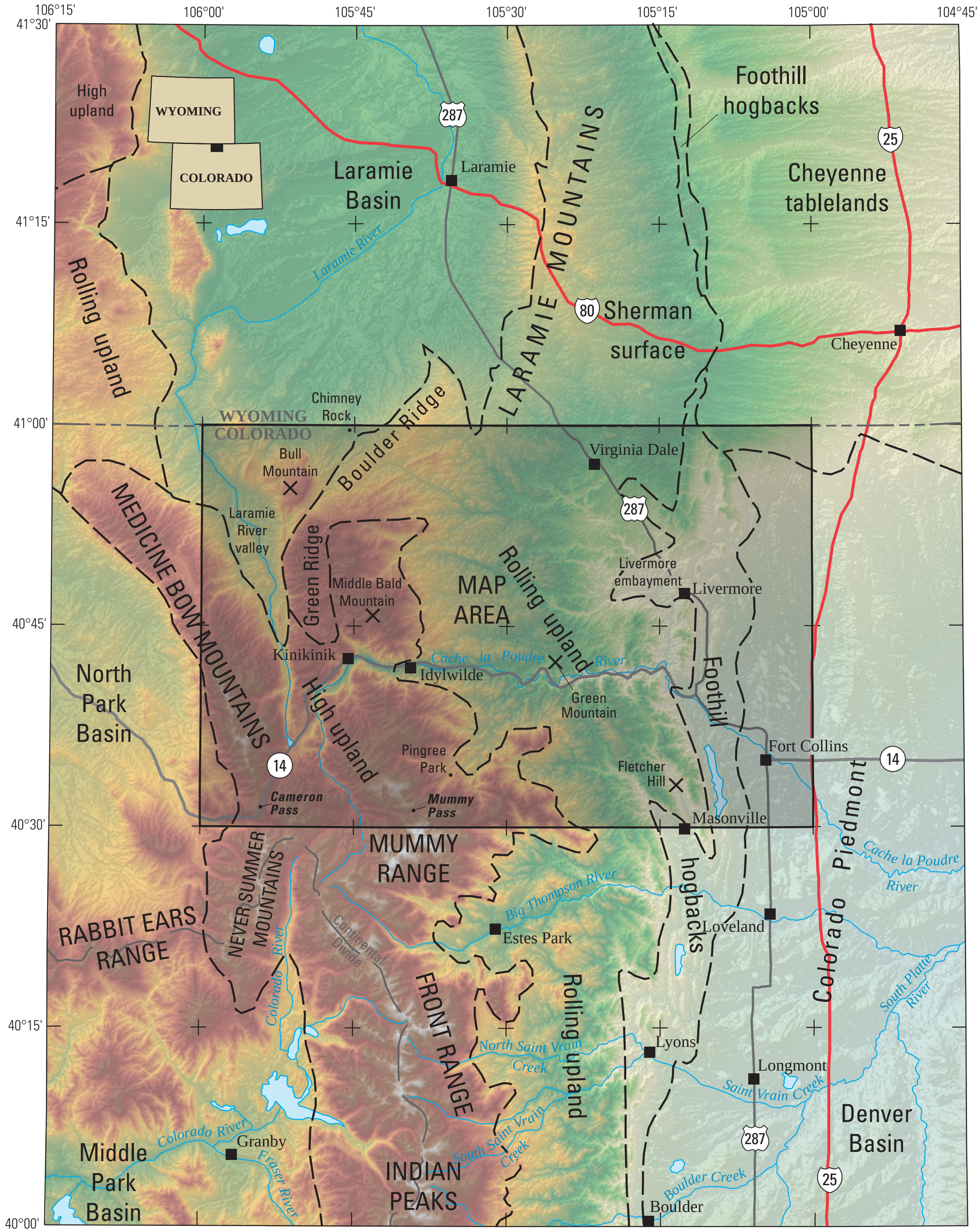
The general landforms of the quadrangle can be described in terms of several slightly overlapping geographic and elevation-bounded zones (fig. 2). The easternmost zone below an elevation of about 1,800 m consists of the gently inclined slopes and broad fluvial valleys in the Colorado Piedmont, including small remnants of the Miocene-Pliocene alluvial fan surface (the Gangplank surface or Cheyenne tablelands of McMillan and others, 2002) in the northeastern corner of the quadrangle. North of the town of Livermore, Colo., the Piedmont merges imperceptibly with the eroded top of the Proterozoic basement known as the Sherman surface (Eggler and others, 1969; Bradley, 1987) that marks the broad gentle crest of the Laramie Mountains north of Virginia Dale. The eastern margin of the Front Range is marked by a foothill zone consisting of hogback ridges formed by upturned sedimentary strata of contrasting erosional resistance. The foothill zone is segmented by a northwest-trending fault just north of Teds Place (junction of Route 287 and Highway 14) that offsets the hogback ridges. A similar but more dramatic fault offset of the hogback belt occurs just south of the map area (Cole and Braddock, 2009). At Livermore, the foothills belt steps westward into the Livermore embayment, a broad, fault-controlled trapezoidal graben marked by uplifted basement blocks flanking a gentle syncline in the upper Paleozoic strata. The northernmost part of the foothills belt has a greater width, lower relief, and is marked by subhorizontal Paleozoic-Mesozoic sedimentary strata forming mesas, separated by sections of inclined strata where the sediments are folded above faulted basement blocks (Matthews, 1978).

The central part of the Front Range uplift within the map area (between about 2,300 and 2,750 m in elevation) is characterized by a gently rolling upland block of crystalline rocks sloping gradually to the east and cut by steep, narrow, and deeply incised canyons which drain to the east (Steven and others, 1997). This rolling upland is interpreted by many to be a relic of widespread erosion during the middle part of the Tertiary Period (for example, Epis and Chapin, 1975; Scott and Taylor, 1986; Steven and others, 1997). The highest part of the map area is the upland terrain of the Mummy Range and Medicine Bow Mountains that is above about 2,900 m in elevation and that is markedly steeper than the incised rolling upland zone to the east and north. The upper reaches of major valleys in the high upland were modified by glacial processes during the Quaternary Period and contain widespread glacial deposits (Madole and others, 1998).

The physiography of the western part of the quadrangle is marked by the north-trending, fault-controlled Laramie River valley and the adjacent Medicine Bow Mountains to the west. The Laramie River drainage flows in a graben formed in a structural syncline composed of Paleozoic and Mesozoic rocks that are flanked by uplifted blocks of Proterozoic basement on the east and west. In the northwestern corner of the quadrangle, the Laramie River runs northwestward (fig. 3) along the foot of Bull Mountain, which consists of folded Phanerozoic strata along the southern margin of the Laramie Basin.

The Medicine Bow Mountains consist of a northwest-trending basement uplift block that is steepest and highest along its western side. The eastern flank of the mountain range is marked by a fairly smooth surface of beveled Proterozoic crystalline rocks that is incised by rather linear, narrow, northeast-trending drainages. Both sides of the range crest were sculpted by valley glaciers during the Pleistocene (Kiver, 1968, 1972).

Several major rivers have headwaters within and near the Fort Collins quadrangle (fig. 3). The Continental Divide intersects with the divide between the North and South Platte River Basins approximately 5 km southeast of Cameron Pass 1.5 km south of the map boundary at the north end of the Never Summer Mountains. The headwaters of the Colorado River Basin sit just south of the Continental Divide in this location within Rocky Mountain National Park. River Basins are defined as that area drained by a river and its tributaries. The North Platte River Basin includes drainage areas within the western quarter of the map area. The Laramie River heads in the glaciated terrain near Cameron Pass and flows northward beyond the quadrangle to join the North Platte River northeast of Laramie, Wyo. The Michigan and Canadian Rivers similarly head on the west slope of the Medicine Bow Mountains and flow northwestward across the North Park Basin to join the North Platte River near Walden, Colo., to the west of the map area. The South Platte River Basin includes drainage areas across the central and eastern parts of the map area. The Cache la Poudre River drains most of this area and heads approximately 13 km southeast of Cameron Pass. The river flows north to Kinikinik and then eastward through a canyon across the Front Range towards Teds Place where it exits the Range and flows southeast to Fort



Base from U.S. Geological Survey National Elevation Dataset, 2010
Universal Transverse Mercator projection, zone 13N
North American Datum 1927

0 4 8 12 16 20 MILES
0 4 8 12 16 20 KILOMETERS

Figure 2. Physiography of the Fort Collins, Colorado, quadrangle. Dashed black lines are physiographic provinces. Black square indicates map area. Selected rivers, creeks, and roads shown.

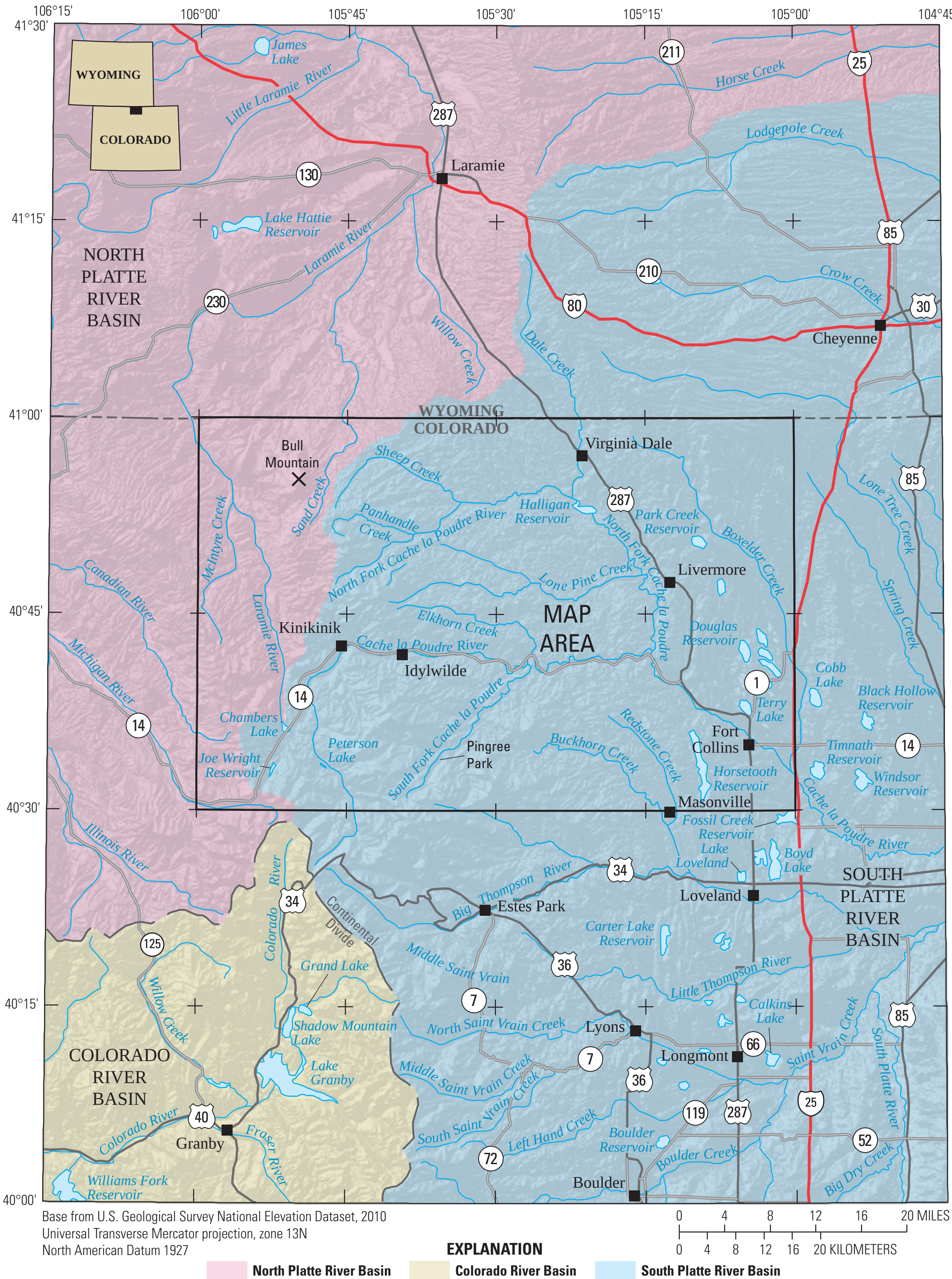


Figure 3. Hydrography of the Fort Collins quadrangle and surrounding area, with the North and South Platte River Basins in the map area, and the Colorado River Basin to the southwest of the map area. River Basins are defined as that area drained by a river and its tributaries. Fort Collins quadrangle outlined in black.

Collins; farther east, it joins the South Platte River near Greeley, Colo. The North Fork Cache la Poudre River runs south-southeast along the eastern edge of the rolling upland block within the map area coalescing several smaller streams that flow east to east-southeast across the range and joins the main Cache la Poudre River near its mouth. Boxelder Creek flows south-southeast along the eastern edge of the foothill hogbacks collecting drainage from the low hills and upper piedmont along the eastern edge of the map area and joins the Cache la Poudre River just off the southeast corner of the map.

Most of the eastern slope of the Front Range is forested, rolling upland. Local broad valleys and grass-covered flats are intermingled with the forested terrain, and are locally referred to as parks (Crosby, 1978). Most of the Front Range landscape is at elevations between about 2,300 m and 2,600 m, and merges gradually westward up into the steeper high upland terrain of the glaciated Mummy Range. On the western margin of the rolling upland adjacent to the higher elevation terrain, the through-flowing drainages coming out of the high upland have their lowest gradients which then increase as streams continue east across the range (Cole and Braddock, 2009, p. 3 and 4).

Compilation Sources and Methods

Much of the geology in the Fort Collins 30'×60' quadrangle was mapped at 1:24,000-scale under several USGS projects between the late 1960s and the 1990s (fig. 4). Proterozoic rocks in the core of the Front Range and the Phanerozoic strata of the foothills belt were mapped by W.A. Braddock and numerous graduate students from the University of Colorado-Boulder through the Northeastern Front Range Project and published at 1:24,000 scale (Abbott, 1976; Braddock, Abbott, Connor, and Swann, 1988; Braddock and Connor, 1988; Braddock, Connor, Swann and Wohlford, 1988; Braddock and LaFountain, 1988; Courtright and Braddock, 1988; Braddock, Wohlford, and Connor, 1988; Eggler and Braddock, 1988; Braddock, Calvert, O'Connor, and Swann, 1989; Braddock, Cole, and Eggler, 1989; Braddock, Eggler, and Courtright, 1989; Braddock, O'Connor, and Curtin, 1989; Nesse and Braddock, 1989; Shaver and others, 1988). Braddock compiled the geology of Rocky Mountain National Park (RMNP) at 1:50,000 scale from his and graduate students′ mapping at larger scales (Braddock and Cole, 1990).

A

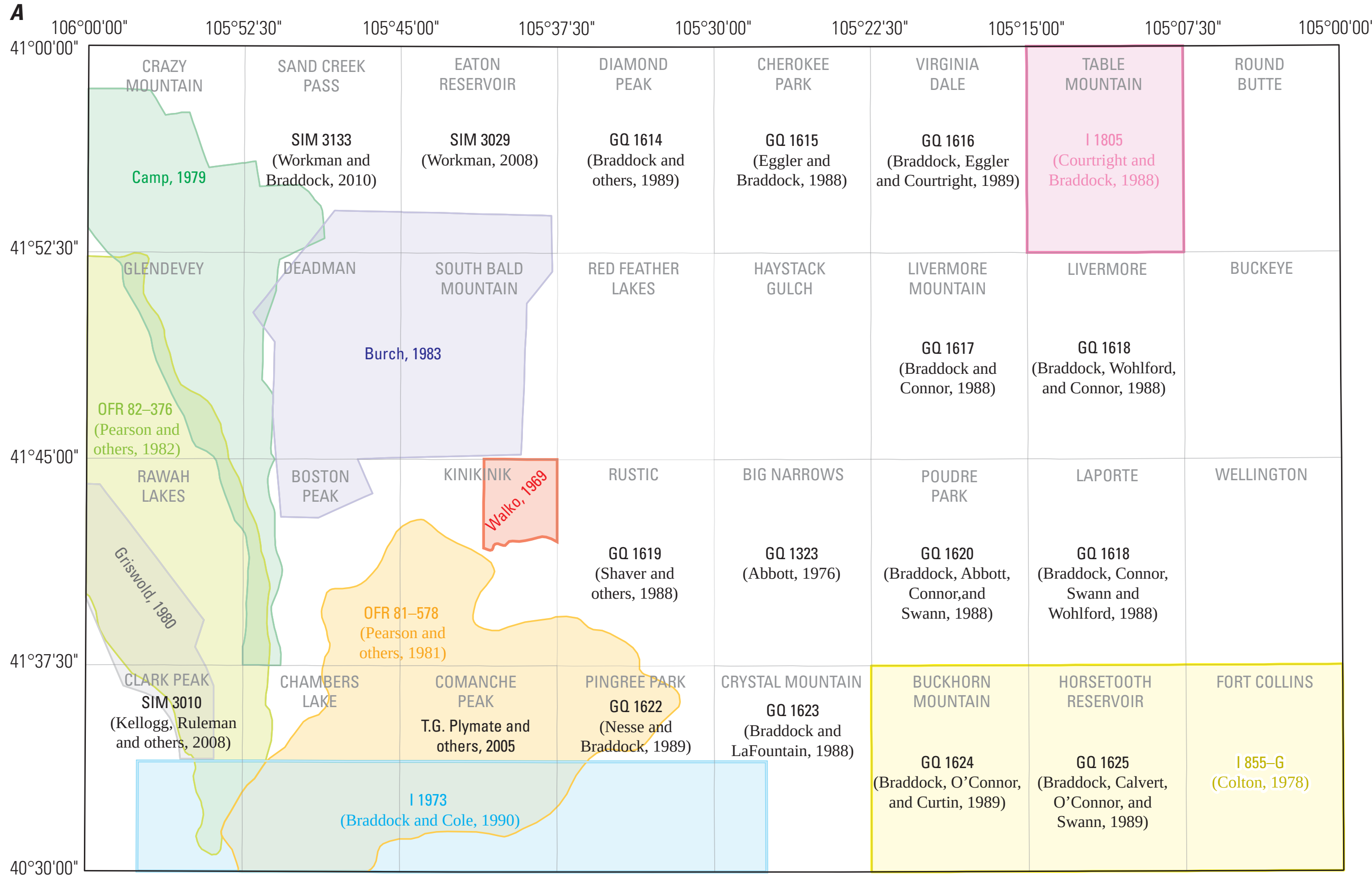
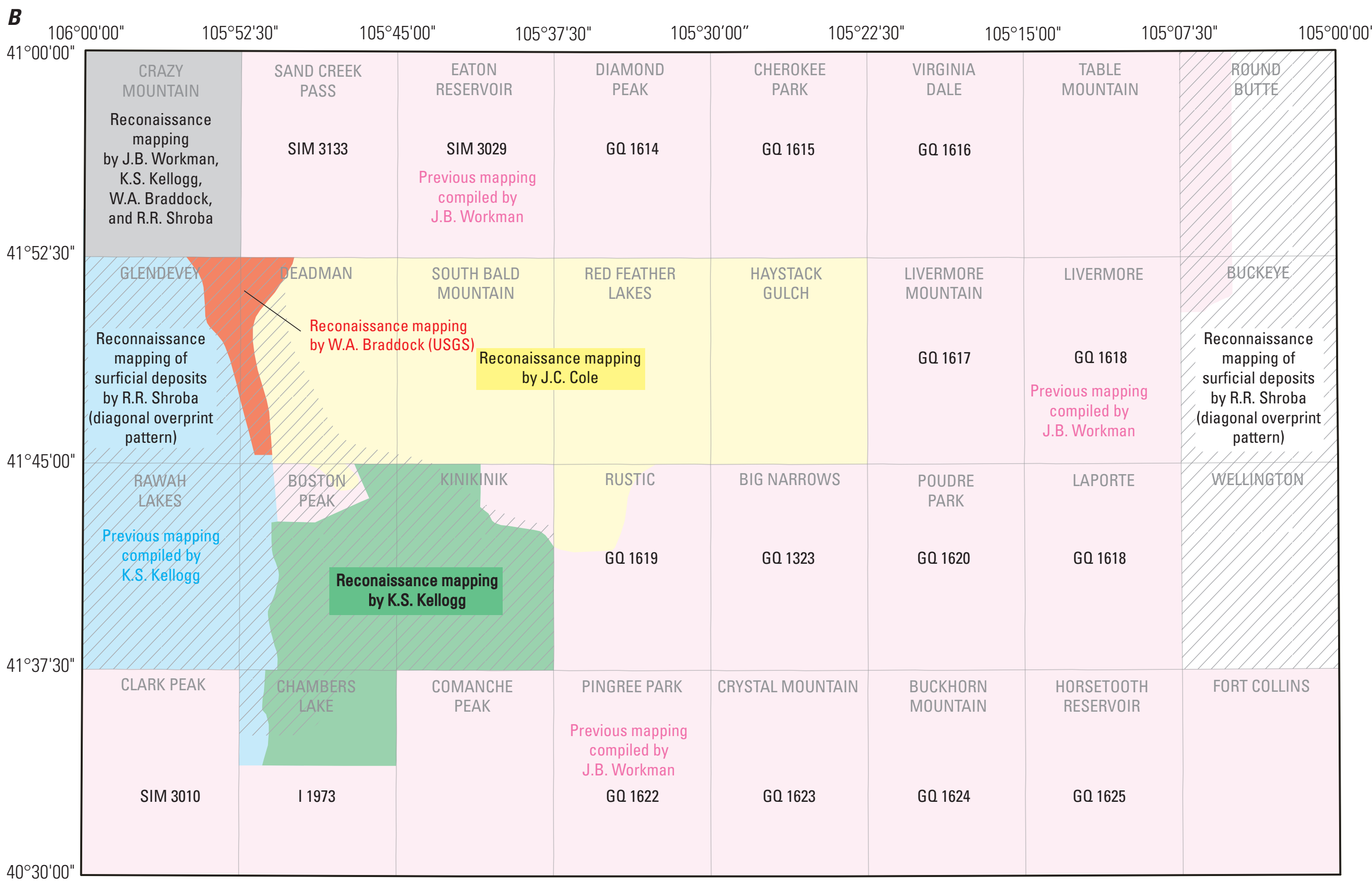


Figure 4 (continued on following page). *A*, Index map showing sources of geologic map data used in compiling the Fort Collins 30'×60' quadrangle. For U.S. Geological Survey publications, report number, authorship, and date of publication are shown. *B*, Index map of compilation responsibilities for new mapping in the Fort Collins 30'×60' quadrangle. For U.S. Geological Survey publications, report number, authorship, and date of publication are shown.



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The USGS did reconnaissance mapping in the southwestern part of the quadrangle in the 1970s to evaluate mineral resource potential in existing wilderness areas (Pearson and others, 1981, 1982). The Laramie River valley was mapped to explore regional structure by the State Geological Survey of Wyoming (Beckwith, 1942) and for graduate studies at Colorado State University (Camp, 1979). Adjoining areas of the southern Laramie Mountains west of Red Feather Lakes (Burch, 1983) and the central Medicine Bow Mountains (Griswold, 1980) were also mapped for graduate theses at Colorado State University. The glacial geology of the Medicine Bow Mountains was studied and mapped by Kiver (1968) from the University of Wyoming. A detailed study of the Proterozoic rocks north of the Cache la Poudre canyon in the vicinity of Idylwilde was completed by Walko (1969) from State University of New York at Buffalo.

New geologic mapping was carried out on the current project to cover areas not previously mapped, including the Eaton Reservoir quadrangle (Workman, 2008), western parts of the Clark Peak quadrangle (Kellogg, Ruleman, and others, 2008), and parts of the South Bald Mountain, Boston Peak, Chambers Lake, Deadman, Haystack Gulch, and Red Feather Lakes quadrangles (Cole and Kellogg) (fig. 4*B*). Previous reconnaissance mapping by W.A. Braddock (USGS emeritus, deceased, 2003) in the Sand Creek Pass and Crazy Mountain quadrangles was updated and completed by Workman (Workman and Braddock, 2010) and Workman, Kellogg, and Shroba (fig. 4*B*), respectively. Geologic mapping, petrologic studies, and geochronologic investigations in the Comanche Peak quadrangle were completed over a number of years by T.G. Plymate and T.D. Moeglin of Southwestern Missouri University and by W.R. Van Schmus of Kansas State University (Plymate and others, 2005).

Surficial deposits in the Fort Collins 7.5' quadrangle and areas immediately to the west in the foothills belt were mapped by Colton (1978). Shroba mapped the surficial geology in the Colorado Piedmont and foothills belt north of Colton's 1978 work based on photogeologic interpretation, limited field work, and comparisons with the geology of areas to the south (Kellogg, Shroba, and others, 2008). Shroba also reviewed and revised the portrayal of surficial geologic units in the Laramie River valley, the Medicine Bow Mountains, and the upper Cache la Poudre River valley, based largely on photogeologic interpretation using analytical stereophotogrammetric techniques. The Quaternary geologic history of these areas has not been studied in detail.

Comprehensive regional study of the Cretaceous marine deposits east of the Front Range was completed by Scott and Cobban (1965, 1986). Correlation of marine Cretaceous beds in the Laramie River valley to the definitive stratigraphy of Scott and Cobban (1986) was assisted by W.A. Cobban (USGS).

Geologic History

The area covered by the Fort Collins 30'×60'quadrangle displays a diverse assemblage of rocks and surficial units that range in age from Paleoproterozoic to Quaternary (figs. 5 and 6). The geology records several major rock-forming events and deformations that are characteristic of the Rocky Mountains of Colorado and southern Wyoming.

The core of the Front Range consists of volcanic and sedimentary rocks that were deposited in the Paleoproterozoic between about 1,790 and 1,725 million years (Ma), and intruded by calc-alkaline magmas and metamorphosed between about 1,725 Ma and 1,695 Ma (Premo and others, 2010b). They were subsequently intruded and locally deformed again during emplacement of widespread Mesoproterozoic granitic intrusions between about 1,440 Ma and 1,350 Ma (DeWitt and others, 2010). All of these older Proterozoic rocks were also deformed by Mesoproterozoic mylonite-bearing shear zones from roughly 1,400–1,200 Ma. The east flank of the Front Range and the Laramie Basin are marked by ridges of upturned Phanerozoic sedimentary rock in the foothills flanking the uplifted Proterozoic rocks. Uplift and denudation of the Proterozoic basement in the late Paleozoic as early as the Pennsylvanian Period (Anasazi uplifts of Nesse, 2007) removed any earlier Paleozoic sediments. The sediments in these strata were initially deposited as early as the Pennsylvanian Period in response. The oldest Paleozoic sediments were deposited adjacent to these now-eroded mountains by braided fluvial systems draining to an adjacent marine environment, and were succeeded by eolian, deltaic, marine, lagoonal, and other fluvial deposits that accumulated slowly from Permian through Jurassic time. By Early Cretaceous time, the dominant depositional environment was a fluvial delta system and lagoons on the margin of the vast Western Interior Seaway; subsidence led to marine incursion and deposition of very thick shales and local limestones and sands. All of these Phanerozoic rocks underlie the foothill hogback belt and the Colorado Piedmont areas of the eastern part of the Fort Collins quadrangle, as well as the Laramie Basin and the lower Laramie River valley. The oldest Pennsylvanian and possibly Permian rocks are missing from sections exposed in the upper Laramie River valley and North Park recording the southwestward onlap of deposits onto the eroded Anasazi uplifts (Nesse, 2007).

A major regional tectonic event known as the Laramide orogeny affected this area beginning in latest Cretaceous and led to the initial uplift of the Proterozoic basement cores of the modern ranges (Tweto, 1975). The eastern margin of the Front Range within the quadrangle rose as a broad monoclinal flexure cut by steep basinward dipping faults that uplifted the Proterozoic basement as the overlying Phanerozoic sedimentary rocks were denuded. The western margin of the early Laramide Front Range in the Laramie River valley is marked by an east-dipping reverse fault that places Proterozoic crystalline rocks over steep and overturned beds of Phanerozoic sedimentary rocks (Beckwith, 1942; Camp, 1979).

The early Laramide orogeny led to withdrawal of the inland sea from areas west of the Front Range and exposed the Upper Cretaceous marine and overlying nonmarine deposits to erosion in the Cameron Pass area (Gorton, 1953; Ward,

EXPLANATION

Post-Laramide rocks

- No — Ogallala Formation (lowermost Pliocene? to middle Miocene)
- N₱t — Troublesome Formation (Miocene to Oligocene)
- N₱n — North Park Formation (Miocene and upper Oligocene?)
- ₱vi — Oligocene volcanic and intrusive rocks
- ₱wr — White River Group (lower Oligocene and upper Eocene)

Laramide

- Twdr — Wind River Formation (Eocene)
- ₱cm — Coalmont and Middle Park Formations (Eocene and Paleocene)
- ₱h — Hanna Formation (Paleocene)
- ₱Kda — Denver and Arapahoe Formations (Paleocene to Upper Cretaceous)
- ₱Ki — Eocene to Late Cretaceous intrusive rocks

Other Cretaceous, Phanerozoic, Proterozoic, and Archean rocks

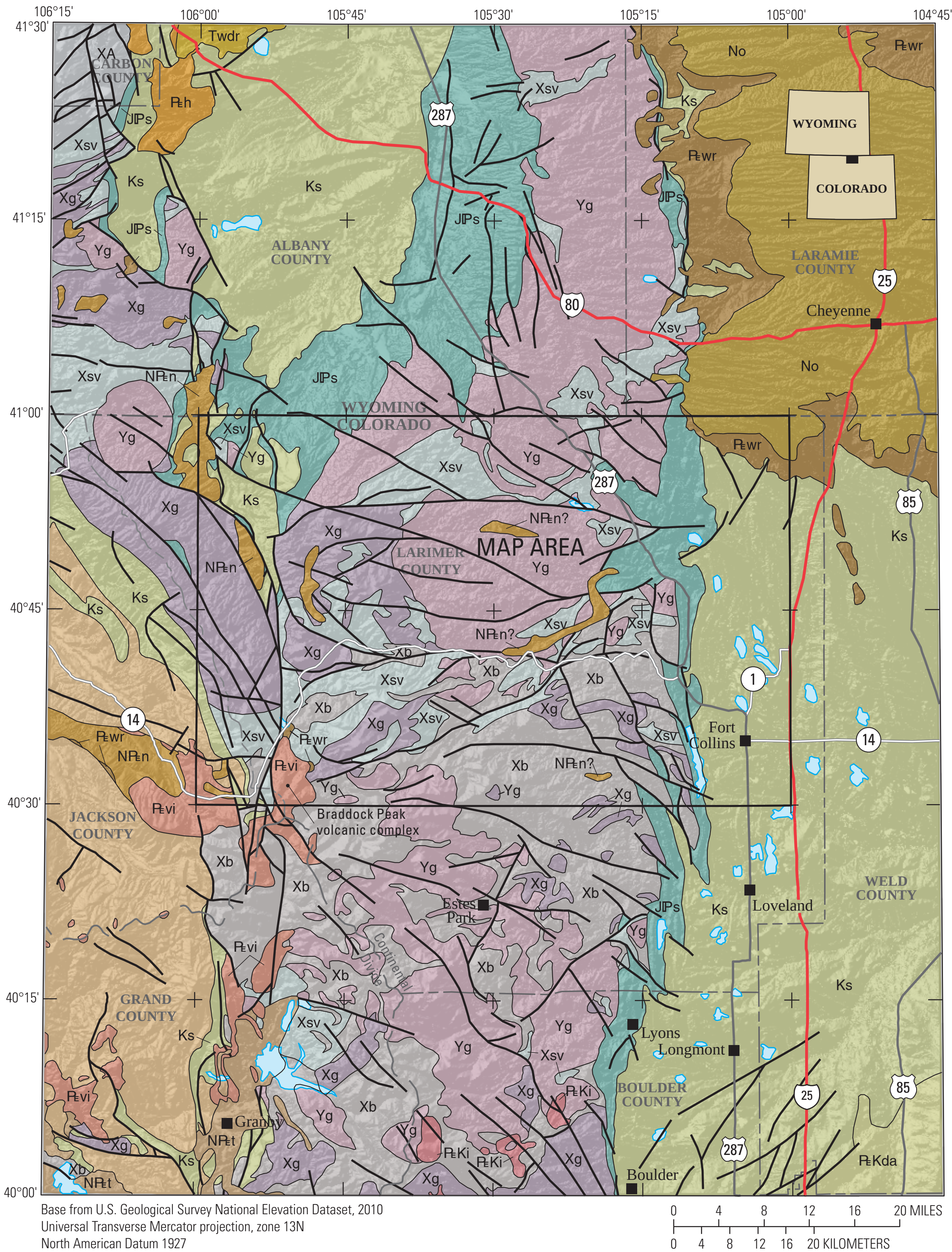
- Ks — Cretaceous sedimentary rocks—Includes some older rocks North and Middle Parks
- J₱s — Jurassic to Pennsylvanian sedimentary rocks
- Yg — Mesoproterozoic intrusive rocks
- Xg — Paleoproterozoic intrusive rocks
- Xb — Paleoproterozoic metasedimentary rocks
- Xsv — Paleoproterozoic metavolcanic and metasedimentary rocks
- XA — Paleoproterozoic and Archean rocks

Water

Faults—Undifferentiated

Contact

Figure 5 (continued on following page). Regional geologic setting of the Fort Collins 30'×60' quadrangle. Modified from Tweto (1979), ver Ploeg and others (1998), Sutherland and Hausel (2004), ver Ploeg and Boyd (2007), and Cole and Braddock (2009).



Base from U.S. Geological Survey National Elevation Dataset, 2010
Universal Transverse Mercator projection, zone 13N
North American Datum 1927

Figure 5. Regional geologic setting of the Fort Collins 30'×60' quadrangle. Modified from Tweto (1979), ver Ploeg and others (1998), Sutherland and Hausel (2004), ver Ploeg and Boyd (2007), and Cole and Braddock (2009).—Continued

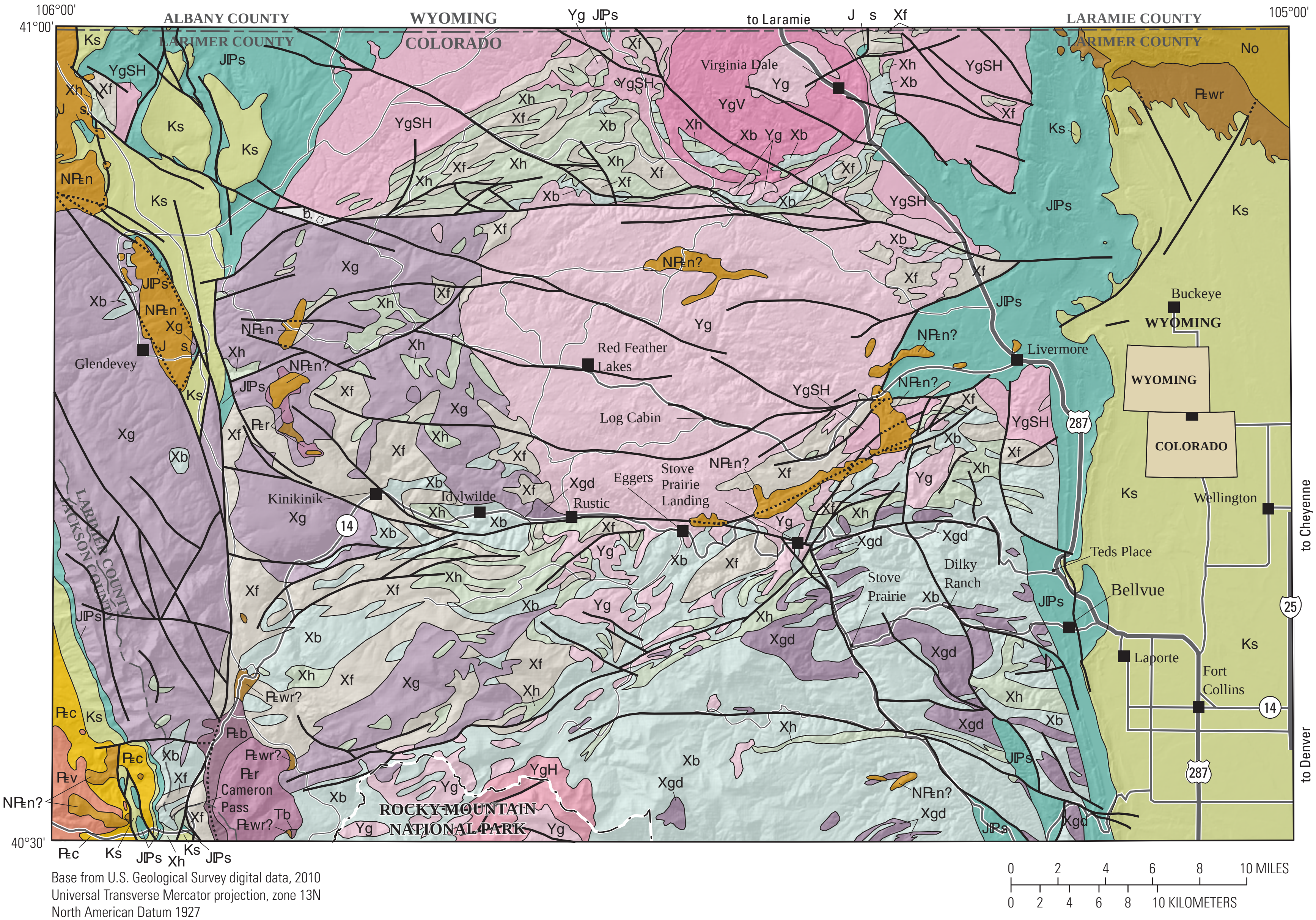


Figure 6 (continued on following page). Simplified geologic map of the Fort Collins 30'×60' quadrangle. Modified from the current study (this report, map sheet) to highlight general distribution of rock age, basic lithology, and structural geometry.

EXPLANATION

No	**Ogallala Formation (lowermost Pliocene? to middle Miocene)**
N₽n	**North Park Formation (Miocene and Oligocene?)**
₽r	**Rhyolite flows (Oligocene)**
₽v	**Dacite and rhyolite flows (Oligocene)**
₽b	**Trachybasalt flows (Oligocene)**
₽wr	**White River Group (lower Oligocene and upper Eocene)**
₽c	**Coalmont Formation (Eocene to Paleocene)**
Ks	**Cretaceous sedimentary rocks**
Jℙs	**Jurassic to Pennsylvanian sedimentary rocks**
Yg	**Silver Plume-type monzogranite (Mesoproterozoic)**
YgV	**Virginia Dale ring-dike complex (Mesoproterozoic)**
Jℙs	**Jurassic to Pennsylvanian sedimentary rocks**
YgSH	**Sherman Granite (Mesoproterozoic)**
YgH	**Granite of Hagues Peak (Mesoproterozoic)**
Xg	**Monzogranite (Paleoproterozoic)**
Xgd	**Granodiorite and trondhjemite (Paleoproterozoic)**
Xb	**Biotite gneiss (Paleoproterozoic)**
Xh	**Hornblende gneiss and amphibolite (Paleoproterozoic)**
Xf	**Felsic gneiss (Paleoproterozoic)**
b	**Fault breccia**
	Fault—Undifferentiated. Dotted where approximate
	Contact

Figure 6. Simplified geologic map of the Fort Collins 30'×60' quadrangle. Modified from the current study (this report, map sheet) to highlight general distribution of rock age, basic lithology, and structural geometry.—continued

1957), and particularly in areas west of this quadrangle. Thick fluvial deposits of the upper Paleocene and Eocene Coalmont Formation (₽c) accumulated in the North Park Basin west of the Laramide highlands. Subsequent folding, possibly in middle Eocene time (Hail, 1965; Tweto, 1975; Cole and others, 2010) deformed the Coalmont Formation west of the Front Range during a distinct period of late Laramide contraction. At this time, the Never Summer thrust fault south of the map area along the western edge of the Never Sumer Mountains uplifted Proterozoic crystalline rocks westward against folded Coalmont Formation sediments. The Medicine Bow Mountains may have risen at this time, as suggested by the absence of Coalmont beds in the Laramie River valley. Minor amounts of Paleocene-Eocene porphyritic intrusive rock in the Rustic 7.5' quadrangle (a part of the historic Manhattan District) indicate some magmatic activity late in the Laramide orogeny.

Most of the Eocene appears to have been a time of erosion and deep weathering, accompanied by a hot, humid climate (Scott and Taylor, 1986). The Proterozoic crystalline rocks in the Laramide and Eocene uplifts were reduced to residual ridge crests and large areas of subdued rolling ground (Steven and others, 1997). This widespread erosion and planation is reflected today in broad areas with nearly concordant hilltop elevations across the northern Front Range, as well as by the Sherman erosion surface across the Laramie Mountains (Eggler and others, 1969; Bradley, 1987). Eocene and Oligocene deposits of the White River Group (₽wr) are rare in the Fort Collins quadrangle, but are preserved in paleoriver channels in the mountain areas (Steven, 1957; Evanoff, 1990) and on the eroded Cretaceous strata east of the Front Range (Courtright and Braddock, 1989; this report).

Volcanic activity during the latter part of the Oligocene Epoch is recorded by basalt flows and rhyolite ash-flow tuffs and flows near the southwestern corner of the quadrangle east and west of Cameron Pass, emanating from the Braddock Peak volcanic complex in the Never Summer Mountains (O'Neill, 1981; Cole and others, 2008; Cole and Braddock, 2009, p. 40). This younger magmatic activity was accompanied and followed by high-angle normal faulting, both of which might have been manifestations of broad regional uplift related to rise of aesthenospheric mantle (Eaton, 1986, 1987) and extensional faulting in the northern extents of the Rio Grande rift. Rapid erosion occurred during this uplift, as indicated by coarse gravel deposits preserved in mountain-area paleo-river channels and by volcaniclastic and arkosic sands and gravels of the North Park Formation (N₽n). Extensional faulting was contemporaneous with North Park Formation deposition, particularly in the North Platte River drainage north of Walden, Colo. (Montaigne, 1957). Ongoing Miocene regional uplift led to broad erosion across the Front Range and deposition of upper Miocene and lower Pliocene gravels and sands of the Ogallala Formation (No) blanketing areas east of the Front Range (Steven and others, 1997).

The Pliocene and younger history of this area is dominated by renewed uplift and erosion (Steven and others, 1997), accompanied by significant climate change to cooler and wetter conditions (Fleming, 1994; Chapin and Kelley, 1997; Bluemle and others, 2001; Williams and Cole, 2007). The drainage system of the South Platte River to the east has gradually eroded through the blanketing Miocene gravels and excavated the hogback ridges flanking the Front Range. Streams in the lower parts of the mountain block, such as the Cache la Poudre River and Buckhorn Creek, have been deeply incised into the Proterozoic crystalline core of the Front Range. Drainage of the North Platte River west of the Front Range is not so deeply incised because base-level adjustments have been slowed by resistant knickpoints north of the North Park Basin (Steven, 1957; Blackstone, 1975).

Climate cooling that began during the Pliocene Epoch continued to the full glacial-interglacial conditions that characterize the Pleistocene (Bluemle and others, 2001). Two major phases of Pleistocene mountain-valley glaciation are well recorded by high-altitude deposits within the Fort Collins quadrangle (Madole and others, 1998), as well as several Holocene glacial advances (Kiver, 1968). The spectacular alpine scenery in the Mummy Range and along the crest of the Medicine Bow Mountains reflects both glacial sculpting in cirques and down-valley transport of rubble by streams of ice. The oldest glacial outwash deposits in the Laramie River valley may be affected by minor normal faulting, but more detailed study is needed. Pleistocene drainage patterns appear to be influenced by possible young movement of the Sheep Creek fault zone in the southern Laramie Basin (Workman, 2008). Quaternary mass-movement deposits are present throughout the mountainous areas of the study area. At lower elevations, the Quaternary is marked by several distinct levels of stream terrace deposits.

Paleoproterozoic Layered Rocks

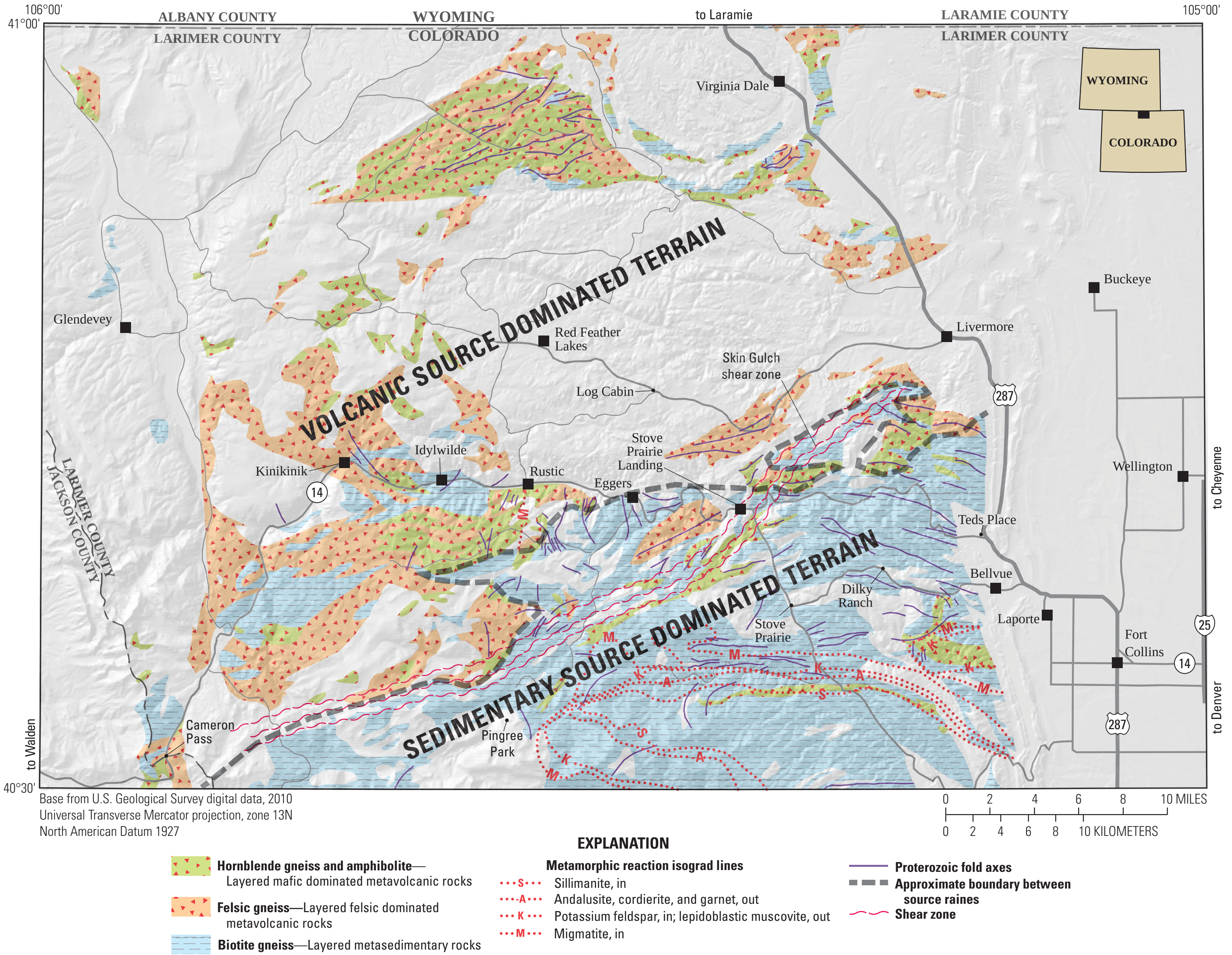
Proterozoic igneous and metamorphic rocks exposed in the Front Range uplift include the oldest rocks in this part of the North American post-Archean, cratonic basement. The metamorphic schists and gneisses in the Fort Collins quadrangle were chiefly derived from mafic and felsic volcanic rocks and interlayered sediments (fig. 7) that were deposited south of the older (Archean) craton that has been documented just north of the Colorado-Wyoming State line (Reed and others, 1987; Reed, 1993). These sediments and volcanic rocks (erupted at about 1,782 Ma to 1,763 Ma) were deposited between 1,790 Ma to 1,725 Ma and were progressively metamorphosed from about 1,725 Ma to 1,695 Ma (Premo and others, 2010b) during the time they were being folded and intruded by calc-alkaline granodiorite, trondhjemite, and granite (Routt Plutonic Suite of Tweto, 1987).

The southeastern part of the Fort Collins quadrangle preserves a fairly complete record of this progressive regional metamorphism in metasedimentary rocks (see figs. 7 and 8; from garnet-staurolite schist to sillimanite-biotite schist to partially melted biotite gneisses with residual high-grade cordierite and (or) garnet; Braddock and Cole, 1979; Nesse, 1984; Cole and Braddock, 2009, p. 19–22). Biotite gneisses farther north and west in the quadrangle universally show partial-melting textures, as do most metasedimentary rocks in the Front Range (Cole and Braddock, 2009, p. 19–22).

Hornblende-bearing mafic schists and gneisses are locally prominent in the Paleoproterozoic metamorphic terrane of the Front Range. They generally form layers that are conformable with the surrounding metasedimentary rocks, are chemically similar to basalt and andesite, contain local relict phenocrysts, and are interpreted to have originated from volcanic flows although some may have been shallow intrusive sills. These rocks typically occur as hornblende schist, hornblende gneiss, or amphibolite. Epidote-bearing calc-silicate gneiss (Xcg) is a rare but distinctive rock type in this part of the Front Range. It is commonly interlayered with the mafic metavolcanic rocks and may have originated from sediments eroded from those volcanic protoliths. A similar origin is inferred for faintly layered, dark-colored, fine-grained gneisses consisting of plagioclase, biotite, epidote, and minor quartz and iron oxide minerals (granoblastic biotite gneiss) that occur as interlayered masses in the canyon east of Bellvue, Colo., and in the northeastern Comanche Peak Wilderness north of the South Fork Cache la Poudre River (Braddock, Abbott, and others, 1988; Shaver and others, 1988; Nesse and Braddock, 1989).

Quartzofeldspathic leucocratic gneisses are conspicuous elements of the metamorphic terrane in parts of the Fort Collins quadrangle, especially north of the Skin Gulch shear zone. These gneisses typically display compositional banding marked by differing proportions of quartz, feldspar, and biotite, or by variations in grain size and their bulk compositions are similar to granite, granodiorite, or tonalite. These felsic gneisses (Xfl) are commonly interlayered with mafic hornblende gneisses and amphibolites (Xh) (Abbott, 1976; Braddock, Cole, and Eggler, 1989; Workman, 2008) and are interpreted to have formed from felsic volcanic rocks. Recent geochronologic study has demonstrated that these compositionally banded and dimensionally foliated felsic gneisses contain zircons that crystallized between about 1,782 Ma and 1,763 Ma (Premo and others, 2010b), consistent with the interpretation that they formed from primary volcanic rocks. Burch (1983) mapped these compositionally banded, medium- to coarse-grained rocks as a “porphyritic phase of the Rawah batholith,” but the zircon studies show that the typical igneous granite of the Rawah batholith (XgR) (our terminology) was not intruded until about 50 million years later. Plymate and others (2005) also demonstrated that these granitic gneisses are much older than the granite of the Rawah batholith in the Comanche Peak quadrangle, and they give an excellent summary of the physical characteristics they used to distinguish the two rock types in the field.

Figure 7 (following page). Proterozoic metamorphic rocks of the Fort Collins 30'x60' quadrangle showing distribution of major metamorphic rock types within the map area. Note the predominance of felsic gneiss mixed with hornblende gneiss and amphibolite with only isolated areas of biotite gneiss in the northern and western parts of the quadrangle as opposed to the southeastern part of the quadrangle where biotite gneiss dominates. The northern assemblage is indicative of interlayered volcanic and volcaniclastic source rocks (volcanic source dominated terrain) while the southern assemblage is indicative of pelitic source rocks (sedimentary source dominated terrain). The approximate boundary between these two terrains (thick gray dashed line) roughly follows the east-northeast trending Skin Gulch shear zone (wavy red lines). Metamorphic reaction isograd lines of Braddock and LaFountain (1988), Braddock, Calvert, O’Connor, and Swann (1989), Braddock, O’Connor, and Curtin (1989), and Nesse and Braddock (1989) are shown (dotted red line) indicating the increasing metamorphic grade to the north and west. See figure 8 for more complete explanation of reaction lines. Geology simplified from geologic map (this report, map sheet).



106°00'
41°00'
105°00'
40°30'
ALBANY COUNTY
LARIMER COUNTY
WYOMING
COLORADO
to Laramie
LARAMIE COUNTY
LARIMER COUNTY
WYOMING
COLORADO
Virginia Dale
Buckeye
Glendevey
Red Feather Lakes
Livermore
VOLCANIC SOURCE DOMINATED TERRAIN
Skin Gulch shear zone
Log Cabin
287
LARIMER COUNTY
JACKSON COUNTY
Idylwilde
Stove Prairie Landing
Kinikinik
Rustic
Eggers
Wellington
to Cheyenne
14
Teds Place
SEDIMENTARY SOURCE DOMINATED TERRAIN
Bellvue
Dilky Ranch
Laporte
25
Stove Prairie
Fort Collins
14
Cameron Pass
Pingree Park
287
to Walden
to Denver
Base from U.S. Geological Survey digital data, 2010
Universal Transverse Mercator projection, zone 13N
North American Datum 1927
0 2 4 6 8 10 MILES
0 2 4 6 8 10 KILOMETERS
EXPLANATION
Hornblende gneiss and amphibolite—Layered mafic dominated metavolcanic rocks
Felsic gneiss—Layered felsic dominated metavolcanic rocks
Biotite gneiss—Layered metasedimentary rocks
Metamorphic reaction isograd lines
S Sillimanite, in
A Andalusite, cordierite, and garnet, out
K Potassium feldspar, in; lepidoblastic muscovite, out
M Migmatite, in
Proterozoic fold axes
Approximate boundary between source raines
Shear zone

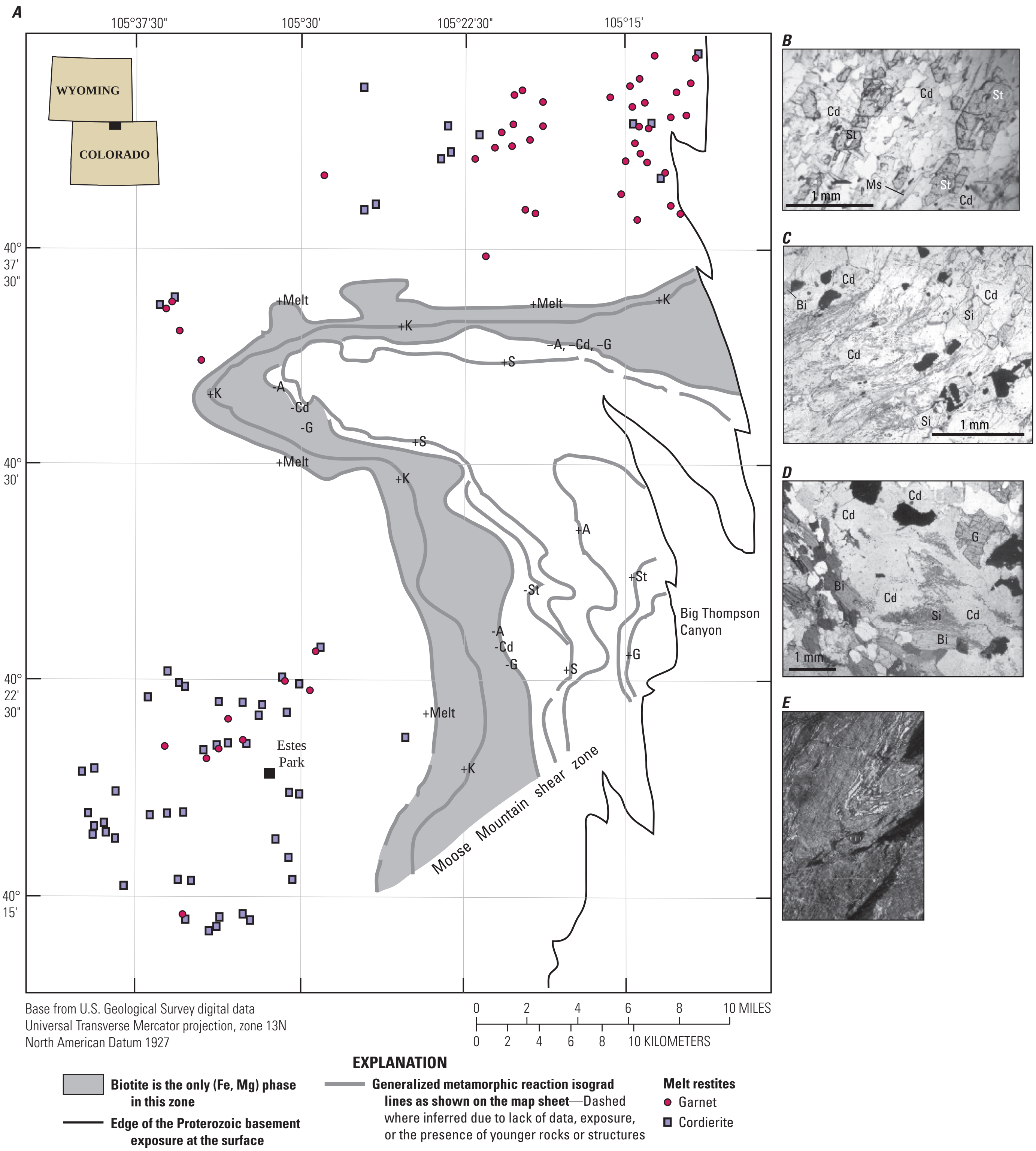


Figure 8. Photographs of thin sections and map showing mineralogy of Paleoproterozoic metamorphic rocks in the northern Front Range (modified from Cole and Braddock, 2009). Definitions of features on the figures as taken from Cole and Braddock (2009). *A*, Sketch map showing distribution of metamorphic-mineral isograds in pelitic rocks, marked by the first appearance (+) or disappearance (-) of andalusite (A), biotite (Bi), cordierite (Cd), garnet (G), potassium feldspar (K), sillimanite (S), or staurolite (St). Line marking appearance of partial-melt textures (+melt) indicates the western and northern extent of unmelted (low-grade) pelitic rocks. Garnet and cordierite in restite phase of partially melted gneisses (dot and square symbols) originated through incongruent melting of biotite and are compositionally and texturally distinct from garnet and cordierite in the lower-grade terrane to the east and southeast. *B*, Photomicrograph showing matrix cordierite (Cd),

quartz (colorless), and muscovite (Ms) with porphyroblastic staurolite (St) in low-grade schist (W.A. Braddock photomicrograph, 1970). *C*, Photomicrograph showing coarse, oriented prisms of sillimanite (Si) intergrown with polygonal cordierite (Cd) that replaces fine sillimanite needles and remnant biotite (Bi) in partially melted biotite gneiss. *D*, Photomicrograph showing polygonal cordierite (Cd) and irregular garnet (G) replacing biotite (Bi) and sillimanite (Si) in partially melted biotite gneiss. *E*, Outcrop photograph showing partial-melt textures (light-colored quartz-feldspar leucosomes surrounded by dark melanosomes containing unmelted biotite, sillimanite, and magnetite) in partially melted biotite gneiss. Leucosomes form rod-shaped bodies elongate parallel to fold axis due to growth during deformation. Lens cap about 2 inches in diameter. (C, D, and E photomicrographs, J.C. Cole, 1972–1974).—Continued

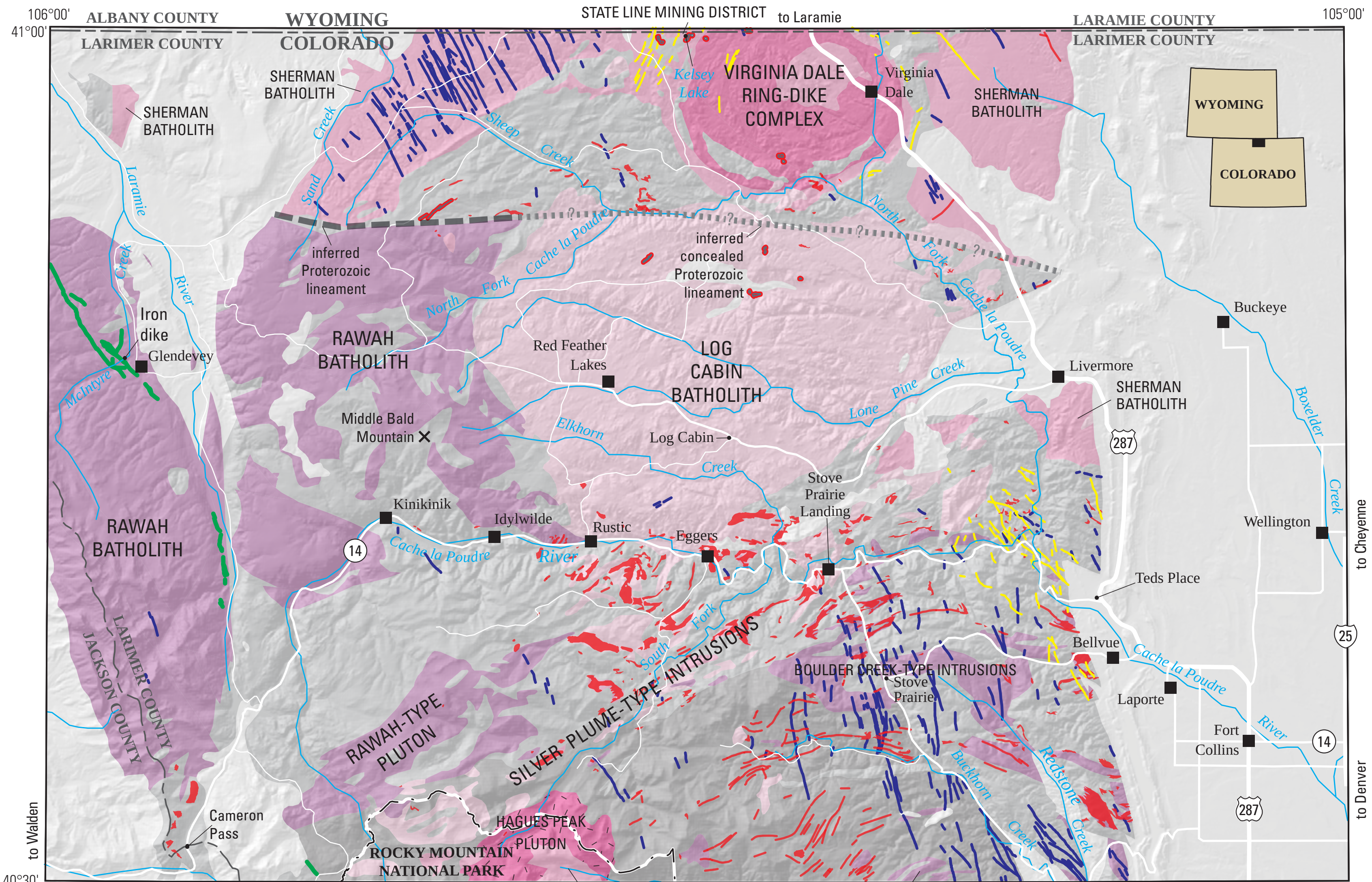
Metamorphic rocks west of the Virginia Dale intrusive complex (fig. 9) in the Diamond Peak and Eaton Reservoir 7.5' quadrangles (Braddock, Cole, and Eggler, 1989; Workman, 2008; figs. 6, 7, and 9) provide strong evidence of volcanic origin for these mafic and felsic gneisses. The three principal rock types are (1) hornblende gneiss and amphibolite (Xh), (2) leucocratic felsic gneiss (Xfl), and (3) biotite felsic gneiss with conspicuous microcline augen (Xfb). These three lithologic units are interlayered on the scale of several to hundreds of meters, and compositionally distinct layers have been mapped out for miles along their strike through complex fold structures. Local lenses and layers of biotite-rich sillimanite gneiss (Xbq) are conformable with compositional layering in the felsic and hornblende-rich gneisses. The three major units are compositionally similar to basalt, rhyolite, and dacite, whereas the biotite-sillimanite gneiss indicates a clastic, pelitic protolith. The outcrop evidence is most consistent with a folded, metamorphosed stack of diverse volcanic rocks and interbedded sediments (volcanic source dominated terrain of fig. 7). Rock types (2) and (3) above produced lead-uranium (U-Pb) sensitive high-resolution ion microprobe (SHRIMP) zircon crystallization ages within the map area of 1,766.6±8 Ma and 1,775.5±4 Ma, respectively (Workman, 2008), consistent with an age of primary volcanic eruption (Premo and others, 2010b). Hornblendite within this interlayered metavolcanic sequence in the Eaton Reservoir 7.5' quadrangle produced one of the oldest U-Pb SHRIMP zircon ages determined to date in the map area (1,779±5 Ma) and may have originated as a komatiitic flow rock or ultramafic synvolcanic intrusive mass (Workman, 2008).

Reconnaissance mapping for this compilation in the forested mountains of the Comanche Peak Wilderness south-southeast of Kinikinik revealed large areas of fine- to medium-grained faintly layered gneiss containing hornblende and biotite in addition to quartz and feldspar. It is locally interlayered with hornblende gneiss and granitic gneiss, and so is probably derived from volcanic or volcaniclastic protoliths. It is intruded in complex fashion by granite of the Rawah batholith and forms large irregular inclusions in that body.

The area south of the Skin Gulch shear zone generally contains metamorphic rocks rich in biotite and sillimanite that are interpreted to be derived from sedimentary protoliths (sedimentary source dominated terrain of fig. 7). Contiguous areas of similar rock to the south of the map area show original sedimentary structures including graded bedding, cross-bedding, scour-and-fill structures, thin conglomerate lenses, and current-bedding lineations (Braddock, 1970). These structures, and the generally fine-grained nature of the parent sediments, are consistent with submarine-fan, turbidity current depositional environments. Braddock (1970) estimated that more than 12.2 km of marine sediment accumulated in this region. The two most common rock types are distinguished from each other by the proportions of original clay/sand: the mica-rich variety (Xbk) was probably derived from shale; the quartz-feldspar-rich variety (Xbq) contains less than about 15 percent mica and was probably derived from sandstone and siltstone. Thin, persistent beds of very mica-rich rock distinguished by conspicuous porphyroblasts of biotite are mapped within the metasedimentary sequence in the southeastern part of the quadrangle (Braddock, O'Connor, and Curtin, 1989). U-Pb SHRIMP zircon data indicate deposition of these sediments occurred between 1,770 and 1,730 Ma (Premo and others, 2012).

The mineralogical and textural distinctions among these varieties of metasedimentary rock diminish in the northern and western parts of the quadrangle due to widespread recrystallization and partial melting during the peak of metamorphism. Most biotite-bearing metasedimentary rocks approximately north of the Skin Gulch shear zone and west of Pingree Park are compiled as biotite gneiss (Xb).

Figure 9 (following page). Proterozoic intrusive rocks of the Fort Collins 30′×60′ quadrangle showing distribution of major plutons and batholiths of both the older Routt Plutonic Suite and younger Berthoud Plutonic Suite. Various crosscutting dikes shown as colored lines. Note east-west trending, inferred Proterozoic shear zone which separates Rawah and Log Cabin Batholiths to the south from Sherman Granite and related rocks to the north. This structure is not exposed and is cut out by the younger East Jimmy Creek fault, Cornelius Creek shear zone, and Halligan Reservoir fault. Geology simplified from geologic map (this report map sheet). Ma, million years.



Base from U.S. Geological Survey digital data, 2010
Universal Transverse Mercator projection, zone 13N
North American Datum 1927

EXPLANATION

Berthoud Plutonic Suite

- Silver Plume-type granite intrusions—Including granite of Log Cabin batholith (1,408–1,406 Ma) and granite of Longs Peak (1,420–1,390 Ma)
- Virginia Dale ring-dike complex (1,412 Ma)
- Sherman Granite (1,412 Ma)
- Granite of Hagues Peak (about 1,480 Ma)

Routt Plutonic Suite

- Boulder Creek-type granodiorite (1,714 Ma)—Granite of Rawah batholith (1,721–1,715 Ma) and trondhjemite of Thompson Canyon (1,726 Ma)
- **Proterozoic rocks, undivided**

- **Kimberlite (Devonian to Neoproterozoic)**
- **Gabbro of the Iron Dike (1,316 Ma)**
- **Aplite dikes (various ages)**
- **Pegmatite (various ages)**
- **Mafic dikes (Mesoproterozoic)**

Paleoproterozoic Intrusive Rocks

Paleoproterozoic intrusive rocks are common in the Fort Collins quadrangle (fig. 9) and consist of hornblende gabbro (Xgbh) and calc-alkaline granitoids ranging from monzogranite to tonalite in composition. These rocks belong to the regional Routt Plutonic Suite of Tweto (1987) intruded between 1,725 and 1,690 Ma (Premo and others, 2010a). Contacts with enclosing metamorphic rocks range from broadly conformable to crosscutting to extremely intricate, but are generally sharp at the outcrop scale.

Two small bodies of Paleoproterozoic hornblende gabbro (Xgbh) are present in the quadrangle and both are smaller than 3 km^2 in extent. One body spans the Cache la Poudre River west of Kinikinik and consists of massive, dark greenish-gray, hornblende metagabbro (Pearson and others, 1981). The second body is located north of Kinikinik near Middle Bald Mountain, is roughly circular in plan, and consists of very fresh-looking, gray, equigranular hornblende gabbro; U-Pb SHRIMP zircon studies indicate the emplacement age is 1,715±7 Ma (Premo and others, 2007a).

Distinctive fine-grained biotite trondhjemite (XjT) intrudes the metasedimentary section in the southern part of the quadrangle. This rock typically forms continuous, concordant sheets that can be traced for miles along the strike of sedimentary bedding (Braddock and others, 1970; Braddock and LaFountain, 1988) or forms more irregular plug-like masses in the Comanche Peak and Pingree Park 7.5' quadrangles (Nesse and Braddock, 1989; Plymate and others, 2005). Braddock and Cole (1979) inferred that the trondhjemite magmas south of this quadrangle were emplaced during the waning stages of regional folding because they crosscut an older set of regional folds but contain aligned biotite in the direction of axial surfaces of the youngest set of regional folds. These observations were confirmed in more detailed work by Barovich (1986), who also determined by U-Pb zircon methods that the trondhjemite was emplaced at 1,726±15 Ma. Plymate and others (2005) determined a U-Pb zircon age of 1,702±6 Ma for similar rock (leucotonalite mapped as XjT) in the south-central part of the quadrangle approximately 10 km south of Kinikinik.

Foliated biotite granodiorite and biotite-hornblende granodiorite (Xgd and Xgdp) are mapped in the area south of the Cache la Poudre River in the eastern part of the quadrangle that are similar to the Boulder Creek Granodiorite (Gable, 1980), named from its type area in the Boulder Creek batholith about 50 km south of this quadrangle. The Boulder Creek batholith is typically a foliated rock containing aligned mafic minerals that are concentrated in schlieren bands, aplitic-pegmatitic zones, and local feldspar porphyry textures. Internal dikes are not common, but generally consist of leucocratic granitic and aplitic rocks or pegmatite. Several large intrusive masses in the Stove Prairie region form crescent-shaped masses (phacoids) in the cores of wall-rock folds that suggest emplacement during regional deformation (Braddock and Cole, 1979; Cole and Braddock, 2009, p. 18). The Boulder Creek batholith was emplaced at 1,713±4 Ma, based on the statistical weighted-mean of values determined from U-Pb SHRIMP on individual zircon grains (Premo and Fanning, 2000; Premo and others, 2010a).

The largest body of Paleoproterozoic intrusive rock is the Rawah batholith (XgR) and associated Rawah-type plutons (Pearson and others, 1981, 1982; Burch, 1983) that consist of leucocratic granitic rocks that underlie most of the western one-fourth of the Fort Collins quadrangle. The exposed part of the Rawah batholith forms most of the basement terrane of the Medicine Bow Mountains and extends eastward to the younger Mesoproterozoic Log Cabin batholith (YgLC), and southward to the latitude of Cameron Pass. East of the Laramie River valley, the northern boundary of the batholith is juxtaposed against older metamorphic rocks by the younger east-west trending Cornelius Creek shear zone and East Jimmy Creek fault. There is no exposure of granite of the Rawah batholith north of this structural feature and no external contact of the batholith with the country rock south of the feature (fig. 9; see discussion on Paleoproterozoic structures below).

Granitic rocks of the Rawah batholith tend to be leucocratic (biotite and sparse hornblende generally make up about 5 percent of the rock), medium- to fine-grained, and fairly massive. Mafic minerals locally are concentrated in schlieren, and the granite may display dimensional alignment of biotite grains, but much of the batholith consists of massive rock. Granite of the Rawah batholith commonly crops out as low knobs and tors with rounded forms due to thermal exfoliation of the massive rock. This characteristic locally gives the appearance that the exposed granite consists of rounded, transported blocks; however, subsurface exposures in widespread road cuts show that the granite of the Rawah batholith is jointed into equant blocky masses that acquire their rounded forms at the ground surface by exfoliation. Within the Medicine Bow Mountains, the Rawah batholith is cut by numerous faults as located by McCallum and others (1983). These faults are largely based upon lineations and only rarely by exposed breccias and are poorly located, but are interpreted to be Tertiary faulting related to uplift of the Medicine Bow Mountains and deposition of the Paleogene to Neogene North Park Formation.

The Rawah batholith intrudes the felsic and hornblende-rich gneisses in a complicated manner. Large blocks of the older gneisses are surrounded by the massive granite and yet retain the regional alignment of compositional banding and mineral foliation (Burch, 1983). Smaller masses of the older gneisses (less than a few hundred meters in greatest dimension) are locally discordant to the regional metamorphic fabric, suggesting they rotated during emplacement of the younger Rawah batholith.

U-Pb data from zircon grains by Premo and Van Schmus (1989), Plymate and others (2005), and Premo and others (2010a) show that the Rawah batholith crystallized between about 1,724 Ma and 1,715 Ma with a statistical weighted-mean of 1,718±4 Ma, although some of the U-Pb systematics are complicated. Several samples contained zircon cores that may have been derived from 1,850–1,750 Ma material (Premo and others, 2010a).

Paleoproterozoic Metamorphism

Metamorphic rocks of the Fort Collins quadrangle record evidence of a single, pervasive regional metamorphic event that culminated in widespread partial melting of the metasedimentary gneisses (Braddock and Cole, 1979; Cole and Braddock, 2009, p. 19–22). Field relations indicate the peak of recrystallization largely coincided with intrusion of the Boulder Creek Granodiorite and equivalent magmas at about 1,715 Ma (Peterman and others, 1968; Braddock and Cole, 1979; Hutchinson and Braddock, 1987; Cole and Braddock, 2009, p. 19). Pelitic rocks (biotite and mica schists; Xbq and Xbk) in the southern part of the quadrangle preserve lower-grade mineral assemblages (middle amphibolite grade) that contain primary muscovite, staurolite, and andalusite. North and westward, these assemblages were metamorphosed to higher pressure-temperature stable assemblages, marked by the sequential (1) appearance of sillimanite (sillimanite-in), (2) disappearance of andalusite, cordierite, and garnet (andalusite-out), and disappearance of staurolite (south of the map area), (3) appearance of potassium feldspar (potassium feldspar-in) and disappearance of lepidoblastic muscovite (muscovite-out), and (4) the onset of partial melting (migmatite-in). Metamorphic reaction isograd lines define the areal occurrence of this progressive increase in metamorphic grade recorded by mineralogy changes across the map area (map sheet, figs. 7 and 8). All of the biotite gneisses in the northern and western parts of the Fort Collins quadrangle show textural evidence of partial melting. High-grade (magnesian) garnet and (or) cordierite are present in many of the partially melted biotite gneisses due to the incongruent melting of biotite (Cole, 1977; Cole and Braddock, 2009; fig. 8).

Partial melting (summarized from Cole, 1977; Cole and Braddock, 2009, p. 19–20) occurred in the pelitic metasedimentary rocks that consisted of varying proportions of quartz, plagioclase, potassium feldspar, biotite, sillimanite, and magnetite. The low-melting fraction of quartz and feldspars melted first (in the presence of water) and segregated into seams and lenses (leucosomes), generally parallel to compositional banding in the host rock. These leucosomes are typically bordered by dark-colored selvages (melanosomes) that contain enriched concentrations of the non-melted fraction of the rock (chiefly biotite, sillimanite, and magnetite). This distinctive texture of leucosome-melanosome segregations within the non-melted host rock is the characteristic of migmatite, and its first appearance has been systematically mapped in the southern part of the Fort Collins quadrangle (Braddock and Cole, 1979; Braddock and LaFountain, 1988; Braddock, Calvert, O'Connor, and Swann, 1989; Braddock, O'Connor, and Curtin, 1989; and Nesse and Braddock, 1989). The fact that the isograd delineating the first appearance of migmatite (migmatite-in isograd line on fig. 7; "+Melt" line on fig. 8) lies generally parallel to the other mineral-reaction-isograds, and in the direction of inferred higher temperatures and pressures, is strong evidence that the leucosomes formed in place by partial melting and were not injected from some external magmatic source (Nesse, 1984).

Regional metamorphism took place during the protracted orogenic event marked by the intrusion of the Boulder Creek Granodiorite and by the formation of kilometer-scale folds of two contrasting trends (Braddock and Cole, 1979; Hutchinson and Braddock, 1987; Cole and Braddock, 2009, p. 19–20). The thermal maximum is interpreted to have coincided with the peak of deformation in the highest-grade rocks as supported by partial-melt leucosome masses that are phacolithic in fold hinges and elongate parallel to fold axes, and by coarse sillimanite and biotite aligned with fold axes as observed within the map area.

Interpreted conditions at the peak of metamorphism have been estimated by several studies. Cole (1977, 2004b) concluded that peak conditions were about 5.5 kilobars (kbar), 675°–725 °C, and undersaturated with water vapor on the basis of regional relations and experimentally calibrated phase equilibria. Nesse (1984) used mineral compositions and phase equilibria to conclude that the muscovite+quartz=potassium feldspar+sillimanite+water reaction (potassium feldspar-in on fig. 7; "+K" line on fig. 8) occurred at 3–4 kbars and about 650 °C and higher temperatures and pressures in the partially melted rocks, under the assumption of water-saturated conditions (higher pressures would have prevailed under water-undersaturated conditions; Cole, 1977). Both authors conclude that pressures greater than about 6 kbars could not have been attained because no kyanite has ever been reported in this region.

Detailed mineralogical and chemical studies in a few scattered localities in the Front Range have led to conclusions widely different from the above. Munn and Tracy (1992), Munn and others (1993), and Munn (1997) reported thermobarometric calculations based on garnet, biotite, and hornblende chemistry that suggested pressures near 7 kbars in the east-central part of the Fort Collins quadrangle. Selverstone and others (1995, 1997) asserted pressures of 8 kbars to 10 kbars based on unpublished chemistry of garnet and plagioclase in staurolite-bearing schists near the Big Thompson River south of the map area, but did not explain how such extreme conditions could have been attained without formation of kyanite and in the absence of partial melting. We discount these conclusions and suggest that the chemical analyses were obtained from non-equilibrium assemblages (Cole, 2004b). Solway (2014) indicated that the mole fractions of grossular garnet and anorthite are too low within the samples analyzed by Munn (1997) to assume equilibrium and the high weight percent of oxides within garnets reported may indicate equipment calibration error.

Retrograde metamorphism is manifest by three distinct kinds of mineral transformations that depend on the extent of prograde metamorphism. The overall patterns of retrograde assemblages indicate that they were not influenced by intrusions of much younger plutons at about 1,400 Ma (Cole, 1977; Cole, 2004b). In the lower-grade schists, aluminous porphyroblasts are replaced by very fine grained sericite and chlorite, accompanied by tourmaline. Retrograde muscovite is common in medium- and high-grade metasedimentary rocks where it forms irregular, non-oriented porphyroblasts that replace sillimanite and biotite; tourmaline and topaz also occur in this assemblage (Cole, 1977). This porphyroblastic retrograde muscovite is mostly confined to rocks near and below the migmatite-in isograd and seems to indicate it formed with water that was released from crystallizing leucosome melts that reacted with potassium feldspar and sillimanite (Cole, 1977). The highest-grade metasedimentary rocks show only limited retrograde reactions, probably because most of the water released from crystallizing partial melts had already migrated to higher, cooler areas of the orogen. Small amounts of wormy andalusite are present in some migmatites, particularly those with abundant high-grade cordierite indicating high degrees of partial melting (Gable and Sims, 1969; Cole, 1977). The origin of this late andalusite is not clear, but textural evidence suggests it is related to breakdown of biotite to andalusite+magnetite under very dry conditions (Cole, 1977).

Selverstone and others (1995, 1997), and Shaw and others (1999b) have asserted that the metamorphic assemblages in this area reflect the combined effects of regional metamorphism at about 1,710 Ma and again at about 1,400 Ma. These statements appear to be based on ambiguous textural relations involving staurolite, and on numerous 1,400 Ma ages determined by argon-argon (Ar-Ar) analysis from prograde minerals and similar U-Pb results for monazite (see also Shaw and others, 1999a). It has been known for decades that most single-mineral isotopic systems in the Colorado basement were reset due to generalized heating that accompanied intrusion of widespread granitic rocks of the Berthoud Plutonic Suite (for example, Peterman and others, 1968). However, the textural and regional field evidence described above clearly shows that the sequential mineral assemblages preserved in the metasedimentary rocks formed during a single major Paleoproterozoic prograde event. The age recorded by closure of isotopic systems within individual minerals does not date the time of growth of the particular minerals.

Mesoproterozoic Intrusive Rocks

Younger Proterozoic intrusive rocks were chiefly emplaced between about 1,440–1,350 Ma (Berthoud Plutonic Suite of Tweto, 1987; DeWitt and others, 2010) and are widespread in the Fort Collins quadrangle (fig. 9). These include the distinctly older granite of Hagues Peak (YgH) and the more widespread units of the Sherman Granite batholith (YgSH), the Virginia Dale ring-dike complex (YgVi, YgVo, and YdV), a regional swarm of northwest-trending mafic porphyry dikes (Yd), biotite granite of the Log Cabin batholith (YgLC, YgLCe, and YgLCp), the northern margin of the Longs Peak-St. Vrain batholith (YgLP), and smaller bodies of granodiorite (Yg, Yge, and Yghp), quartz diorite (Yqd), gabbro (Ygbh), aplite (Ygay and Ygao), and pegmatite (YXp). In addition, an unusually long, narrow persistent ferrogabbro dike swarm known as the Iron Dike (Ygb) was intruded at about 1,316 Ma and is exposed along the eastern flank of the Medicine Bow Mountains (rubidium-strontium [Rb-Sr] isochron age; Braddock and Peterman, 1989).

The oldest magmas of the Berthoud Plutonic Suite are relatively sparse in this area and are more mafic than the abundant, younger magmas. The granite of Hagues Peak (south-central border of the quadrangle) is a biotite monzogranite to granodiorite that is distinguished by large microcline phenocrysts and as much as 15 percent biotite, both of which are flow-aligned; it was intruded at about1,442 Ma (U-Pb on zircon; Aleinikoff and others, 1993). Small masses of undated biotite-hornblende quartz diorite (Yqd) are present in the same area near Mummy Pass and are crosscut by the granite of Hagues Peak and by widespread granite of the Longs Peak batholith (Plymate and others, 2005). Small bodies of hornblende gabbro (Ygbh) were identified by Eggler (1968) peripheral to the Virginia Dale ring-dike complex (see below) so that he interpreted them to be related to the mafic rocks of the complex (although they may be much older). Similarly, irregular intrusions of hornblende granite porphyry (Yghp) have been mapped in the Paleoproterozoic metavolcanic rock terrane west of the Virginia Dale ring-dike complex (Eggler and Braddock, 1988; Braddock, Cole, and Eggler, 1989; Workman, 2008) that are crosscut by the Sherman Granite; however, they are interpreted to be Mesoproterozoic because they crosscut the metamorphic rocks, they show no structural fabric, and their mineralogy and chemistry suggest affinities with the magmas of the Virginia Dale ring-dike complex.

The southern portion of the Sherman batholith is widely exposed in low hills and broad plains across the northern boundary of the quadrangle. The batholith continues northward in the Laramie Mountains of Wyoming for a distance of 80 km north of the map area. In the Laramie Mountains, the batholith is exposed for 25 km east-to-west but to the south in the map area it spans the entire width of the quadrangle implying that it underlies a significant part of the Laramie Basin. The Sherman Granite is quite uniform throughout the batholith and consists of red-weathering, coarse-grained, equigranular syenogranite with biotite and sodium-rich amphibole aggregated in clots (Eggler, 1968). The batholith rocks are geochemically alkaline to peralkaline, consistent with the presence of accessory fluorite, common zircon, and the sodium-rich amphiboles (Anderson and Thomas, 1985; Anderson and Cullers, 1999). The age of intrusion is established at 1,433±1.5 Ma, based on zircon studies (Frost and others, 1999). The Sherman Granite typically weathers to a thick mantle of quartz-feldspar grus and is not well exposed (Eggler and others, 1969). Widespread chlorite alteration forms a high-standing, more resistant zone within the intrusion at the western end of Boulder Ridge (Workman, 2008; Workman and Braddock, 2010). Along Boulder Ridge at the southern edge of the Laramie Basin, a distinctive set of lineations within the Sherman batholith parallels the outer contact of the intrusion (see map sheet). Workman (2008) shows these features as faults that cut the younger, northwest-oriented mafic dike swarm, but these features are most likely related to late stage expansion of the batholith that influenced the propagation of later extensional fractures during intrusion of the dike swarm.

The southernmost part of the Sherman batholith is marked by the distinctive Virginia Dale ring-dike complex, which is genetically related to the batholith. It was studied in detail by Eggler (1968), and the following description is largely based on his work. The ring-dike complex consists of nested, nearly concentric, ring-shaped intrusions of distinctive cap rock and main phase granites and diorite that were emplaced in a cauldron-like structure. The outer ring-dike zone is filled with Sherman Granite (YgSH) that merges northward with the main mass of the Sherman batholith. The next inner zone of the complex consists of a partial arcuate ring of granite-diorite hybrid rocks (YdV) and blocks of country rock; textures in the hybrid rocks indicate the granitic and dioritic magmas were both liquid at the time of emplacement. There are fragmental and magmatically mixed rocks, ranging from diorite to monzogranite, that form a partial annular zone between the distinctive cap rock monzogranites in the central part of the complex and the Sherman Granite in the outer zone of the Virginia Dale ring-dike complex. The distinctive central cap rocks of the complex are divided into two zones called the outer cap rock (YgVo) and the inner cap rock (YgVi) that both consist of porphyritic biotite monzogranite but are distinguished from each other by size of feldspar phenocrysts, by degree of flow alignment, and by the abundance of biotite-rich schlieren bands. Eggler (1968) used gravity and structural data to infer the nested ring-dikes are steeply inclined outward and that the form of the complex arose through gravitational foundering of the central block of country rock.

Mafic porphyry dikes (Yd) form a persistent and widespread swarm that trends north-northwest through the metamorphic rocks of the Front Range (Peterman and others, 1968). These distinctive dikes are typically 1 to 5 m thick and tens of meters to several kilometers long and are especially common in the southeastern and northern areas of the Fort Collins quadrangle. They consist of basalt and mafic andesite with conspicuous plagioclase phenocrysts in a fine-grained groundmass with diabasic texture (Hepp, 1966; Kellogg, 1973). These dikes crosscut older batholiths of the Berthoud Plutonic Suite (Sherman Granite and the Virginia Dale ring-dike complex) and are intruded and deformed by younger granites of the suite (Longs Peak and Log Cabin batholiths; Eggler, 1968; Peterman and others, 1968; Cole and Braddock, 2009, p. 14 and 22). Their emplacement age is constrained by the ages of these batholith granites between about 1,430 Ma and 1,405 Ma.

Silver Plume Granite is a recognized lithodemic-unit name (Lovering and Goddard, 1950; Tweto, 1987) for widespread intrusive rocks in the Front Range that form irregular batholiths, simple ovoid plutons, and dikes. The name is based on the type area at Silver Plume, Colorado (about 80 km south of the Fort Collins quadrangle), where characteristic mineralogical and textural traits are displayed (Tweto, 1987). Granites of the Silver Plume type are typically biotite syenogranite or monzogranite, commonly porphyritic with flow-aligned feldspars and biotite grains, contain moderate amounts of biotite (5 to 12 percent), and are relatively homogeneous (Cole, 1977). Silver Plume-type granites are geochemically peraluminous and locally contain magmatic garnet or sillimanite (Cole, 1977), as well as post-crystallization secondary muscovite (Cole, 1977; Anderson and Thomas, 1985). Throughout the Front Range, granites that possess Silver Plume characteristics have been correlated with the type rock-unit, and the name Silver Plume Granite has been used in order to express the general similarities in age, texture, and composition. However, each batholith of Silver Plume-type granitic rocks conveys its own history and it is likely that each arose at somewhat different times under somewhat individual circumstances.

In the interest of clarity, and in concert with the compilers of adjacent 30'×60' quadrangles, we elected to restrict use of the term Silver Plume Granite to the Silver Plume batholith in its type area. We describe correlated rock masses elsewhere in the northern Front Range as Silver Plume-type granites. Each individual intrusive complex is designated according to the historically used name of the pluton or batholith where it intruded. In this quadrangle, granite of Longs Peak (YgLP) denotes the Silver Plume-type granitic rocks within the Longs Peak-St. Vrain batholith and granite of the Log Cabin batholith (YgLC) denotes Silver Plume-type granitic rocks in that pluton.

The granite of Longs Peak is only mapped in the Fort Collins quadrangle along the south-central border where it forms the northernmost margin of the Longs Peak-St. Vrain batholith (Cole and Braddock, 2009, p. 22–23). The most typical rock is coarsely porphyritic, biotite monzogranite, which contains conspicuous tabular phenocrysts of flow-oriented microcline, typically 1 to 2.5 cm long, set in a fine- to medium-grained matrix of quartz, feldspars, biotite, and accessory minerals. This trachytic feldspar foliation is a mappable feature within the batholith and defines internal structure formed by flow patterns of the magma as it intruded (Cole, 1977; Cole and Braddock, 2009, p. 35). The granite of Longs Peak was intruded at 1,420±25 Ma (Rb-Sr isochron; Peterman and others, 1968).

The Log Cabin batholith is exposed in the center of the Fort Collins quadrangle and forms a simple, ovoid pluton approximately 32 km (east-west) by 21 km (north-south) in dimension. The northern contact of the batholith with older metamorphic and intrusive rocks follows but is locally cut by a series of younger east-west brittle faults (Cornelius Creek shear zone and Halligan Reservoir fault). The batholith consists primarily of medium-grained, subporphyritic biotite syenogranite, with a coarsely porphyritic phase (YgLCp) along the western and southern margins intermingled with a distinctly more equigranular phase (YgLCe). The pluton sharply crosscuts the metamorphic country rock along steep contacts, and appears to have caused some plastic deformation in the wall rock due to inflation during emplacement (Abbott, 1976; Cole, 1977). Analysis of magmatic zircons (U-Pb SHRIMP) indicates the coarse, porphyritic phase crystallized at 1,406±13 Ma and the medium-grained phase at 1,408±15 Ma (DeWitt and others, 2010; Premo and others, 2012); that is, the two phases are essentially contemporaneous although crosscutting field relations suggest the porphyritic phase was intruded first. The Log Cabin batholith is a prominent positive magnetic anomaly against the surrounding metamorphic rocks and a steep gradient coincides with its external contact (Zietz and Kirby, 1972); it also coincides with elevated values of uranium and thorium in airborne spectrometric data (Duval and Zietz, 2000).

Small bodies of Silver Plume-type granite (Yg) are present in scattered locations across the Fort Collins quadrangle and they are mapped as biotite syenogranite. The most prominent body is a small, sub-circular plug that was intruded near the center of the Virginia Dale ring-dike complex following emplacement of the peralkaline granites related to the Sherman batholith (Eggler, 1968). Numerous small bodies of biotite syenogranite are mapped along the Skin Gulch shear zone. Some of these bodies may be displaced blocks of the larger Log Cabin and Longs Peak-St. Vrain batholiths, but most are individual bodies that were deformed by the younger shear zone.

The Silver Plume-type granites are representative of a suite of similar granitic intrusive rocks that were emplaced in the North American craton at about 1,400±25 Ma along a broad belt between southern California and Labrador (Anderson and Thomas, 1985). These granites are compositionally similar, chiefly biotite monzogranite or syenogranite, and are either metaluminous or slightly peraluminous (Anderson, 1983). Most have initial strontium-isotope ratios that are similar to the calculated 1,400-Ma mantle and thus do not seem to have assimilated large amounts of more-radiogenic wall rock. Many share the characteristic porphyry texture with the Silver Plume or the rapakivi texture of mantled feldspar phenocrysts. They generally have simple crosscutting relations with wall-rock structures (in regional context), and Anderson (1983) referred to them as “anorogenic” granites due to the general absence of evidence for coeval regional deformation. These granites do not seem to have formed through melting above a descending oceanic-crustal slab because they lack the compositional diversity typical of that environment, have few basalts associated with them, and no supportive plate-tectonic context has been identified for this part of North America at 1,400 Ma (Anderson and Cullers, 1999). We believe that their widespread occurrence, compositional homogeneity, and primitive isotopic character indicate they formed as a result of fundamental changes in mantle structure (possibly related to mineralogical phase changes; Cole, 1977) at 1,400 Ma. Anderson and Bender (1989) also argued that the widespread intrusion of anorogenic, potassic granite across North America at this time indicates a significant, non-tectonic event in which thermal upwelling of mantle caused major melting of undifferentiated lower crust.

The youngest Proterozoic rock in the Fort Collins quadrangle is the Iron Dike (Ygb), a distinctive intrusion swarm that consists of iron-rich augite ferrogabbro. Its chemistry was studied in some detail by Wahlstrom (1956), and Cole (1977) described its form, contact relations, and mineralogy. Braddock and Peterman (1989) reported an emplacement age of 1,316±50 Ma based on a mineral-whole-rock Rb-Sr isochron. The Iron Dike consists of a swarm of north-northwest trending sub-vertical dikes that can be traced from just west of Boulder, Colo., through Rocky Mountain National Park and into the Fort Collins quadrangle; the Iron Dike continues along the east side of the Medicine Bow Mountains as far as the Wyoming-Colorado State line (Pearson and others, 1982; Braddock and Cole, 1990). The combined length of the swarm is approximately 150 km. Thickness ranges from 1 m in some of the thinner dikes to as much as 40 m. Contacts with the Proterozoic wall rock are typically chilled within a few centimeters of the margin (Cole, 1977). The Iron Dike swarm was hot enough during intrusion to cause local grain-contact melting in the Silver Plume-type granite (Cole, 1977; Braddock and Peterman, 1989).

Kimberlite

Numerous small bodies of kimberlite (DZk) intrusive rock (not all large enough to map) are present in the Fort Collins quadrangle and they have been actively prospected for diamonds since the 1970s. These kimberlites are collectively referred to as the State Line District because they have been identified a few kilometers north in Wyoming and as far as 20 km south of the Colorado State boundary in the North Fork Cache la Poudre River drainage. An excellent summary of these unusual rocks, their geologic setting, and the diamond production history was prepared by Hausel (1998), and the following remarks are summarized from that report. Numerous reports pertinent to this subject are referenced in Hausel (1998).

These kimberlites occur in pipes and dikes within the Sherman Granite, the granite of the Log Cabin batholith, and the surrounding metamorphic country rock. They typically contain abundant phlogopite, pyrope garnet, chromian diopside, and ilmenite with widespread carbonate and serpentine alteration products. Kimberlites also contain nodules of ultramafic mantle and lower crustal rocks, including peridotite, eclogite, pyroxenite, and granulite as well as megacrysts of garnet, illmenite, and diopside.

As of the early 1990s, mining was underway on about a dozen kimberlite localities in the State Line District. More than 16,000 tonnes was processed from the 10 smaller sites, from which more than 130,000 stones were recovered. The largest mine at Kelsey Lake had installed a mill and operated between 1996 and 1999, recovering nearly 1,000 carats of industrial stones and several gem-quality diamonds larger than 28 carats raw weight.

Fossiliferous Cambrian through Silurian limestone blocks are contained in some of the kimberlite pipes in the State-line area, and initial fission-track studies supported a Devonian age of emplacement (Naeser and McCallum, 1977). More recent work by Lester and others (2001) shows that at least the kimberlites in the North Fork Cache la Poudre River drainage and some other Front Range localities were emplaced at about 700 Ma to 600 Ma during the Neoproterozoic.

Pre-Cenozoic Sedimentary Rocks

Paleozoic and Mesozoic sedimentary rocks are exposed on both the east and west flanks of the Front Range uplift in the Fort Collins quadrangle (fig. 10). Comprehensive description and discussion of these units is largely beyond the scope of the regional summary that accompanies this map compilation. Excellent summaries of the Phanerozoic units are available for this area, including Scott and Cobban (1986), Weimer and LeRoy (1987), and Weimer (1996). Detailed measured sections and stratigraphic summaries are also compiled in Lee (1927), which despite its vintage retains much useful descriptive information. Beckwith (1942) and Camp (1979) contain observational descriptions of the Phanerozoic rocks in the Laramie River valley, and Workman and Braddock (2010) provide descriptions of the Phanerozoic rocks in the southern Laramie basin. These papers and many of the source geologic maps form the basis for the following short summations.

The oldest sediments deposited along the eroded margins of the uplifted Front Range Proterozoic crystalline basement are somewhat different along the eastern, northern, and western margins (fig. 11), due to variations in the uplift duration and depositional environments during the late Paleozoic deformation in Pennsylvanian and later time (Anasazi uplifts of Nesse, 2007). The Pennsylvanian and Permian Fountain Formation (Pℙf; arkosic conglomerate and sandstone; 198 to 268 m thick) records the initial deposition of alluvial fans along the eastern and northern flanks of the uplift.

East of the Front Range in the Denver Basin, the Fountain Formation is overlain by Permian Ingleside Formation (Pi; planar-bedded sandstone deposited in shallow marine and tidal-flat; 46 to 67 m thick), Owl Canyon Formation (Po; red siltstone deposited in tidal-flat and desert-lake(?) settings; and pinches out south of the Fort Collins quadrangle; maximum thickness 84 m), and the unconformably overlying Lower Permian Lyons Sandstone (Pl; eolian cross-bedded sandstone and fluvial sand; 1 to 15 m thick). The Lyons is conformably overlain by Upper Permian and Lower Triassic Lykins Formation (ŦRPl; red siltstone, gypsum, fine sandstone, and thin limestone beds deposited in restricted marine or saline lake environments; includes the Upper Permian Forelle Limestone Member (Pgfsu); 152 to 183 m thick).

Along the northern margin of the Front Range (Laramie Basin and Laramie River valley), the Fountain Formation thins and eventually pinches out to the south. Within the Laramie Basin, it is overlain by the Middle Pennsylvanian to Lower Permian Casper Formation (Pℙc; facies contemporary of the Ingleside Formation; trough-cross-bedded eolian sandstones deposited in tidal-flat; maximum 29 m thick in map area), which pinches out just south of the Colorado-Wyoming border, but thickens north of the map area, interfingering with the Fountain Formation. The contact between the two is a time-transgressive facies boundary that becomes younger southwestward against the Anasazi uplift.

In the Laramie Basin, the Fountain and Casper Formations are overlain by the Goose Egg Formation (facies contemporary of the Owl Canyon Formation, the Lyons Sandstone, and part of the lower Lykins Formation), which is divided here into a lower (Pgl) and upper part (ŦRPrgu). The lower part of the Goose Egg Formation includes the Lower and Upper Permian Satanka Shale Member (red shale, siltstone, and sandstone, gypsum, and dolomite deposited in restricted marine or saline lake environments; 88 m thick) and the Upper Permian Forelle Limestone Member (the Forelle Limestone Member is marine; about 7 m thick). The Satanka Shale Member is here divided into a lower part (Pgsl) and an upper part combined with the thin Forelle Limestone (Pgfsu). The lower part of the Satanka Shale Member (Pgsl) encloses a poorly exposed unconformity (most of the lower Leonardian stage is missing) that is equivalent to the unconformity gap beneath the Lyons Sandstone (Pl). The top of a sandstone-rich horizon (top of the lower part, as mapped) is inferred to correlate with the top of the Lyons Sandstone in the Denver Basin. Red beds continue up section above the Forelle Limestone Member in the Laramie Basin which include the Upper Permian and Lower Triassic upper part of the Goose Egg Formation (Little Medicine, Freezeout Shale, Ervay, and Difficulty Shale Members) and Lower Triassic Red Peak Formation (ŦRPrgu; facies contemporary of the upper Lykins Formation; red shale, siltstone, and sandstone and gypsum deposited in restricted marine or saline lake environments; combined thickness 177 m). The top of the Goose Egg Formation is not a mappable contact within the map area due to poor exposure. West of the Front Range in the Cameron Pass area, this equivalent interval above the Forelle Limestone Member (244 m thick) was previously called the Chugwater Formation by Kellogg, Ruleman and others (2008).

South and west of North Middle Mountain in the Laramie River valley, the Pennsylvanian and most of the Lower Permian rocks pinch out against the eroded Proterozoic crystalline rocks along the flank of the late Paleozoic Arapaho uplift (fig. 10). West of Cameron Pass along the eastern boundary of the North Park Basin, Proterozoic rocks are overlapped by only the uppermost few meters of the Lower and Upper Permian Satanka Shale and the Upper Permian Forelle Limestone Members of the Goose Egg Formation (included in unit ŦRPrgu at this location; Gorton, 1953; Ward, 1957; Braddock and Cole, 1990; Kellogg, Ruleman and others, 2008), and this condition persists along the entire western side of the Medicine Bow Mountains (Kinney, 1970, 1971). This onlapping relationship reflects the fact that basement uplifts locally remained emergent until Late Permian time (Anasazi uplifts of Nesse, 2007).

In most areas of the Fort Collins quadrangle, the Upper Permian and Lower Triassic red bed sequence is truncated upward by a Middle Triassic disconformity, upon which the Upper Triassic Jelm Formation was deposited (orange-pink, cross-bedded, fine-grained, nonmarine sandstone; maximum 79 m thick in northwest part of map). The Jelm Formation thins significantly southward along the Foothills Hogback and is absent in the Cameron Pass area (Gorton, 1953; Ward, 1957; Kellogg, Ruleman and others, 2008). The Upper and Middle

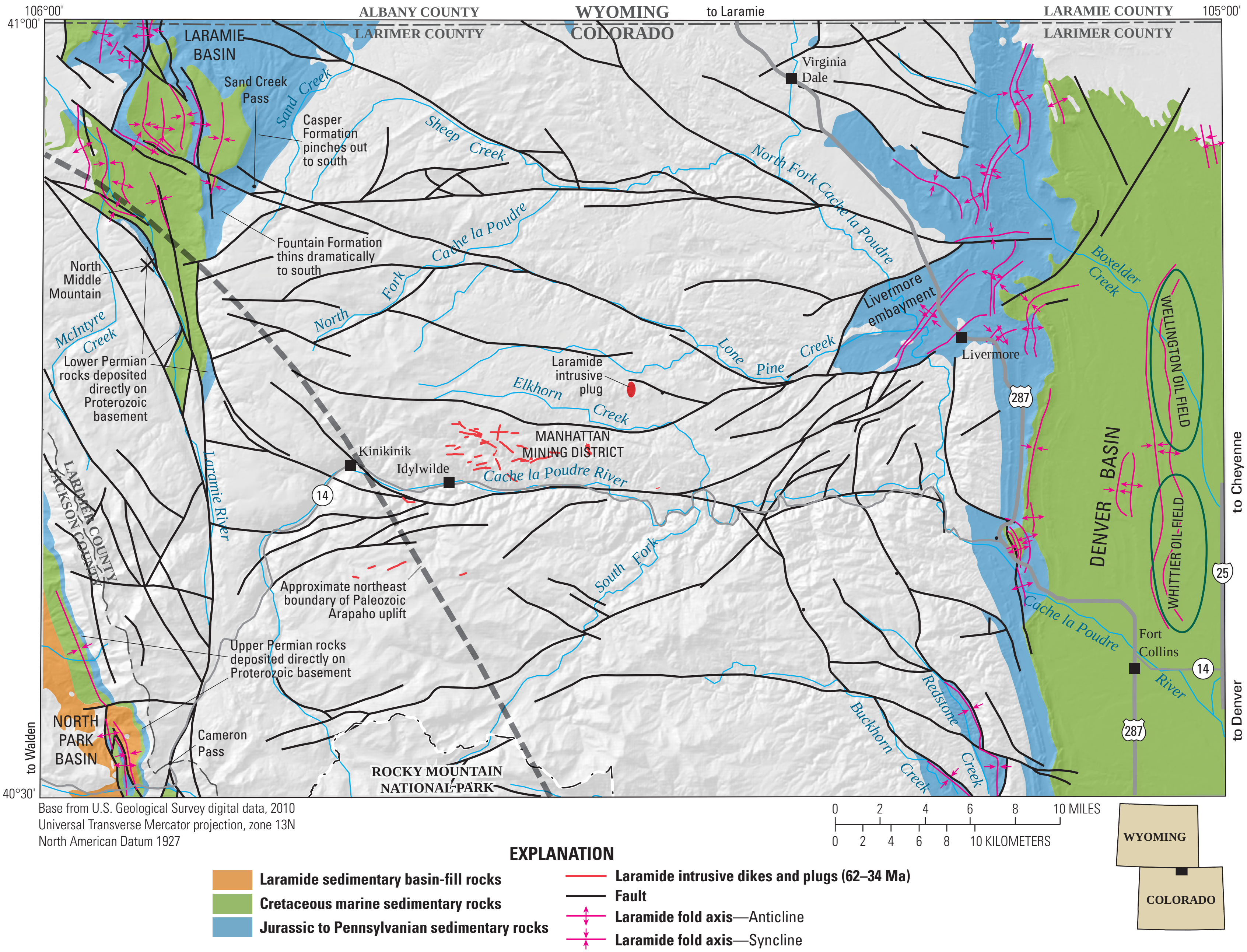


Figure 10. Laramide and older sedimentary rocks of the Fort Collins 30′×60′ quadrangle. Paleozoic and Mesozoic sedimentary rocks are exposed on both the east and west flanks of the Front Range uplift in the Fort Collins quadrangle. The thick dashed gray line depicts the northeast boundary of the Arapaho uplift. Ma, million years.

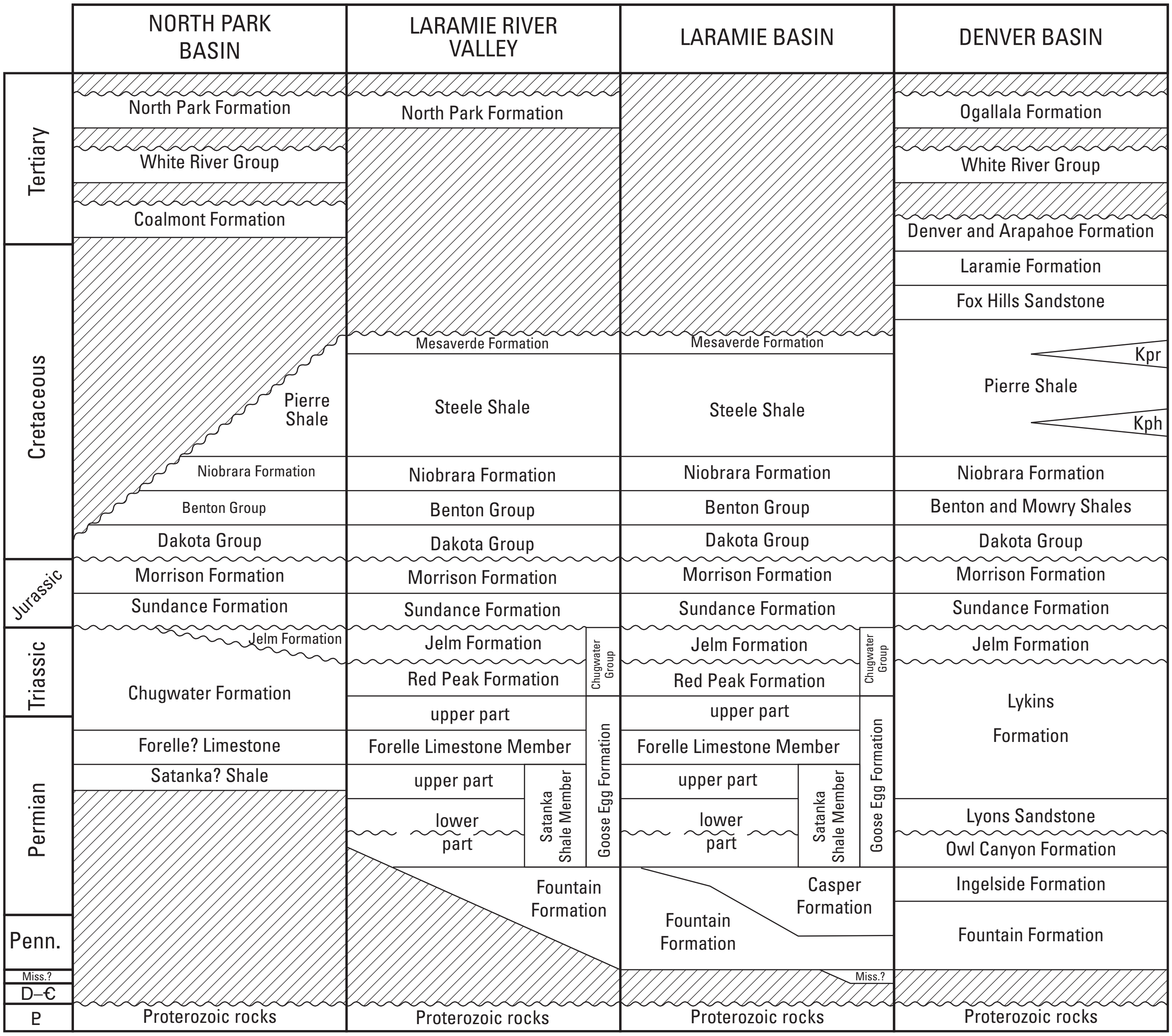


Figure 11. Correlation of sedimentary rocks across Fort Collins 30'×60' quadrangle for the Denver Basin, Laramie Basin, Laramie River valley, and the North Park Basin. Kpr, Richard Sandstone Member, Larimer Sandstone Member, Rocky Ridge Sandstone Member and two intervening unnamed shale members; Kph, Hygiene Sandstone Member. Ꝑ, Proterozoic rocks; D–Є, Devonian through Cambrian; M, Mississippian; ℙ, Pennsylvanian.

Jurassic Sundance Formation (fine-grained, yellowish-tan, tabular sandstone deposited in shallow-water marine environments; about 10 to 40 m thick) disconformably overlies the Jelm Formation (Chugwater Formation at Cameron Pass where Jelm is absent) across the entire quadrangle. The Sundance represents the return of near-shore marine conditions in this area in Middle Jurassic time as the late Paleozoic uplift had been eroded to sea level. The Jelm and Sundance Formations (₮js) are mapped as one unit in this study.

The Upper Jurassic section consists of about 85 to 95 m of nonmarine Morrison Formation (Jm; variegated fluvial claystone, siltstone, and thin sandstone deposited in floodplains and freshwater lakes and swamps) that lies conformably above the Sundance Formation. The top of the Morrison Formation is a regional unconformity representing marine transgression.

The vast, shallow Western Interior Seaway flooded the center of North America beginning in Early Cretaceous time. The marginal-marine Lower Cretaceous Dakota Group (Kd; sandstone, shale, and sparse limestone; 85 to 97 m thick) was deposited across the whole of the Fort Collins quadrangle. It generally crops out as three sandstone ledges with intervening shale beds in the Foothills Hogback. Here, the base is called the Lytle Formation (chert-pebble conglomerate and sandstone with overlying shaly beds deposited on a channeled floodplain; about 18 m thick) which is overlain by the transgressive Plainview Formation (9 m thick), deep-water Skull Creek Shale (about 27 m thick), and beach and tidal-flat sands of the Muddy Sandstone (12–30 m thick). The Muddy Sandstone is locally divided into the lower Fort Collins and upper Horsetooth Members. The Plainview Formation, Skull Creek Shale, and Muddy Sandstone are equivalent to the South Platte Formation of the Denver Basin south of Boulder (MacKenzie, 1965). Within the Laramie Basin, the lower Dakota-equivalent is called the Cloverly Formation (equivalent to both the Lytle Formation and the Plainview Formation; about 45 m thick) which is overlain by the Thermopolis Shale (equivalent to the Skull Creek Shale; 20 m thick) and the Muddy Sandstone (20 m thick) at the top.

Combined subsidence and sea-level rise near the end of Early Cretaceous time led to the return of full marine conditions that persisted throughout most of Late Cretaceous time. Shale, thin-bedded limestone, and sparse sands accumulated in the Western Interior Seaway across this entire area and are known as the Lower and Upper Cretaceous Benton Group (Kbm) consisting in the Denver Basin (from bottom to top) of Mowry Shale (3 to 20 m thick but locally absent), Graneros Shale (49 m thick), Greenhorn Limestone (79 m thick), and Carlile Shale (24 m thick) and in the Laramie Basin (from bottom to top) of the Mowry Shale and Frontier Formation (168 m thick). The overlying Niobrara Formation (Kn) consists of the Fort Hays Limestone Member (5 m thick) and the Smoky Hill Shale Member (20 m thick).

Increased rates of subsidence are recorded by the Upper Cretaceous Pierre Shale across the Fort Collins quadrangle (Higley and Cox, 2005). Subsurface data show that the Pierre is approximately 1,675 m thick in North Park (partly eroded; west of this quadrangle) and 2,075 m thick in the deepest parts of the Denver Basin near Denver, Colo., and also near Cheyenne, Wyo. Scott and Cobban (1986) measured about 2,300 m in the eastern part of the map area, all deposited in about 14 million years (Obradovich and Cobban, 1975; Obradovich, 1993). The isopach patterns of Late Cretaceous deposition in the Denver Basin suggest that the accelerated subsidence may have been caused by crustal flexure, a possible harbinger of the Laramide Front Range uplift. From base to top, the Pierre Shale is compiled on this map as the lower shale member (Kpl, about 792 m thick), Hygiene Sandstone Member (Kph, 74 m thick), middle shale member (Kpm, 259 m thick), an upper alternating sandstone and shale member (Kpr, 160 m thick), and the upper shale member (Kpu, about 1,012 m thick; Scott and Cobban, 1986). Withdrawal of the Western Interior Seaway from the Denver Basin in latest Late Cretaceous is marked by strandline marine deposits (Kfh , Fox Hills Sandstone) and coeval, interfingering, and younger deposits (Laramie Formation) of coastal plain, coal-forming swamp, and delta-plain environments (Roberts, 2005). The Fox Hills is only preserved in the northeasternmost area of the Fort Collins quadrangle and the Laramie Formation lies entirely east of the quadrangle.

West of the Front Range in the Laramie Basin and Laramie River valley, the Upper Cretaceous beds above the Niobrara Formation are called the Steele Shale (Kss) and Mesaverde Formation (Kmv) according to practice in south-central Wyoming (Lynds and Slattery, 2017). The Steele Shale is a thick, uniform, dark-gray, marine shale in this area and is at least 731 m thick (Beckwith, 1942; Camp, 1979). Sandstone beds are common in the upper exposed part of the Steele and they contain ammonites of the *Baculites reesidei* Elias zone of Scott and Cobban (1986), equivalent to the upper sandy member (Richard Sandstone Member [Kpr]) of the Pierre Shale. The Steele Shale is overlain by marine shale and sandstone and nonmarine sandstone assigned to the Mesaverde Formation; Beckwith (1942) and Camp (1979) estimate more than 610 m of Mesaverde are preserved in the Laramie River valley syncline but the top is eroded. No equivalent to the regressive Fox Hills Sandstone or the Laramie Formation is preserved west of the Front Range due to Paleocene erosion.

Laramide Synorogenic Sedimentary Rocks

The landscape of much of the Rocky Mountains area changed dramatically as the Western Interior Seaway receded near the end of Cretaceous time due to worldwide sea-level decline combined with broad tectonic uplift driven by compression across the western half of North America. The outlines of most of the modern mountain ranges in this part of Colorado were established when compressional forces and low-angle subduction (Dickinson and Snyder, 1978) initiated uplift of mountain-scale crustal blocks. The deformation (tilting and uplift) began at somewhat variable times in different places (Tweto, 1975; Kluth and Nelson, 1988; Cole and others, 2010). The end of marine deposition and the transition to coastal and fluvial environments are generally taken to mark the onset of the Laramide orogeny (Tweto, 1975; Kluth and Nelson, 1988; Raynolds, 2002), and are best recorded east of the Front Range.

As the basement blocks rose, denudation removed some or all of the Cretaceous and older sedimentary rocks from uplifted areas and shed synorogenic sediments into the adjoining Denver-Cheyenne foreland basin east of the Front Range (Tweto, 1975; Raynolds, 2004). In the eastern part of the Fort Collins quadrangle, the retreat of the Western Interior Seaway is marked by the recessional Fox Hills Sandstone (Kfh) and the overlying (but broadly contemporary) Laramie Formation consisting of coastal-plain, swamp, and delta-plain deposits of sandstone, claystone, carbonaceous shale, and coal (Roberts, 2005). The Laramie Formation (Upper Cretaceous) has been eroded from the eastern part of the quadrangle, but is exposed southward in the Estes Park 30'×60' quadrangle (Cole and Braddock, 2009) and northward in the Cheyenne 30'×60' quadrangle (ver Ploeg and others, 1998). Southeast of the map area, the synorogenic deposits of the Denver Basin sit conformably above this regressive sequence (Raynolds, 2002; Dechesne and others, 2011)

The record of Laramide uplift is notably different west of the Front Range in this area. Late Cretaceous to early Paleocene erosion was much more protracted in the area of North Park than along the eastern range margin because neither the Fox Hills Sandstone nor the Laramie Formation-equivalent remains (Hail, 1965; Kinney, 1970; Tweto, 1975). Instead, the Pierre Shale was deeply (but variably) eroded prior to deposition of the synorogenic upper Paleocene and Eocene Coalmont Formation (₽c). For example, all of the upper shaly part of the Pierre is preserved in the nearby Denver-Cheyenne and Laramie Basins (more than 610 m) but was removed from the North Park area west of the map area (Kinney, 1970; Tweto, 1975), whereas all 1,675 m or more of the Pierre was removed from the Cameron Pass area prior to Coalmont deposition (Gorton, 1953; Ward, 1957; Braddock and Cole, 1990; Cole and others, 2010).

In summary, the Late Cretaceous to early Paleocene uplift of the Front Range Proterozoic basement appears to have been strongly asymmetric. The Denver-Cheyenne Basin flexed downward during mountain uplift and accumulated deposits that recorded the recession of the inland seaway and the fluvial aggradation of synorogenic deposits. However, the western flank of the Front Range remained above sea level through early-middle Paleocene time while Upper Cretaceous rocks were eroded. The downwarp that created the North Park structural basin did not begin to subside until middle Paleocene time when the lower part of the Coalmont Formation was deposited (Roberts and Rossi, 1999).

The age of the Coalmont Formation is not known in detail and can only be loosely defined from paleobotanical evidence as middle Paleocene to early Eocene (Hail, 1965; Izett, 1968; Roberts and Rossi, 1999). The basal Coalmont was most likely time-transgressive over older, tilted and eroded formations as the Front Range rose and the North Park Basin subsided. Cole and others (2010) dated clasts within the basal Windy Gap Volcanic Member of the Middle Park Formation (Coalmont Formation equivalent) as 61 Ma, indicating a Paleocene age for basin formation. The duration of the erosional gap between the eroded Upper Cretaceous marine units and the basal, fluvial Coalmont Formation cannot be quantified on the basis of present data. The Coalmont Formation was broadly folded in the North Park Basin and beneath the west-vergent fault blocks of the southern Medicine Bow Mountains west of Cameron Pass sometime during or following deposition, most likely during the Eocene (Hail, 1965).

Laramide Intrusive Rocks

Late Cretaceous to Eocene intrusive rocks are common farther south in the Front Range along the trend of the Colorado Mineral Belt (Lovering and Goddard, 1950; Cole and Braddock, 2009). These plugs and dikes consist of mafic-alkalic and alkali-calcic varieties that were emplaced in two main pulses at about 78–68 Ma and 62–45 Ma.

In contrast, no Late Cretaceous intrusive rocks are present in the Fort Collins quadrangle, and Paleocene to Eocene intrusive rocks are rare and are chiefly limited to minor dikes and small plugs in the Manhattan mining district north of Rustic (Shaver and others, 1988) and in scattered localities farther south (Nesse and Braddock, 1989). A brief description of the Manhattan district intrusions (along with potassium-argon [K-Ar] and fission-track dating results) is presented by McCallum and Naeser (1977) and summarized here. Most of the dikes are dacite (₽dp) and andesite (₽ap) porphyries containing phenocrysts of feldspar with either hornblende or biotite. The dikes are a few meters to several tens of meters wide and as long as 1.2 km; trends are highly variable. Ages of intrusion based upon zircon and apatite fission track data range between about 62 and 55 Ma (Paleocene; adjusted to modern radiometric decay constants by J.C. Cole). Dacite dikes with tridymite phenocrysts altered to alpha quartz exposed within the mining district (mapped as unit ₽dp) produce fission track ages of 54 and 58 Ma (not adjusted; McCallum and Naeser, 1977). A small hourglass-shaped plug of flow-banded rhyolite (₽rp) east of Manhattan, Colo., within the Proterozoic Log Cabin batholith was intruded in late Eocene time at about 37 to 34 Ma (fission track on zircon and apatite, adjusted; McCallum and Naeser, 1977). Mining activity in the Manhattan district was limited to a few decades in the late 1800s and early 1900s and primarily exploited sparse gold in quartz-pyrite veins near the porphyry intrusions (Pearson and others, 1981).

Post-Laramide Intrusive and Volcanic Rocks

Post-Laramide magmatic activity is recorded throughout much of central and southern Colorado during the Oligocene Epoch, typified by intermediate calc-alkalic or differentiated high-silica magmas (Steven, 1975). South of the Fort Collins quadrangle in the Never Summer Mountains and near Cameron Pass lay major centers of Oligocene activity in the northern Front Range. The following discussion is largely summarized from O′Neill (1981) Braddock and Cole (1990), and Cole and others (2008).

The Braddock Peak volcanic complex consist of local flows of dark basalt, trachyandesite, and flow breccia (₽b) that appear to lie in paleovalleys, and dacitic to rhyolitic ash and welded tuff (₽v where undivided) that generally overlie the mafic rocks. The volcanic strata are only preserved in the southwestern part of the Fort Collins quadrangle east and southwest of Cameron Pass on the southern margin of the Medicine Bow Mountains, and farther north on Green Ridge, a long narrow hilltop in the west-central part of the Fort Collins quadrangle that is east of the Laramie River valley (fig. 12). Volcaniclastic sediment is interbedded in several locations (explicitly mapped as unit ₽bs North of Chambers Lake). The youngest preserved volcanics (₽r) consist of a rhyolite ash-flow tuff with conspicuous smoky quartz phenocrysts, and an overlying crystal-poor, flow-banded rhyolite flow that displays contorted flow-folding above a local basal vitrophyre. The thickness of all units is highly variable because these volcanic rocks accumulated on a deeply eroded landscape and because of post-eruption erosion.

The basaltic and trachyandesitic rocks (29.6±0.2 Ma; Knox, 2005) are about the same age as granodiorite of the Mount Richthofen stock (29.7±3 Ma; Marvin and others, 1974) exposed just south of the map area at the northern end of the Never Summer Mountains. The youngest rhyolitic rocks (28.6±0.03 to 27.7±0.1 Ma; Knox, 2005) are similar in age to the highly differentiated granite porphyry of the Mount Cumulus stock (28.2±0.7 Ma; Marvin and others, 1974) exposed just south of the Mount Richthofen stock, consistent with these intrusive bodies being the source of the volcanic deposits.

Post-Laramide Sedimentary Rocks

Erosion characterized most of the early and middle parts of the Eocene Epoch in this region (Tweto, 1975; Epis and Chapin, 1975; Scott and Taylor, 1986). Thin fluvial deposits that are correlated with the upper Eocene to lower Oligocene White River Group (₽ɛwr; fig. 12) are exposed both east and west of the Front Range in the Fort Collins quadrangle. Courtright and Braddock (1989) mapped White River Group deposits in the northeastern part of the quadrangle (about 250 ft thick), consisting of white, olive-gray, or pink, massive, clayey siltstone with thin beds of arkose, pebble gravel (Brule Formation) and overlying beds of red, purplish-red, or gray siltstone and minor sandstone and coarse conglomerate (Chadron Formation). Ash beds within the White River Group in this area range in age between about 35.5 Ma and 30 Ma (Larson and Evanoff, 1998). Paleocurrent analysis indicates drainage toward the southeast at this time in the Colorado Piedmont (Steven and others, 1997).

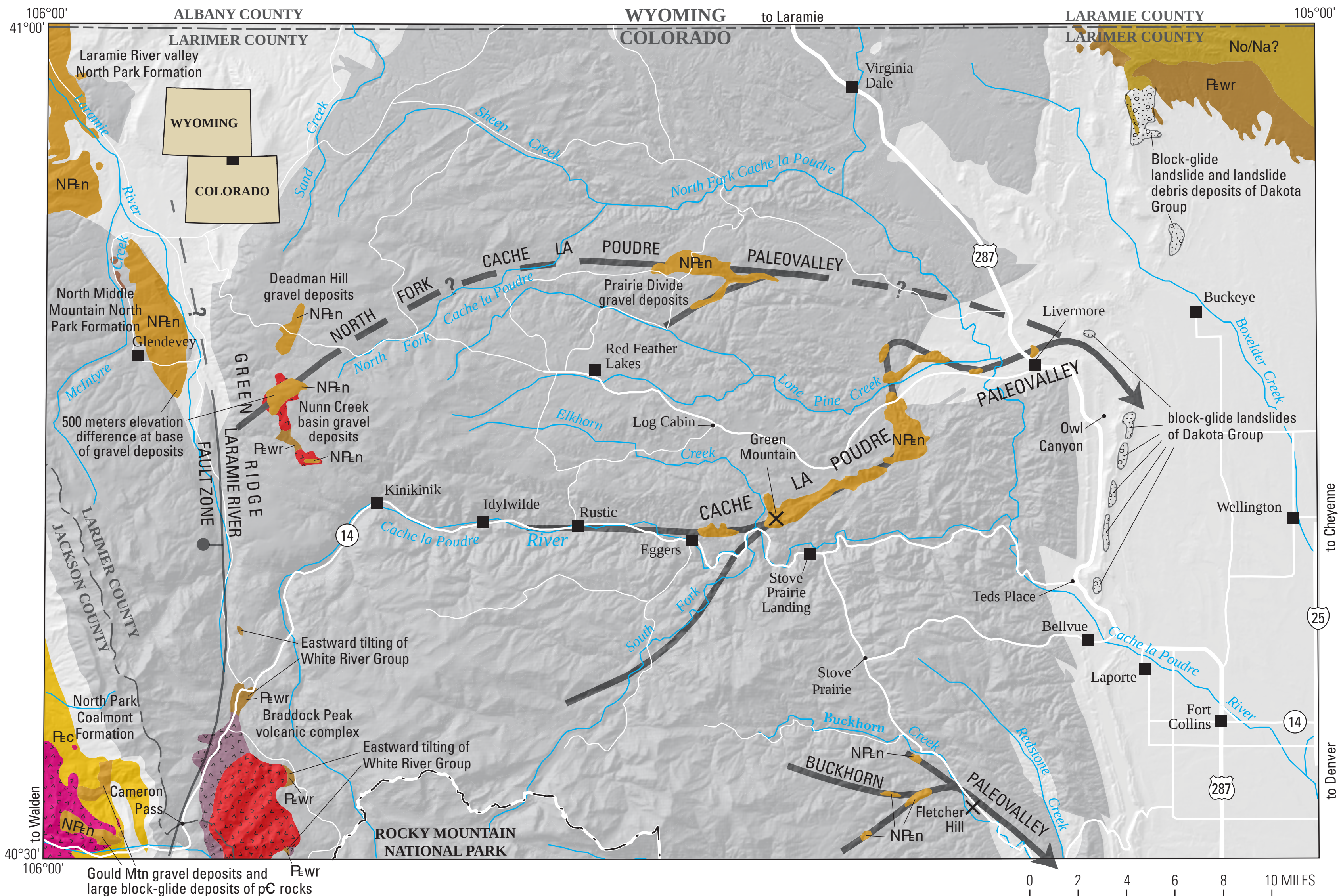
Sparse exposures in the southwestern part of the quadrangle of unnamed sediments (₽ɛs) around the shores of Chambers Lake (Izett, 1975), as well as near Peterson Lake display gray and pale orange, fine-grained tuffaceous mudstone, micritic limestone, and immature conglomerate that may correlate with the White River Group (Braddock and Cole, 1990) because they underlie middle Oligocene volcanic rocks (₽ɛr and ₽ɛb) (about 30 Ma to 28 Ma). Older fluvial gravel deposits (₽ɛgo) on Green Ridge east of the upper Laramie River valley also appear to underlie Oligocene volcanic rocks. These gravels are tentatively correlated with the White River Group due to stratigraphic position, but stratigraphic position is uncertain here due to poor exposure and possible unmapped faults in the area. Unmapped thin beds of fine-grained, ashy deposits poorly exposed at the base of the North Park Formation (N₽ɛn) in the Laramie River valley may also correlate to the Chadron Formation of the White River Group. Where these sediments are preserved in the mountainous areas of northern Colorado and southern Wyoming, they typically occupy drainage systems eroded into the Proterozoic basement (Steven, 1957; Evanoff, 1990).

Upper Oligocene and Miocene fluvial sediments were deposited in several locations in the Fort Collins quadrangle in somewhat contrasting geologic settings. In the northeastern area on the Colorado Piedmont, beds of light-brown, massive siltstone, very fine grained sandstone, and minor arkosic gravel are preserved disconformably on top of the White River Group sediments (Courtright and Braddock, 1989). These Arikaree Formation (Na?) sediments appear to have been transported by southeast-trending streams similar to those that deposited the White River Group (Steven and others, 1997).

Regional tilting is inferred to have taken place in early Miocene time based on the erosional truncation of the Oligocene and lower Miocene formations prior to deposition of middle Miocene sediments of the Ogallala Formation (Izett, 1975; Steven and others, 1997; Cole and Braddock, 2009, p. 39–41). The Ogallala Formation (No), exposed in the northeast corner of the map area, consists of brown, poorly sorted, medium- to coarse-grained arkosic sandstone and conglomerate rich in granite clasts (some as large as 1 m in diameter, derived from the Sherman Granite). Regional tilting is also indicated by a shift to northeast paleocurrent directions in the Ogallala and by abundant rhyolite clasts in southern Wyoming, northeast of the map area, which probably originated from the volcanic deposits of the Braddock Peak volcanic complex south of Cameron Pass (Blackstone, 1975).

Gravelly fluvial sediments of the North Park Formation (N₽ɛn) are preserved in this quadrangle in the northern part

Figure 12 (following page). Post-Laramide deposits and features of the Fort Collins 30′x 60′ quadrangle. Thin fluvial deposits are preserved both east and west of the Front Range in the Fort Collins quadrangle that are correlated with the upper Eocene to lower Oligocene White River Group (₽ɛwr). Oligocene volcanic deposits of the northern edge of the Braddock Peak volcanic complex overlie these fluvial deposits in the southwestern corner of the quadrangle with distal flows extending north onto Green Ridge. Coarse fluvial gravel deposits overlie and contain clasts of the volcanic rocks. These gravels are also present in the Laramie River valley, eastern North Park Basin, and in high-level positions in the landscape on top of the Front Range. High-level gravel deposits are interpreted by Scott and Taylor (1986) to define the axis of several Oligocene to Miocene paleovalleys (Cache la Poudre, North Fork Cache la Poudre, and Buckhorn paleovalleys), which drained the volcanic terrain and uplifts in the west eastward onto the plains where sediments were deposited in the Miocene Arikaree Formation and Miocene to Pliocene(?) Ogallala Formation (No/Na?; combined here and on cross section *E–E′*). The upper Laramie River valley is interpreted as an Oligocene to Miocene structural graben formed by the inferred north-south striking Laramie River fault zone. This graben was filled by gravels of the North Park Formation (N₽ɛn). Oligocene to Miocene block-glide landslides developed within the Dakota Group along the Foothill hogbacks belt on the eastern side of the Front Range which override White River Group sediments and are overlain by Ogallala Formation. pЄ, Precambrian; Ma, million years.



Base from U.S. Geological Survey digital data, 2010
Universal Transverse Mercator projection, zone 13N
North American Datum 1927

EXPLANATION

- No/Na? **Ogallala Formation (Pliocene? to Miocene)**
- NPєn **North Park Formation (Miocene and Oligocene)—** And associated gravel deposits
- **Rhyolite flows (Oligocene; 27 Ma)**
- **Dacite and Rhyolite flows (Oligocene; 28.5 Ma)**
- **Trachybasalt flows (Oligocene; 29.6 Ma)**
- Pєwr **White River Group and pre-volcanic sediments (Oligocene to Eocene)**
- Pєc **Coalmont Formation (Eocene to Paleocene)**
- **Proterozoic rocks, undivided**
- **Fault zone**—Dashed and queried where location is approximate. Ball and bar on downthrow block
- **Paleovalley**—Dashed and queried where location is approximate. Arrow shows direction of flow

of the Laramie River valley and are inferred to be upper Oligocene(?) and Miocene based on landscape position and lithologic similarity to strata in the type area west of the Medicine Bow Mountains (Montagne and Barnes, 1957; Hail, 1965; Camp, 1979; Cole and others, 2010). The North Park Formation in the Fort Collins quadrangle consists of tan to white, calcareous sandstone and conglomerate with lesser amounts of white, light-gray, and pink calcareous siltstone and shale. It contains abundant clasts of flow-banded rhyolite and quartz-bearing welded tuff that closely resemble the felsic rocks of the Braddock Peak volcanic complex near Cameron Pass. The North Park Formation has not been studied in detail here, but it appears to have been transported in a fluvial stream system that was probably fault-bounded between the Medicine Bow and the Laramie Mountains, respectively, and followed a course similar to the modern Laramie River (Blackstone, 1975).

Scattered relics of bouldery, very poorly sorted, coarse-grained gravel, conglomerate, and sandstone deposits (NPEgy) are preserved in several localities in the quadrangle (fig. 12). Most of these were compiled in a regional map by Scott and Taylor (1986) and interpreted as remnant valley-fill of prior drainage systems that produced paleovalleys (Cache la Poudre, North Fork Cache la Poudre, and Buckhorn paleovalley on fig. 12) that incised the mature landscape that formed in late Oligocene time. These paleovalleys and the coarse bouldery fill deposits sit high in the modern landscape above deeply incised modern river valleys that suggest Miocene uplift of the Front Range (Steven and others, 1997) as well as primary Oligocene volcanic topography (Cole and others, 2010), but the ages of deposition are poorly known.

Volcanic rocks are inferred to be interbedded with the boulder gravel deposits in one location in the Fort Collins quadrangle, and this relationship provides an important constraint on the time of deposition. Gravel is preserved both below and above quartz-bearing rhyolite tuff (PEr) in the southern Laramie Mountains between Nunn Creek Basin and Deadman Hill on the Deadman 7.5' quadrangle on Green Ridge just east of the southern Laramie River valley. This tuff was dated at 27.7±0.1 Ma (Knox, 2005) and is correlated with the rhyolite erupted from the Braddock Peak volcanic complex and preserved southeast of Cameron Pass (O′Neill, 1981). Gravel beneath the rhyolite ash-flow tuff contains clasts of Precambrian rock as well as mafic and intermediate volcanic porphyries eroded from the Braddock Peak volcanic complex. The overlying gravel contains common clasts of the 27.7-Ma rhyolite as well as some of the older intermediate and mafic volcanic rocks from the same complex. The paleovalley in the Nunn Creek Basin area that contains these gravel and volcanic deposits loses elevation as it goes northward towards the Deadman Hill gravel deposits (at about 3,050 m elevation) and is presumed to have connected northeastward approximately along the modern upper drainage of Panhandle Creek (fig. 3) to the North Fork Cache la Poudre paleovalley in the Prairie Divide area (at about 2,400 m elevation) where similar gravels are preserved (Prairie Divide gravel deposits of fig. 12). Farther east, these gravel deposits project downward to the Livermore valley where gravel rests on top of beveled Paleozoic strata at about 1,920 m elevation. These gravel deposits suggest a possible Miocene course of the North Fork Cache la Poudre River, but without proper age control or detailed clast provenance, correlation of these deposits is speculative.

Boulder gravel deposits are well preserved just north of the modern canyon of the Cache la Poudre River between about Eggers and the town of Livermore. The bottom of the paleovalley declines from about 2,180 m elevation on the west to about 1,920 m on the east of the Livermore embayment. At Green Mountain (about 3 km northwest of Stove Prairie Landing), modern erosion through these gravel deposits shows that they were at least 210 m thick or, stated differently, that the paleovalley was at least 210 m deep during deposition. Small patches of boulder gravel are preserved high on the landscape along the former drainage of the South Fork Cache la Poudre River as well between about 2,500 m and 2,300 m elevation.

The combined drainage of the North Fork and main fork of the Cache la Poudre paleovalleys passed across the Livermore embayment and crossed the upturned sedimentary strata of the foothills hogbacks and flowed southeastward down a course approximately through the modern Campbell Valley northeast of Owl Canyon. This interpretation is suggested by the elevation of the relict stream gravel deposits in relation to the modern heights of the upturned hogback ridges in this area. Scott and Taylor (1986) inferred the former Cache la Poudre River discharged northeastward across the eroded Upper Cretaceous strata, but that would not have been possible because the channel was already established at a lower elevation than the Paleozoic rock hogbacks (see Cole and Braddock, 2009, p. 41–43, fig. 12).

The former drainage of the Buckhorn paleovalley is preserved by remnant gravel deposits between the modern Buckhorn Creek canyon and Stringtown Gulch in the southeastern part of the Fort Collins quadrangle (Braddock, O′Connor, and Curtin, 1989). These Miocene to Pliocene(?) drainages were also established at lower elevation than the eastern edge of the Front Range (and tilted hogback ridges of Paleozoic strata), and were diverted near Fletcher Hill southeastward down a fault-controlled valley of modern Buckhorn Creek toward the town of Masonville, just southeast of the city of Fort Collins.

Boulder gravel is also preserved about 100 m higher than the modern drainage of the Michigan River near the southwestern corner of the Fort Collins quadrangle (Gould Mountain gravel deposits; fig. 12). These deposits contain common clasts of the Upper Oligocene quartz-bearing rhyolite tuff erupted from the Braddock Peak volcanic complex and are inferred to be Miocene because they are preserved at higher elevations than Pleistocene glacial gravels in the same drainage.

All of these fluvial gravel deposits share characteristics with the Oligocene(?) and Miocene North Park Formation (Hail, 1965; Camp, 1979) in that they locally overlie the 27.7 Ma rhyolite tuff, they contain common clasts of the rhyolite and other Oligocene volcanic rocks, and they appear to indicate drainage that was approximately radial from the

Braddock Peak volcanic complex. The high-level gravel deposits preserved in canyons that cut into the Proterozoic basement only differ from the North Park Formation in that they lie on basement rock rather than Oligocene or Eocene strata.

Quaternary Deposits

Quaternary deposits in the Fort Collins quadrangle primarily reflect the climatic fluctuations during the last 1.8 million years. They are composed of stream deposits chiefly at lower elevations extending beyond the mouths of mountain canyons, glacial and glaciofluvial deposits at high elevations, and various other deposits related to mass wasting and eolian processes.

Main-Stream Fluvial and Pediment Deposits

The Quaternary geomorphic history of the quadrangle reflects the influences of persistent stream erosion and episodic deposition that has taken place since early Pliocene time. East of the pre-Quaternary mountain front (in the vicinity of the modern foothills hogback belt), the South Platte River drainage incised and removed much of the Tertiary sedimentary apron (Ogallala Formation and older units) and exposed the tilted resistant layers in the foothills hogback belt while upstream river valleys became deeply entrenched in the mountain block (for example, Steven and others, 1997). Continued erosion in the Colorado Piedmont has led to incomplete preservation of various surficial deposits near the eastern margin of the quadrangle. Similar processes have acted on the Laramie River drainage near the western margin of the quadrangle. The main Quaternary water-lain units east of the mountain front are modern and prehistoric stream alluvium on valley floors, flights of fluvial terrace deposits that record the positions of former floodplains, and pediment deposits (Qp) that probably were graded to the level of former floodplains.

Considerable study during the last five decades has been devoted to the fluvial terrace and pediment deposits along the western margin of the Colorado Piedmont east of the Front Range and to the record of progressive drainage incision and episodic deposition. Scott (1960, 1963) described five prominent alluvial units at different levels in the South Platte River drainage southwest of Denver. He used height above modern stream level, surface morphology, as well as soil and other weathering characteristics to establish a nomenclature scheme. Subsequent work has validated his observations, allowed correlation of terrace and pediment deposits elsewhere along the mountain front (Scott, 1975; Colton, 1978), and provided better control on the ages of these deposits (summarized by Madole, 1991).

Correlation of terrace and pediment deposits is uncertain from place to place, particularly among the older units because there are few numerical ages, dating methods have uncertainties, and local geology exerts considerable control on drainage evolution (Madole, 1991). For example, correlation based on terrace height above modern stream level can be unreliable locally, especially along the western margin of the Colorado Piedmont. In this area, stream capture is common owing to differences in flow regime, load characteristics, and gradients between stream channels that drain upland areas (flowing over cobble alluvium) versus those that head in the piedmont (flowing over erodible Pierre Shale, for example). Some terrace deposits may not have correlatives elsewhere along the western margin of the piedmont, because they are the products of local stream-channel avulsion and stream piracy (Madole [stops 2–6] *in* Dethier and others, 2003). Figures stated below for deposit heights represent average values in locations near the mountain front.

The oldest well-preserved deposit in the Colorado Piedmont is the Verdos Alluvium (Qv). It includes pediment deposits that cap southeast-sloping surfaces cut on Pierre Shale near the northeast corner of the quadrangle, as well as three valley-fill or terrace deposits on the east side of Dry Creek southwest of Wellington. These deposits are at one and locally two levels. Lower (younger) deposits are about 34–37 m above stream level. Two smaller, higher (older) deposits are about 43–49 m above stream level. Higher (older) deposits of the Verdos Alluvium in the Denver area locally contain the Lava Creek B volcanic ash (640 ka; Lanphere and others, 2002) of early middle Pleistocene age (Madole, 1991). The top of the Verdos Alluvium is much lower than the top of the alluvium that underlies a high-level surface, about 6 km east of Wellington, just east of the quadrangle. Deposits that underlie the high-level surface are about 73–92 m above Boxelder Creek, and may be correlative with or predate the Rocky Flats Alluvium in the Denver area (Scott, 1960, 1963).

The next youngest deposit below the Verdos is designated the Slocum Alluvium (Qs), which is widespread for several miles east of the foothills hogback belt along the eastern margin of the Front Range. The Slocum consists of pediment and valley-fill or terrace deposits at two levels. Lower (younger) deposits are commonly pediment deposits about 9–15 m above stream level. Higher (older) deposits are pediment and valley-fill or terrace deposits about 15–18 m above stream level. These latter deposits typically cap small hills. Slocum Alluvium south of the Denver area is considered to be about 240 ka, but its age is not well constrained (Madole, 1991).

Although the Louviers Alluvium underlies terraces along some of the major streams immediately east of the foothills hogback belt south of Loveland (Colton, 1978), it was not identified within the Fort Collins quadrangle. Deposits of Louviers Alluvium may locally underlie eolian deposits along the Cache la Poudre River and Boxelder Creek near Fort Collins or they may be buried by younger alluvium. Louviers Alluvium in the Denver area was deposited during the Bull Lake glaciation (Scott, 1975; Madole, 1991), about 170–120 thousand years (ka) (Schildgen and others, 2002; Sharp and others, 2003; Pierce, 2004).

The Broadway Alluvium (Qb) underlies prominent low terraces and includes valley-fill deposits along the Cache la Poudre River and its major tributary streams east of the foothills hogback belt. Deposits underlie valley-floor alluvium (Qa) in floodplains along major streams as well as terraces about 7.5 m above the Cache la Poudre River and about 3 to 7.5 m above major tributary streams. The Broadway also forms gravelly alluvial aprons along Sand Creek and the upper reaches of Rawhide Creek and Spottlewood Creek, near the northeast corner of the quadrangle. Radiocarbon ages indicate that deposition of the Broadway was broadly coeval with Pinedale glaciation, about 30–12 ka (Madole and Shroba, 1979; Nelson and others, 1979; Madole, 1986, 1991). Deposition ceased by about 10–11 ka (Holliday, 1987).

Alluvium on valley floors (Qa) in the Colorado Piedmont postdates the Pinedale glaciation and is probably of Holocene age based on its topographic position relative to Broadway Alluvium. Post-Pinedale alluvium (Qa) fills stream channels, forms floodplain deposits and underlies adjacent low terraces less than 4.5 m above major streams and their major tributaries east of the foothills hogback belt and in the Laramie River. However, this youngest alluvial unit (Qva) in the mountains and the Laramie River valley locally contains narrow deposits of Pinedale outwash (Qgp).

Glacial and Glaciofluvial Deposits

Landforms and surficial deposits in the high mountain country of the Fort Collins quadrangle record the history of Pleistocene and Holocene glaciation in considerable detail. The prominent glacial cirques along range crests, classic U-shaped valley cross-sections formed by glacial action, and characteristic forms of lateral and terminal moraines all attest to the extent of glaciation and are major scenic attractions.

Early work by Lee (1917, 1923) and Richmond (1960) in the Front Range identified the main elements of the glacial landscape and established evidence for multiple glacial advances and retreats. Subsequent detailed work by Madole (1969), Madole and Shroba (1979), Shroba and Birkeland (1983), and Birkeland and others (2003) in the Front Range and by Kiver (1968, 1972) in the southern Medicine Bow Mountains has added further information about the glacial stratigraphy, soil characteristics, and ages of glacial events. A comprehensive regional investigation by Madole and others (1998) provides a summary of much of the relevant information on glaciation within the quadrangle. The following paragraphs are summarized in part from the above sources as well as from other sources cited elsewhere in this report.

Deposits of two major Pleistocene glacial episodes are recognized in high mountain valleys within the quadrangle, representing the regional Bull Lake and Pinedale glaciations (Richmond, 1960). Although scattered remnants of deeply weathered till of pre-Bull Lake age may be locally preserved near the lower limit of glaciation in the Laramie River valley (Kiver, 1968), none were mapped owing to poor exposure and lack of strongly weathered and disintegrated surface boulders. The oldest mapped deposits accumulated during the Bull Lake glaciation. These deposits consist of till and glaciofluvial sediment that formed during one or more glacial advances during late and middle Pleistocene (roughly 190–120 ka; possibly as old as 300 ka, Madole and others, 1998). The Pinedale glaciation occurred during the late Pleistocene (about 30–12 ka) and produced the most extensive and best preserved moraines and glaciofluvial terraces within the quadrangle. The area of ice accumulation during the last two major glacial episodes seems to have been similar. Glaciers were largely confined to mountain valleys above an elevation of about 2,325 m. Perennial snowfields probably locally mantled parts of the intervening upland areas during glacial episodes, and high ridgelines appear to have remained exposed during most of the Pleistocene Epoch.

Till and outwash deposits of the Bull Lake glaciation (Qtb) are preserved beyond the Pinedale terminal moraines in the Laramie River valley. The form of the moraine crests is typically subdued but still discernible, some of the moraine boulders are partly disintegrated, and soils have clay-enriched B horizons. Multiple moraine-crest ridges suggest minor advances and retreats during the Bull Lake glaciation.

Till and outwash deposits of the Pinedale glaciation (Qtp) are widespread in the upper part of major mountain valleys in the western part of the quadrangle. Sharp moraine-crests, fresh glacial boulders (some retain glacial polish and striations), and thin weakly developed soils all indicate that these deposits accumulated during the last major glaciation. Pinedale terminal moraines are only slightly incised by stream erosion and locally impound outwash sediments that cover flat-floored valleys that underlie low terraces along the upper reaches of the Laramie and Cache la Poudre Rivers. Kettles and kettle lakes are locally common in areas of Pinedale drift. Well-preserved Pinedale moraines show that two or more advances and retreats occurred during the Pinedale glaciation; parallel lateral moraines and nested terminal moraines are conspicuous in many of the major glacial valleys.

Two additional glacial units and one minor post-glacial unit are shown on the map sheet. Till of latest Pleistocene age forms two or more moraines as much as 0.5 to 2.2 km beyond cirque headwalls at elevations as low as 3,220 to 3,415 m near present timberline on the east flank of the Medicine Bow Mountains. Rock-glacier deposits (Qr) are present in the cirque-basin in the Mummy Range, Never Summer, and Medicine Bow Mountains at elevations greater than about 3,200 m. Most of these tongue-shaped, ice-cored and lobate, ice-cemented masses of talus boulders and locally ablation drift near cirque headwalls formed during Holocene time, but some of the larger deposits well beyond the cirque headwall may date to late Pleistocene (Meierding and Birkeland, 1980; Braddock and Cole, 1990). Organic-rich sedimentary deposits (peat in fens and bogs and carbonaceous silt; Qo) are shown in several areas on till of Pinedale age (Qtp). These deposits are preserved chiefly north of Chambers Lake and along tributaries to the upper Cache la Poudre canyon in the southwestern part of the quadrangle. Detailed records of late Pleistocene and Holocene glacial environments have been constructed from study of these lake and bog sediments in the Front Range south of the Fort Collins quadrangle (Madole, 1976, 1980; Davis, 1988).

Mass-Movement Deposits

Mass-movement deposits are widespread in parts of the Fort Collins quadrangle, but they have been mapped chiefly in areas where they are especially thick, extensive, or important as indicators of geologic and past climatic conditions.

Colluvium (Qc) is widespread on moderate slopes adjacent to steeper terrain, for example in the foothills hogback belt. Colluvium is also shown in high-altitude areas on the map where frost action causes bedrock to fracture and move slowly downslope under the influence of gravity.

Talus deposits (Qta) are largely confined to the bases of steep slopes in the high mountainous terrain. Talus cones and aprons are mapped most commonly near the base of steep bedrock slopes that were scoured by glacial ice.

Landslides (Qls) are present in the Fort Collins quadrangle in a number of contrasting geologic settings; some are old and seem to be relatively stable at present, while others remain active today. Several high-altitude landslide deposits involve masses of Proterozoic crystalline rock, particularly in the Laramie River valley near Chambers Lake where the rock has been weakened by faulting. Landslides are also common within the foothills hogback belt. These masses involve unconsolidated clay, silt, and sand mixed with blocks of rock several meters in diameter that have slid down the dip-slope of the Dakota Group (Kd), Fountain Formation (ℙPf), and Lyons Sandstone (Pl), in order of decreasing frequency.

Some landslide masses within the Dakota Group (fig. 12) involve bedding-plane slip beneath the first sandstone member of the Plainview Formation that allowed large blocks to glide down-dip and override younger strata to the east. Some of these block-glide landslides, near the northeast corner of the quadrangle, are known to be Oligocene in age because they are overlain by Miocene and Pliocene(?) Ogallala Formation (Braddock, 1978). This distinctive class of landslides is described in greater detail in the following Structure section.

Eolian Deposits

Loess (Qlo) consists chiefly of sandy silt, and is common east of the foothills hogback belt where it mantles gently sloping surfaces. Loess deposits are commonly 3–11 m thick. Loess-derived soils are well suited for agricultural use; they are among the most productive soils in the quadrangle. Although inactive today, loess commonly accumulated downwind of active floodplains and decomposed Cretaceous shale and minor sandstone as a result of high-wind conditions that accompanied glaciations during the late and late middle Pleistocene.

Structure

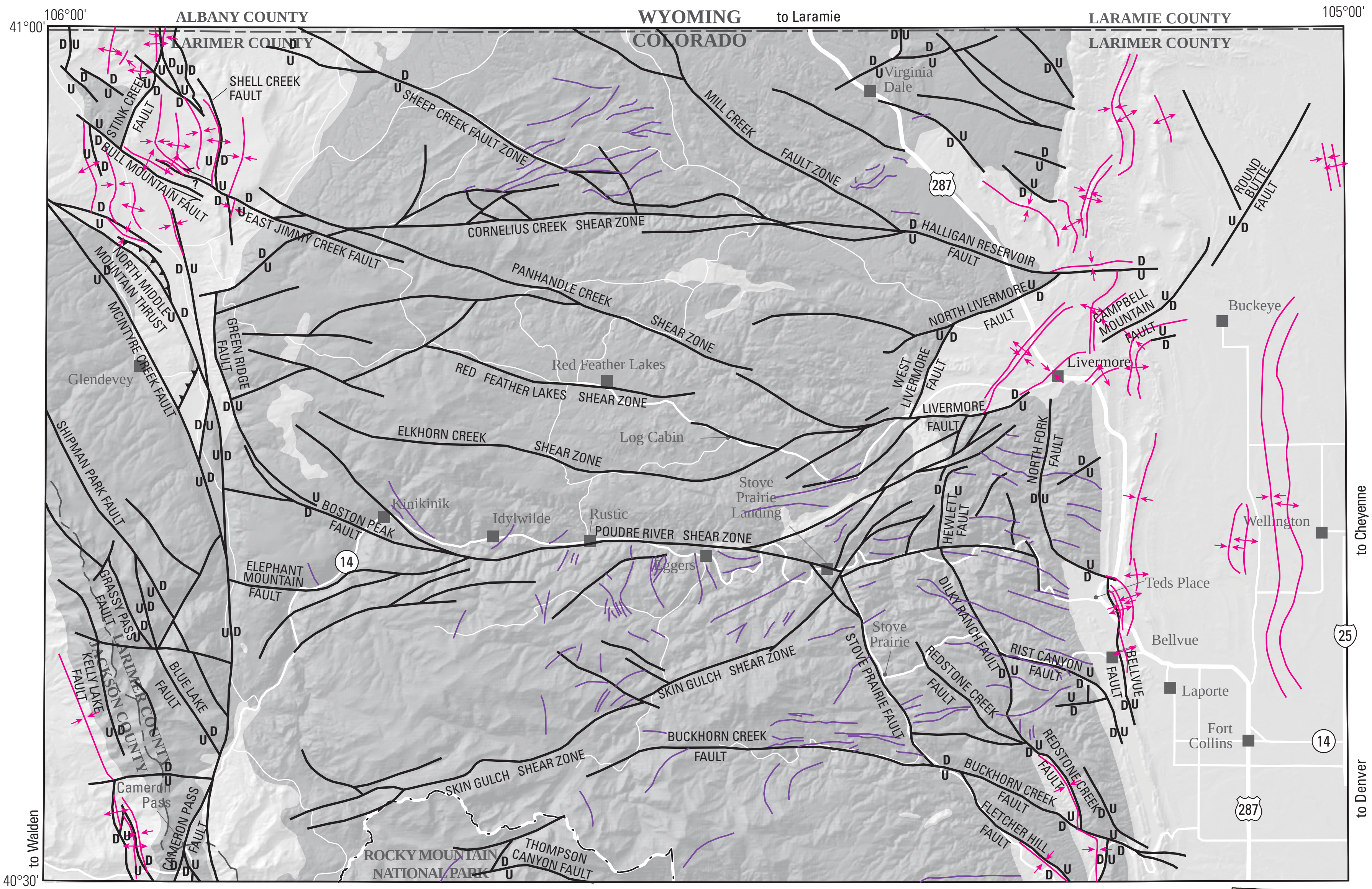
The geology of the Fort Collins quadrangle records a complex structural history spanning from the Paleoproterozoic to the late Cenozoic (fig. 13). The earliest deformation is recorded within the metamorphic rocks of the Front Range (fig. 7), followed by structures that formed during intrusion of the Mesoproterozoic granitic rocks of the Berthoud Plutonic Suite (fig. 9) and subsequent faulting under deep-crustal conditions. Phanerozoic deformation related to the Ancestral Rocky Mountains orogeny (Pennsylvanian age) is not explicitly recorded in the quadrangle, but is inferred from depositional patterns of sediments shed from the uplifted mountain blocks (fig. 10). The Laramide orogeny, beginning in Late Cretaceous time, exerted a major influence on the Front Range region by raising Proterozoic crystalline rocks to similar elevations as Upper Cretaceous marine sediments. Synorogenic sediments were folded and faulted during a second phase of Laramide contraction and uplift in Eocene time. Localized volcanic and intrusive activity was accompanied by renewed uplift and extensional block faulting in late Oligocene and early Miocene time (fig. 12). The most recent uplift of the northern Front Range and the Medicine Bow Mountains, in conjunction with climate change since the Pliocene, has produced most of the modern landscape and removed much of the lower Tertiary cover from the foothills and plains regions.

Paleoproterozoic Structures

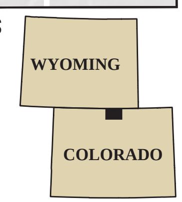
Within areas of low metamorphic grade along the southeastern edge of the map, Proterozoic rocks of the sedimentary source dominated terrain (fig. 7) preserve graded bedding and cross-bedding which record the facing direction of beds that define original major east-west folds (Braddock and Cole, 1979; Nesse and Braddock, 1989; Cole and Braddock, 2009). These first-generation, regional-scale folds are interpreted to have formed while the original sediments were saturated with water (Braddock, 1970) prior to metamorphism at 1,713±30 Ma (Peterman and others, 1968). All folds of this period are overturned toward the north and the spacing of adjacent anticlinal culminations implies a fold wavelength greater than 15 km (Nesse and Braddock, 1989).

Folds attributable to this first stage of deformation can only be reliably identified in the southern part of the Fort Collins quadrangle where metamorphic recrystallization was less pervasive and primary sedimentary structures are preserved. All of the central, northern, and western parts of the quadrangle were strongly metamorphosed to the extent that pelitic metasedimentary rocks characteristically show evidence of partial melting (Cole and Braddock, 2009; p. 19–20). Folds formed in the dominantly volcanic terrane west of Virginia Dale, for example, share a dominant east-west orientation with

Figure 13 (following page). Map showing major structural elements of the Fort Collins 30'x60' quadrangle. Dark gray areas are Proterozoic crystalline basement rocks and light gray are Phanerozoic deposits. Major faults and shear zones are shown with names (FLT, fault) and inferred sense of offset (U, upthrown block; D, downthrown block; teeth on upper plate of thrust fault) where known. Proterozoic fold axes (red lines) are shown within crystalline basement rocks and Laramide folds (magenta lines; arrows indicate fold type) are shown within Phanerozoic rocks.



Base from U.S. Geological Survey digital data, 2010
Universal Transverse Mercator projection, zone 13N
North American Datum 1927



EXPLANATION

Proterozoic rocks, undivided

Fault—U indicates upthrown block; **D** downthrown; teeth on upper plate of thrust faults

Proterozoic fold axis

Laramide fold axis—Anticline

Laramide fold axis—Syncline

the first-generation soft-sediment folds in the sedimentary terrane, but they do not show northward overturning and may have formed at a somewhat different time.

Second- and third-generation Paleoproterozoic folds are widely developed across the Fort Collins quadrangle consisting of antiforms and synforms with wavelengths of (at most) a few kilometers (summarized from Braddock and Cole, 1979; Hutchinson and Braddock, 1987). Second-generation folds (and the crenulation cleavages related to them) generally trend east or northeast; third-generation folds and cleavages trend northwest or north. Both fold sets produce structures of similar scale and geometry with steep fold axes, and display axial-plane cleavage.

Kilometer-scale folds related to the second event are present in the southeastern and eastern parts of the quadrangle. Compositional layering and mineral foliation are predominantly oriented east-northeast in the central and western parts of the quadrangle, probably reflecting second-generation folding. Third-generation folds are well developed in the southeastern area between Pingree Park and Stove Prairie (Braddock, O′Connor, and Curtin, 1989; Nesse and Braddock, 1989), and related crenulation cleavages are widespread in the metasedimentary rocks. This northwesterly fold trend is known to be the younger of the two because it consistently overprints second-generation structures, although the two fold trends probably represent essentially conjugate shear directions that formed during a protracted contractional event. Deformation that produced the crossing sets of second- and third-generation folds may have been a continuation of the contraction implied by the major first-generation wet-sediment folding. The overturned first-phase folding indicates contraction oriented roughly north-south, and the same orientation is suggested by the younger northeast and northwest (conjugate) folds.

All of this folding took place at lower metamorphic grades (sillimanite-grade or lower) before the thermal peak of metamorphic recrystallization passed through these rocks (summarized from Cole, 1977; Cole and Braddock, 2009; p. 19–20). The index porphyroblastic minerals biotite, garnet, cordierite, staurolite, and andalusite consistently overprint the crenulated fabric displayed by the matrix micas (muscovite and biotite). The porphyroblasts are irregular and their internal inclusions of quartz and feldspars show no helicitic patterns that would indicate rotation during growth. The matrix micas are shingled around the hinges of crenulation folds, rather than kinked by the folds, indicating the micas recrystallized after folding.

Higher-grade metamorphic rocks (above the first occurrence of sillimanite), including most of the Fort Collins quadrangle (see fig. 7) show evidence of mineral growth and recrystallization more nearly coincident with peak metamorphism (Cole, 1977; Cole and Braddock, 2009; p. 19–20). Both biotite and (especially) sillimanite are weakly to strongly aligned parallel to hinges of the late folds. Migmatite leucosomes form phacolithic masses in the hinge zones of late folds indicating anatectic melt was accumulating and migrating during deformation.

The difference in timing between peak deformation and peak recrystallization in low- vs. high-grade metamorphic rocks is expectable. As a consequence of the low thermal conductivity of rocks, the variation in peak recrystallization timing reflects the delay in transmitting heat through the deforming orogen. The deformation was probably broadly synchronous across the region and at depth, but the thermal maximum arrived later in the lower-grade terranes as the temperature front migrated upward and outward from the greater pressure and temperature conditions in the core of the orogen after folding had ceased.

The broadly coeval second- and third-generation folding coincided with the intrusion of Paleoproterozoic magmas at about 1,715±10 Ma (Braddock and Cole, 1979; Hutchinson and Braddock, 1987; Cole and Braddock, 2009). This interpretation is supported by the observation that granodiorite bodies near Stove Prairie, for example, intruded and expanded within the hinges of these folds. The trondhjemite of Thompson Canyon locally contains a biotite foliation that is parallel to third-phase crenulation cleavage in adjacent rocks but discordant to the margins of the intrusive bodies (Braddock and Cole, 1979; Barovich, 1986). The Rawah batholith (fig. 9) does not show any consistent internal foliation beyond localized flow alignment of biotite, and inclusions of metamorphic wall rocks frequently indicate rotation of foliation planes from the regional patterns.

The northernmost exposure of the granite of the Rawah batholith (XgR) in the southern Laramie Mountains is defined by the east-west oriented Cornelius Creek shear zone (fig. 13). This structure is a brittle breccia zone of mixed lithologies and inferred Laramide age (Workman, 2008). No mylonitic rocks have been found in this area, but no systematic structural study has been conducted to date of the Cornelius Creek shear zone. Rocks of the Rawah batholith are completely absent north of this shear zone within the older Paleoproterozoic metavolcanic section (volcanic source dominated terrain of figure 7). Although inclusions of wall rock are present south of the shear zone, there is no northern outer contact of the Rawah batholith present in the area. Based upon external contact relationships of the Rawah batholith with older metamorphic rocks in other areas, the juxtaposition of rock types across the shear zone implies a large offset. However, the potential Laramide offset along this structural trend is moderate at best as observed to the east where Mesoproterozoic and Phanerozoic contacts are offset along the Halligan Reservoir fault and to the west along the East Jimmy Creek and Bull Mountain faults where Phanerozoic rocks in the Laramie River valley are offset. Therefore, the Laramide motion along the Cornelius Creek shear zone is inferred to cut out or reactivate a post-Rawah-age structure of uncertain orientation and nature (inferred Proterozoic lineament on fig. 9). The northern boundary of the Mesoproterozoic Log Cabin batholith to the east of this inferred structure is surprisingly linear east to west along the strike of the younger Laramide faults. This contact shows normal intrusive relationships along the trend with only moderate (hundreds of meters) to minor (tens of meters) offsets on the younger faults within the trend. The largest offsets (approximately 1.5 km) occur east of Halligan Reservoir. Therefore, the inferred structure to the west must pre-date intrusion of the Log Cabin batholith.

The southern contact of the Mesoproterozoic Sherman batholith (YgSH) is sharp in the vicinity of Boulder Ridge where it appears to closely follow the structural trend within the older, intruded metamorphic terrain. The western end of the Cornelius Creek shear zone separates Sherman Granite to the north from the Rawah batholith to the south. It is unclear if the Sherman batholith was cut by the inferred Proterozoic structure in this location or if the Mesoproterozoic intrusive contact was following an older structural trend. We prefer the later interpretation, but the relationships are ambiguous. The northern contact of the Log Cabin batholith, the younger Laramide faults, and the older inferred Proterozoic structure all define an east-west striking lineament which crosses the entire width of the Front Range (fig. 9).

Mesoproterozoic Structures

The oldest intrusive rocks of the Mesoproterozoic Berthoud Plutonic Suite of Tweto (1987) are only exposed in the southern part of the map area. The granite of Hagues Peak (1,480 Ma; Braddock and Cole, 1990) is a biotite monzogranite to granodiorite that is distinguished by large microcline phenocrysts and as much as 15 percent biotite, both of which are flow-aligned. Small masses of older biotite-hornblende quartz diorite are cut by the granite of Hagues Peak (fig. 9).

The most voluminous intrusive rocks of the Berthoud Plutonic Suite are the younger biotite monzogranite to syenogranite plutons and batholiths emplaced at about 1,400 Ma (Silver Plume Granite and equivalents; Braddock and Cole, 1979). These granites are representative of widespread similar intrusions that have been identified across the North American continent between Labrador and southern California (Anderson, 1983). Based on similarities in composition, isotopic characteristics, and petrology, these extensive 1,400 Ma granites are interpreted as products of continent-wide melting of the lower crust, possibly related to fundamental changes in the underlying mantle at that time (Cole, 1977; Anderson, 1983; Anderson and Bender, 1989; Anderson and Cullers, 1999). This magmatic event cannot be sensibly related to any known or inferred contemporaneous oceanic arc-trench system nearby, and the lack of magmatic chemical diversity further distinguishes the 1,400 Ma granites from the magmatic suites typical of magmatic arcs (Anderson and Bender, 1989; Anderson and Cullers, 1999).

The Mesoproterozoic granites have been described as “anorogenic” because many of these plutons are simple, elliptical structures that sharply crosscut the country rock and were emplaced in the absence of regional deformation (Anderson, 1983). In this part of the Colorado Front Range, the regional tectonic setting during emplacement is interpreted to be nearly neutral or slightly extensional, the latter inferred from the widespread swarm of north-northwest-trending mafic dikes (fig. 9) that were intruded during the Silver Plume event (Cole, 1977; Anderson and Cullers, 1999; Cole and Braddock, 2009; p. 22–23).

In the Fort Collins quadrangle, the four major Mesoproterozoic intrusive bodies are the Sherman batholith, the Virginia Dale ring-dike complex, the Log Cabin batholith, and the northern margin of the Longs Peak-St. Vrain batholith. The Sherman batholith is exposed across the very northern boundary of the quadrangle and extends several tens of kilometers northward in the Laramie Mountains of Wyoming. The Virginia Dale ring-dike complex is genetically and magmatically related to the Sherman batholith but represents a discrete intrusive center where both mafic and felsic magmas were emplaced together. The Log Cabin batholith is an oval intrusion near the center of the Fort Collins quadrangle. Small bodies of leucocratic biotite granite are present in various locations within the quadrangle and they are similar to the granites of the Log Cabin body in terms of mineralogy, texture, and crosscutting relations. The Longs Peak-St. Vrain batholith lies mostly to the south of this area in the Estes Park quadrangle (Cole and Braddock, 2009; p. 35), but its northernmost lobe is exposed in the Comanche Peak area (Plymate and others, 2005).

Sherman Batholith and Virginia Dale Ring-Dike Complex

The Sherman batholith is a compositionally uniform body of red-weathering, coarse-grained granite that contains sodic amphiboles, common zircon, and fluorite (metaluminous to slightly peralkaline chemistry; Eggler, 1968). Most of the batholith is exposed in the Laramie Mountains of southern Wyoming but it continues southward to surround the Virginia Dale ring-dike complex and is exposed in isolated locations west of the Laramie Basin. The total exposed extent of the main Sherman batholith is approximately 80 km × 25 km, but regional aeromagnetic data and outcrop patterns suggest it is a larger, continuous body beneath the cover of Phanerozoic sedimentary rocks in the Cheyenne and Laramie Basins. Similar granite correlated with the Sherman is also exposed in tilted basement blocks south and southwest of Livermore, Colorado. Geophysical modeling (Eggler, 1968) shows the Sherman batholith as a sheeted intrusion dipping to the southeast, which is supported by apparent offset along faults at the intrusion margins. Northeast-trending structures on Boulder Ridge within the Sherman Granite are parallel to the inferred sheeting orientation and may be fractures or joints formed during late-stage cooling and expansion in the batholith. These structures appear to offset younger mafic dikes (Workman, 2008) although kinematic relationships are not well constrained.

The well-exposed ring-dike complex near and west of Virginia Dale, Colo., is a distinctive composite intrusive body that was studied in detail by Eggler (1968); the following summary is based largely on his work. The Virginia Dale complex consists of concentric rings of texturally distinct intrusive granites, diorite, and hybrid magmatic mixtures of granitic and dioritic magmas, as well as a crescent-shaped relic of the metamorphic country rock. Most intrusive contacts dip steeply outward away from the ring center. This geometry was interpreted by Eggler (1968) to indicate that successive phases of the intrusive complex were emplaced following subsidence of conical, central blocks into the underlying Sherman batholith. The hybrid rocks are significant because they show chilled contacts of dioritic (basaltic) magma against fluid granite magma, as well as evidence of commingling of mixed magmas. The contacts of the intrusive rocks with metamorphic country rock are sharp, and the only sign of contact alteration in the surrounding terrane is the addition of fluorite. Metamorphic mineral assemblages and textures are not modified, indicating the Virginia Dale complex was emplaced in the crust at pressure-temperature conditions in equilibrium with the high-grade metamorphism that had taken place 300 million years earlier (Cole, 2004b).

Log Cabin Batholith

The Log Cabin batholith is a steep-sided, oval, pluton consisting of porphyritic and equigranular varieties of biotite monzogranite. It measures about 23 km by 32 km with its long dimension aligned east-west, parallel to the prevailing metamorphic foliation in the country rock. The external contacts are sharp and no contact metamorphic effects were noted. Some preexisting folds in the metamorphic country rock appear to have been compressed into tighter configurations as a result of outward expansion during emplacement of the Log Cabin batholith (Abbott, 1970, 1976), but otherwise the regional stress conditions are inferred to have been neutral to mildly extensional (Cole, 2004b). The northern boundary of the batholith is roughly parallel to an inferred older east-west trending structure as described above defining the northern boundary of the Rawah batholith (fig. 9).

Longs Peak-St. Vrain Batholith

The Longs Peak-St. Vrain batholith is a large, irregular body of porphyritic biotite monzogranite that is exposed in the core of the Front Range from the southern margin of the Fort Collins quadrangle southward for more than 65 km. Cole (1977) and Cole and Braddock (2009; p. 35–36) summarize the main compositional and structural features of this complex body. Its form is distinctive because the Silver Plume-type magmas that intruded it were anomalously dry and viscous and the wall rocks responded with intense plastic deformation and rotation during emplacement.

Mylonite-Bearing Shear Zones

Several mylonite-bearing fault zones are present in the Fort Collins quadrangle and they are interpreted to have formed during Mesoproterozoic time. The most prominent such zone, and the most thoroughly studied, is the Skin Gulch shear zone (fig. 13). The following summary is based on Abbott (1970, 1972) and Nesse and Braddock (1989). The Skin Gulch shear zone consists of a broad band of steeply dipping, plastically deformed rock, ranging from mylonite gneiss to phyllonite to mylonite that traverse lithologic-unit contacts. Sense of movement on the zone is inferred to be largely vertical with southeast side up based on S-C fabric within the mylonites and a pervasive mineral alignment that plunges steeply in the foliation plane. The 300–600 m-wide zone trends east-northeast through the south-central part of the quadrangle. East of Stove Prairie Landing, where it crosses the Cache la Poudre canyon, the shear zone turns eastward and disperses into numerous thinner shear zones. West of Pingree Park where it diverges from the South Fork Cache la Poudre River, the Skin Gulch shear zone similarly turns westward and thins and disperses. A parallel mylonite-bearing fault zone is present farther west (near Peterson Lake), but north of the western end of the continuous Skin Gulch shear zone. The total amount of offset across the shear zone is hard to quantify because no major rock-unit contacts are obviously displaced. Rock units north and south of the zone are largely similar, although felsic gneisses are far more prominent to the north and Paleoproterozoic granodiorite intrusions are far more common to the south. The Skin Gulch shear zone also generally coincides with the northern margin of strongly magnetic Paleoproterozoic basement rocks, which contrast markedly with subdued magnetic susceptibility in similar rocks north of the zone; this contrast has not been adequately investigated or explained. Solway (2014) estimated offset of approximately 1 to 6.5 km based upon estimated pressure and temperature values from pseudosection analysis. The fault zone appears to slightly offset 1,400 Ma mafic dikes, and Abbott (1972) determined homogenization of rubidium and strontium within the shear zone at about 1,200 Ma but with large reported errors. Allen (2005) dated similar mylonites in the Front Range using Ar-Ar techniques and determined a 1,400 Ma age arguing for a post-Berthoud suite episode of mylonitization.

Abbott (1976) describes the Elkhorn fault zone as similar in character to the Skin Gulch shear zone and it traverses the southern margin of the 1,400 Ma Log Cabin batholith. It has a generally east-west orientation, dips moderately to steeply southward, and ranges in width from a few tens of meters to 600 m. The Elkhorn fault may connect with the Livermore fault to the east where mylonites also dip moderately southward. Brittle deformation is pervasive within the Elkhorn fault zone which may indicate younger faulting that cuts the older mylonite zone.

Cavosie and Selverstone (2003) report physical, isotopic, and structural characteristics of deformed amphibolites and calcareous rocks in the south-central part of the Fort Collins quadrangle that they designate the Buckhorn Creek shear zone (unit Xh mapped just south of and cut by the Buckhorn Creek fault). They interpret this narrow zone as a relic of original ocean-floor basalt and gabbro that was deformed in an oceanic transform fracture zone. This interpretation is unlikely for several reasons. The rocks in this zone are surrounded by many thousands of feet of metamorphosed shales and sandstones, and are interlayered with calc-silicate gneisses and probable metavolcanic rocks, not only here but in numerous locations throughout the Front Range. That is, the rock assemblages north and south of the proposed “suture” are largely indistinguishable. Other differences cited by Cavosie and Selverstone (2003) north and south of the feature are gradational, not abrupt, and subsequent analysis of detrital zircons in metasedimentary rocks (Premo and others, 2007) shows no distinction in age populations across the feature. The entire metamorphic terrane was intensely folded and metamorphosed as a unit. The more straightforward interpretation is that these amphibolites and related rocks are simply interlayered with the surrounding metasedimentary rocks.

Arapaho Uplift (Ancestral Rocky Mountains)

Compression along the southern edge of North America during the late Paleozoic generated by the collision and suturing of North America with South America and Africa and (or) intervening arc terranes generated intracratonic block uplifts known as the Ancestral Rocky Mountains (Kluth, 1986). Nesse (2007) proposed renaming these tectonic highlands the Anasazi uplifts and used the term Arapaho uplift for the highlands of northern Colorado in the map area to clarify the lack of coincidence of these uplifts with the later Rocky Mountain and Front Range uplifts of the Late Cretaceous to Tertiary. There is no direct evidence to indicate any mapped faults within the map area were active during this late Paleozoic event, but the presence of the Arapaho uplift is indicated by the sedimentary record of alluvial fans and the onlapping sequence recorded above the eroded Proterozoic basement (fig. 10). A comprehensive analysis of the Paleozoic Arapaho uplift is beyond the scope of this study, but some observations are worth noting here.

Within the eastern (Denver Basin) and northern (Laramie Basin) parts of the map area, coarse to medium arkosic conglomerates of the Pennsylvanian and Permian Fountain Formation (ℙPf) record the erosion and transport of clasts of the Proterozoic basement towards the east and northeast from the inferred uplift over a slope of coalescing alluvial fans. To the north, in the Laramie Basin, the Pennsylvanian and Permian Casper Formation (ℙPc), with abundant carbonate beds and carbonate-cemented sandstones, interfingers with and overlies the Fountain Formation recording the presence of a marine slope and intermittent marine incursions into the area. The Casper Formation thins rapidly at the southern end of the Laramie Basin and pinches out just north of Sand Creek Pass (Workman and Braddock, 2010) indicating the edge of marine incursion and increasing paleo-elevations to the southwest. To the south of this location, the Fountain Formation also thins dramatically to the south. It is not clear if onlapping relationships or localized unconformities cause the thinning, but at North Middle Mountain and to the south in the Laramie River valley, the Lower and Upper Permian Satanka Shale Member of the Goose Egg Formation (Pgfsu) is deposited unconformably on the Proterozoic basement. Along the western side of the Medicine Bow Mountains, most of the Satanka is absent and only the Upper Permian part of the unit is present above the Proterozoic basement. These relationships weakly constrain the location of the northeast boundary of the Arapaho uplift (thick gray dashed line on fig. 10).

Depositional patterns in the Fountain Formation along the eastern side of the Front Range indicate a steep mountain front existed (Howard, 1966); however, Kluth and McCreary (2006) indicate that no major structure defined the northeast boundary of the northwest-oriented uplift. The sparse preservation of upper Paleozoic rocks due to uplift and erosion of the Front Range during the Cretaceous to Tertiary Laramide orogeny make more detailed study difficult. Without the sedimentary record, it is not possible to determine if any of the faults cutting the Proterozoic basement in the Front Range were active during the late Paleozoic.

Laramide Orogeny

Tweto (1975) described the Laramide orogeny as a prolonged regional structural event that began in Late Cretaceous time (about 69 Ma), marked by withdrawal of the Cretaceous Western Interior Seaway and by deposition of synorogenic, nonmarine fluvial sands at about 68 Ma. As deformation continued, basement blocks rose and shed debris into flanking subsiding basins. The Denver Basin east of the Front Range contains a relict alluvial fan complex that records rather continuous sedimentation over at least 6 million years, producing more than 600 m of fluvial sediment (Raynolds, 2003; Dechesne and others, 2011). Tweto considered that the Laramide uplift and sedimentation continued constantly on a regional basis through the Paleocene Epoch and into the Eocene. Raynolds (2002, 2004) has shown that the Denver Basin deposits comprise two fluvial sequences that are separated by a significant gap of approximately 8 million years (roughly 64 Ma–56 Ma), indicating a more episodic history. The evidence in the Fort Collins quadrangle also indicates uplift and deposition were episodic, and that the absolute timing, orientation, and style of deformation may have been quite variable.

Structures related to the Laramide orogeny are common in the Fort Collins quadrangle. They include reverse faults and fault-propagation folds along the eastern mountain front, as well as low-angle thrusts, reverse faults, and footwall folds on the western margin of the range. Syn-tectonic deposits of the Paleocene and Eocene Coalmont Formation in the Laramide North Park Basin are exposed in the southwest corner of the map area (fig. 10). Major brittle fault zones within the Proterozoic basement rocks of the mountain blocks are inferred to have moved during Laramide deformation, or later, and are marked by broad zones of brecciation, iron-oxide alteration, and some silicification.

Early Laramide Structures

The upturned sedimentary units in the foothills hogback belt on the east flank of the Front Range record the tilting and folding that accompanied mountain uplift in the early Laramide deformation. In contrast to areas farther south, no master west-dipping fault is exposed here and the range front is best described as a broad monoclinal flexure. From the area of Horsetooth Reservoir north to about Livermore, the range margin consists of fault-bounded, gently tilted blocks of Proterozoic basement and inclined Phanerozoic strata that are progressively folded over the rigid blocks (Matthews and Work, 1978; Sterns, 1978; Matthews, 1987; Erslev, 1991).

Faults and related fault-propagation folds similar in timing and style to those exposed at the range front are present west of the range front along Redstone Creek and in the vicinity of Stove Prairie and Dilky Ranch (fig. 6) as well as east of the range front where folds in the Wellington and Whittier oil fields (fig. 10) reflect blind basement faults below. The main contractional faults are moderate-displacement (as much as 300 m), high-angle cylindrical reverse faults that dip basinward to the east (see cross sections *E–E′*, *F–F′*, and *G–G′*). Erslev (1991) proposes a trishear fault-propagation fold model for this style of structure where a zone of complex deformation propagates shear upwards through the upper plate of a blind thrust. This blind thrust beneath the eastern edge of the Front Range is proposed as an east-vergent backthrust accommodating the large west-vergent overthrusting of the Never Summer thrust fault on the western edge of the Front Range (Erslev, 1993; Erslev and Rogers, 1993; Erslev and Selvig, 1997; Erslev and Holdaway, 1999; Erslev and others, 2004; Erslev and Larson, 2006; Erslev and Koenig, 2009). Within the range front on the eastern side of the map area, this study provides no new information about any crustal scale fault model; however, new mapping along the western edge of the Front Range in the map area does not support the degree of overthrusting described by O′Neill (1981) in the Never Summer Mountains to the south of the map area. The Livermore embayment (fig. 10) is a trapezoidal structural depression bounded by east-northeast-trending high-angle basement faults. The absence of tilting in this area is consistent with primarily vertical motion on steep faults and indicates that, at least locally, considerable uplift was achieved in the absence of significant lateral contraction. However, this does not contradict the possibility of a low-angle structure at depth accommodating large amounts of lateral contraction. Tetreault and others (2008) describe the role of oblique slip in forming some of the asymmetrical folding in the Livermore area. From Livermore north to the Wyoming State line, the range front is marked by uplifted, non-tilted basement blocks flanked by fault-propagation folds in the overlying sedimentary strata that die out up section, but no exposure of faults at the surface (Matthews and Work, 1978).

Within the map area, the Denver-Cheyenne basin is a broad, symmetrical structure with about 3 km of structural relief on the Proterozoic basement between its deepest part and the foothills hogback belt (Haun, 1968). The basin axis is located about 40 km east of the range front. None of the syn-tectonic basin fill deposits are exposed within the map area. In contrast, the basin is much deeper and more asymmetric near Golden, Colo., to the south (Dechesne and others, 2011), where the axis is only 3 km east of the range front and where the basement is faulted over the Phanerozoic strata on a west-dipping master reverse fault (Weimer, 1996; Higley and Cox, 2005).

Other north-trending, east-vergent structures may also have formed during early Laramide deformation. The reverse fault on the west side of Red Mountain (north segment of “Bull Mountain fault” of Beckwith [1942] and Camp [1979]), the Stink Creek fault between Crazy Mountain and Bull Mountain, the Shell Creek fault between east and west Bull Mountain, and the West Jimmy Creek fault south of east Bull Mountain dip steeply at depth because the surface of the uplifted basement block and Phanerozoic strata are nearly horizontal (that is, neither folded nor tilted). The folding of the sedimentary strata is extremely localized near the uplifted edge of the basement block. The low-angle inclinations of these faults shown in cross-section by both Beckwith (1942) and Camp (1979) are unlikely, based on the rather straight trajectory of the fault trace over steep topography. Farther west (outside the Fort Collins quadrangle), the western margin of the Laramie River valley (in southern Wyoming) is formed by a north-trending monocline of tilted Paleozoic strata adjacent to uplifted Proterozoic basement (Beckwith, 1942).

The north-trending, east-vergent North Middle Mountain thrust fault is exposed along the eastern edge of North Middle Mountain in the Laramie River. This moderate- to low-angle fault is significantly deformed by younger high-angle structures which cross it at several locations. The North Middle Mountain thrust fault is defined by a tight fault-propagation fold cut locally by the thrust fault with offset of up to hundreds of meters but generally minimal offset accompanied by significant attenuation of the near-vertical to overturned Phanerozoic section within the middle limb of the fold. At the north end of the structure along the Laramie River near Bull Mountain, the entire section from the lower Satanka Shale Member of the Goose Egg Formation to the Niobrara Formation is approximately 15–20 m thick across a vertically dipping exposure (see cross section *A–A′*). The dip of the fault and axial fold planes steepens to the south as inferred vertical structural relief increases. The depth of the narrow basin south of North Middle Mountain is constrained by drill hole data (Continental Oil Co., Pollock 1–B, Colorado Oil and Gas Conservation Commission, 2008) which indicate 1,642 m depth to the top of the Dakota Group and therefore approximately 2 km of vertical relief (see cross section *C–C′*).

The north-trending structures are interpreted to have formed in latest Cretaceous to Paleocene time because they can be reasonably related to patterns of withdrawal of the Cretaceous Interior Seaway, deposition of the regressional Upper Cretaceous Fox Hills Sandstone and Laramie Formation, and deposition of syndeformational strata, particularly east of the Front Range (Tweto, 1975; Raynolds, 2002, 2004). The Laramie Basin (north of this quadrangle; fig. 2) also preserves a sedimentary record of sea-level decline, shoreline regression, and syn-uplift deposits that spans the Late Cretaceous to early Tertiary interval (Blackstone, 1975).

In contrast, the western side of the Front Range and the Medicine Bow Mountains record a different chronology as well as contrasting styles and orientations of deformation. Taken together, these features suggest a distinct, younger period of deformation that is described in the next section.

Late Laramide Structures

The Upper Cretaceous Fox Hills Sandstone (Kfh) marks the withdrawal of the Cretaceous Interior Seaway and it was deposited at about 68–67 Ma across much of eastern Colorado and Wyoming (Scott and Cobban, 1986; Dechesne and others, 2011). However, the Fox Hills is not present in the Laramie River valley (Beckwith, 1942), the North Park Basin west of the Medicine Bow Mountains (Hail, 1965; Kinney, 1970), or in the Kremmling area (Izett and Barclay (1973). Rather than accumulating sediment, these areas were eroded during Late Cretaceous-early Paleocene time and at least 600 m of the upper Pierre Shale (Kp) and equivalent Steele Shale (Kss) and overlying Mesaverde Formation (Kmv) were removed in most areas (Hail, 1965; Tweto, 1975) prior to deposition of the syn-uplift Coalmont Formation (₽c). The age of the lower Coalmont is not well known and so the onset of sedimentation is also uncertain. Fossil pollen from the lower part of the formation in North Park (Sudduth coal beds and others) is middle Paleocene (Roberts and Rossi, 1999), whereas Paleocene and Eocene pollen are present in the middle and upper parts of the formation (Hail, 1968).

The Coalmont Formation rests on the uplifted and eroded middle part of the Pierre Shale within the North Park Basin and onlaps successively older formations around the margins of the basin (Cole and others, 2010). Hail (1965, 1968) estimated the Coalmont to be more than 2,750 m thick at its greatest preserved extent, and so the North Park Basin represents a substantial structural reversal from Late Cretaceous to Paleocene time. The area where marine Pierre Shale was removed subsequently subsided and accumulated thick fluvial deposits of the Coalmont Formation. Sedimentology of the Coalmont is not well known, but the interplay of mountain uplift, tilting, and basin subsidence is indicated in its gross architecture. Hail (1968) reported that the lower Coalmont consists of arkosic sandstone with conglomerate beds marked by pebbles and cobbles of porphyritic volcanic rocks inferred to be derived from southern source areas. The middle part of the Coalmont (as thick as 1,830 m) consists of arkosic sandstone, conglomeratic sandstone (Proterozoic, Dakota, and volcanic porphyry clasts), and mudstone, probably derived from adjacent uplifts or reworked in the basin. The incomplete upper part of the Coalmont (more than 400 m thick) overlies the middle part with slight angular unconformity; it consists of carbonaceous shale, sandstone, mudstone, and economic coal beds (Roberts and Rossi, 1999).

The nature of the Coalmont Formation indicates uplift was occurring east and west of the North Park Basin during sedimentation and that volcanic material was removed early from the uplifts along with Proterozoic debris from the basement blocks. This is similar to the “unroofing stratigraphy” recorded in the Denver Basin by the andesite-clast-bearing Denver Formation (Upper Cretaceous to lower Paleocene) and the overlying Proterozoic-clast-bearing “D1 sequence” (Raynolds, 2004; Dechesne and others, 2011). However, the Coalmont sequence is distinctly younger (middle Paleocene to lower Eocene) and documents a separate period of mountain uplift in the North Park area (Cole and others, 2010).

The late Laramide structures within North Park all deform the younger parts of the Coalmont Formation and are thus post-late Eocene in age, or possibly younger. In the part of the North Park Basin that is immediately west of the Fort Collins quadrangle, the most conspicuous structures are regularly spaced, upright, asymmetric anticlines and synclines that trend northwest (Kinney, 1970, 1971). These folds are essentially parallel to the southwestern margin of the uplifted, Proterozoic-cored Medicine Bow Mountains. The mountain front is marked by a prominent topographic step where the less resistant Phanerozoic strata meet the resistant Proterozoic rocks, but the contact is unfaulted at least as far south as the Canadian River drainage. The dip of the nonconformity at the base of the Permian red-beds (Satanka Shale) increases from about 35° to 65° from north to south as the crest of the range rises from about 3,050 m to nearly 3,960 m elevation. South of the Canadian River drainage, the nonconformity contact is offset by an east-dipping reverse fault and locally the footwall beds are overturned, but the amount of offset appears to be small (Braddock and Cole, 1990; Kellogg, Ruleman, and others, 2008). South of the map area in the Mount Richthofen 7.5' quadrangle, 10–15 km of horizontal overhang is indicated along the Never Summer thrust fault (O′Neill, 1981), but there is no indication of this fault exposed within the map area. Kellogg, Rulman, and others (2008) project this thrust faulting above the surface of the map area north of the Michigan River and indicated isolated outcrops of Proterozoic rocks west of the range front as klippe, but we reinterpreted these blocks as simple slide blocks off of the range front. There is no other evidence of a major overthrust north of the Michigan River. The structural incongruity north and south of the Michigan River remains unresolved by the current mapping.

The western flank of the Front Range uplift (southern Laramie Mountains) is marked by a conspicuously linear, north-south escarpment of elevated Proterozoic basement rocks (Green Ridge area east of the southern Laramie River) against folded Phanerozoic rocks in the Laramie River valley. From Middle Mountain northward to Bull Mountain, the Paleozoic strata are steep to moderately overturned westward along the east side of the valley, consistent with the east-dipping Green Ridge fault. The dip of the lower plate sediments implies a low- to moderate-angle fault, but the trend as mapped across significant topographic changes does not support a low angle. The Paleozoic through Lower Cretaceous strata are strongly attenuated and locally cut out along the fault trace (Beckwith, 1942; Camp, 1979). The Green Ridge fault appears to lose throw suddenly to the north dying out in the Phanerozoic section north of the Deadman Hill Road, where the entire section is intact with the Paleozoic strata dipping gently northwestward into the Laramie Basin. To the south, this fault swings around to a west-northwest orientation, cutting across the southern end of Green Ridge, where it juxtaposes older felsic gneisses against the granite of the Rawah batholith (Boston Peak fault). The structure is well exposed as a narrow breccia zone where it crosses the Cache la Poudre canyon just north of Boston Peak. The overall form of this structure is an arcuate, moderate-angle, southwest-vergent fault. At the valley’s southeastern end, the fault merges with a fault zone that trends northwest through the Proterozoic rocks north of the Cache la Poudre canyon. Near the mouth of Deadman Creek, the nearly vertical Green Ridge fault cuts abruptly down section in the lower plate across the strongly tilted, north-south striking Lower Cretaceous into the Proterozoic basement. This geometry suggests that the fault is cutting across an older fold. The orientation and cross cutting relationships of these structures indicate that they are part of the late Laramide deformation described above in North Park.

The Bull Mountain fault at the south end of Bull Mountain, the East Jimmy Creek fault, and the Panhandle Creek shear zone, which extends across most of the width of the Front Range, form a left-stepping, en echelon set of west-northwest oriented faults which cut and deform the older north-south oriented faults and folds along the Laramie River valley. The Bull Mountain anticline, just north of the Bull Mountain fault, is a tight, vertical fold which closely parallels the fault indicating significant compression across the fault. The fault geometry suggests possible left-lateral oblique-slip motion, but no definitive slip indicators were observed. Several smaller faults with similar orientations to the north also cut the older north-south structural grain. Within the map area, the similarly west-northwest trending Sheep Creek and Mill Creek fault zones and the Red Feather Lakes shear zone may be contemporaneous with the Bull Mountain fault zone, but the lack of sufficient crosscutting relationships precludes more specific age control on these structures. The north end of North Park is defined by a similar set of west-northwest trending faults which cut and deform older north-south oriented faults and folds (Steven, 1957; Cole and others, 2010).

These northwest and west-northwest structures appear to form an identifiable group of elements that lie in subparallel proximity to each other forming a pervasive structural grain throughout the northwestern Front Range and North Park Basin, extending north into the southern Laramie Basin and Saratoga Valley of Wyoming. They deform the Coalmont Formation (where it is present) and therefore appear to be post-late Eocene and younger than the north-trending faults and folds of the Front Range that were mostly active in Late Cretaceous and Paleocene time, about 67 Ma to 63 Ma (Tweto, 1975).

It is significant that no Coalmont-age strata are present in the Laramie River valley, either in the Fort Collins quadrangle or northward in the southern Laramie Basin (Blackstone, 1975). This observation suggests these areas were part of the elevated terrain that was being stripped of the upper Pierre Shale prior to Coalmont deposition, and that it remained high during Coalmont time. It seems contrived that the Coalmont Formation might have been deposited in the Laramie River valley, only to be completely removed prior to deposition of the North Park Formation during the Miocene.

If the post-late Eocene folding of the Coalmont Formation is genetically related to the parallel form of the Medicine Bow Mountains, then the Medicine Bow uplift must be considerably younger than the Front Range uplift. Kelley and Chapin (2004) used partial-annealing of fission tracks in apatite crystals to show that the northern Front Range was uplifted during the Late Cretaceous to early Paleogene (about 76 Ma to 44 Ma). Prior reconnaissance data from the southern Medicine Bow Mountains were inconclusive (Cervany, 1990, quoted in Kelley and Chapin, 2004).

An enigmatic transverse east-west trending structure is inferred in the Cameron Pass-Michigan River area that is, most likely, contemporaneous with the Never Summer thrust fault exposed to the south of the map area (Gorton, 1953; Ward, 1957; O′Neill, 1981; Kellogg, Ruleman and others, 2008). This fault is largely covered by Quaternary deposits in the floor of the valley and by Oligocene volcanic rocks to the east. The fault is reasonably inferred because structures to the north and south do not correlate properly along the trend of the Michigan River valley. Conspicuous folds that involve the whole section from the Satanka Shale to the Coalmont Formation north of the valley are absent to the south. The Coalmont rests unconformably on Benton Group in the footwall north of the valley (that is, all Pierre Shale eroded), but at least 1,220 m of Pierre Shale is preserved beneath the Never Summer thrust fault to the south (O′Neill, 1981). Most high-angle normal faults that post-date the Eocene also truncate or terminate at the valley, suggesting the underlying structure is fundamentally different in the two areas.

Post-Laramide Structures

The Eocene Epoch was marked by declining Coalmont sedimentation (North Park area), accelerated weathering due to an intensely warm, moist climate, and widespread erosion throughout the Southern Rocky Mountain region (Epis and Chapin, 1975; Tweto, 1975). These factors formed a topographically subdued landscape over large areas characterized by rolling hills and broad valleys (Steven and others, 1997) between relics of mountainous terrain. This late Eocene eroded landscape is well preserved southwest of Denver beneath ash flows of the Wall Mountain Tuff (35 Ma), but no marker deposits of this age are present in the northern Front Range. Scott and Taylor (1986) inferred that much of the central part of the Front Range block in the Fort Collins quadrangle, lying between about 2,285 m and 2,750 m elevation, represents relics of the Eocene landscape, but it is equally or more likely that this area of broadly concordant hilltop summits continued to develop during Oligocene-early Miocene time (Evanoff, 1990; Steven and others, 1997). Beveled, rolling upland areas include the Green Ridge area and all of the mature, lower elevation Laramie Mountains landscape north of the Cache la Poudre River from Red Feather Lakes eastward across the eroded Virginia Dale ring-dike structure and across the Paleozoic and Mesozoic sediments to the east.

Oligocene sediments and volcanic strata are present in a few areas of the Fort Collins quadrangle (fig. 12), but most have been removed by subsequent erosion. Fluvial and lacustrine volcaniclastic sediments of the White River Group crop out above tilted and eroded pre-Cenozoic strata in the northeastern corner of the quadrangle where they record a prolonged period of basin aggradation and storage of far-traveled volcanic ash (Blackstone, 1975; Larson and Evanoff, 1998). Similar tuffaceous mudstones are preserved in scattered localities surrounding Chambers Lake and Peterson Lake (Izett, 1975; Braddock and Cole, 1990), which might represent an old valley system buried by volcaniclastic sediment (see Evanoff, 1990, for similar conditions in the Laramie Mountains of Wyoming). No obvious structures are associated with this time period in the region.

Braddock Peak Volcanic Complex

Late Oligocene time is marked by volcanism and intrusion in the southwestern corner of the Fort Collins quadrangle. This magmatic activity and related faulting reflects the Never Summer igneous complex, most of which is exposed immediately south of this area (O′Neill, 1981; Braddock and Cole, 1990; Cole and Braddock, 2009). Cole and others (2008) introduced the term Braddock Peak complex to replace Never Summer igneous complex. Only minor exposures of Oligocene intrusive rocks occur in the map area so the term Braddock Peak volcanic complex is used here. Oligocene volcanic rocks include alkali basalts and trachyandesite flows in the vicinity of Joe Wright Reservoir and slightly younger rhyolite ash-flow tuffs and extrusive flows farther east in the Bald Mountain-Flat Top Mountain-Iron Mountain area. Thin ash-flow tuff is also present north of Gould Mountain in the extreme southwestern corner of the quadrangle, and dacitic flows are mapped nearby to the north along the North Fork Michigan River (Kellogg, Ruleman and others, 2008). Recent geochronologic study by Knox (2005) and previous work (see Cole and others, 2008) indicates all volcanic and intrusive rocks of the Braddock Peak volcanic complex were emplaced between about 29.6 Ma and 27.1 Ma. The mafic lavas occupy lower positions in the landscape and may have flowed down contemporaneous canyons, whereas the rhyolitic rocks primarily blanket the higher parts of the Oligocene landscape.

Local extensional faulting and uplift are inferred to have accompanied magmatic activity in the area of the Braddock Peak volcanic complex. Interlayered mafic and felsic volcanic rocks are tilted and anomalously thick in the Little Yellowstone area (Braddock and Cole, 1990), which is a synvolcanic, fault-bounded half-graben south of this quadrangle in Rocky Mountain National Park. In the Fort Collins quadrangle, boulder gravel deposits are present in paleochannels both above and below the rhyolite ash-flow tuff in the Nunn Creek basin areas (fig. 12). Contact relations in these localities indicate a valley system existed prior to volcanic eruption, and that the gradients were sufficient to allow transport of 15- to-30-cm-diameter boulders many kilometers north from their source areas. Once the late Oligocene volcanic rocks were erupted across the landscape, the valley system remained intact and the streams were still capable of transporting 30 cm boulder gravel containing many clasts of the rhyolite ash-flow tuff. The paleovalley system that was developed across the mature rolling landscape of the Green Ridge area appears to have been integrated with paleodrainage below and to the east between Prairie Divide and Livermore (North Fork Cache la Poudre paleovalley on fig. 12).

Very similar sand and gravel deposits correlated with the Oligocene(?) and Miocene North Park Formation (N₽n) are present in the Laramie River valley north of Middle Mountain (Camp, 1979). These fluvial sediments have not been studied in detail, but they contain clasts of the upper Oligocene rhyolite ash-flow tuffs exposed within the Braddock Peak volcanic complex along with clasts of durable Proterozoic basement units. The nature and clast-size attributes of all these channel-bound fluvial units strongly suggest that stream gradients were steep (renewed uplift) and they form a regional network that seems to have radiated outward from the Braddock Peak volcanic complex.

Laramie River Fault Zone

For several reasons, we infer substantial extensional faulting in the Laramie River valley at or following the time of deposition of these upper Oligocene to Miocene fluvial units. First, we note that the North Park Formation (N₽n) deposits on North Middle Mountain are approximately 425 m lower in elevation than the probable correlative channel deposits preserved on Green Ridge to the east (Deadman Hill and Nunn Creek basin gravel deposits on fig. 12). This disparity suggests a north-trending normal fault between Middle Mountain and Green Ridge that might be responsible for tilting the Medicine Bow Mountains block eastward and producing the moderate slope of its eastern flank.

Second, Izett (1975), Camp (1979), and McCallum and others (1983) all inferred a significant north-northwest-trending normal fault along the west side of the Laramie River valley between North Middle Mountain and the main part of the Medicine Bow Mountains. We concur that the McIntyre Creek fault exists and reinterpret faulting along the east side of North Middle Mountain originally mapped as part of the North Middle Mountain thrust fault as younger normal faulting. A fault is required to explain the juxtaposition of Cretaceous rocks against the Proterozoic rocks along the west side of Middle Mountain which is inferred to be a normal fault. This normal faulting is responsible for the alignment of the upper Laramie River valley southward to Chambers Lake, where Eocene and Oligocene White River Group (₽wr) is tilted eastward along the lakeshore. The Shipman Park fault is also interpreted here to be a younger normal fault. All these normal fault displacements must have taken place following eruption of the 28 Ma rhyolites of the Braddock Peak volcanic complex, but are poorly understood.

Block-Glide Landslides

The east-dipping strata of the foothills hogback belt have been substantially disrupted by large landslide complexes, exclusively within strata of the Dakota Group. Detailed mapping by Braddock (Braddock and Eicher, 1962; Braddock, 1978) showed that these landslides are characterized by gravity-driven detachment of parts of the tilted Dakota section along stratigraphic zones of weakness, causing detached blocks to slide down the dip slope over the contemporaneous land surface overriding younger strata at the toe of the dip slope. The detached blocks were folded in the process of sliding over the underlying, intact strata. These landslide complexes have been mapped between Laporte and the Wyoming State line (Braddock and Eicher, 1962; Courtright and Braddock, 1989). Evidence indicates that some of the block-glide landslides formed during Oligocene time because the slide complex locally overlies basal conglomerate of the White River Group and is overlain by Miocene and Pliocene(?) Ogallala Formation

(Braddock, 1978). On geomorphic grounds, it appears that many other block-glide landslides formed during the Pleistocene because the elevation at which the detached block broke and overrode the land surface coincides with one of the major pediment surfaces that formed during early Pleistocene erosion. These displaced blocks are represented on the geologic map as a "broken block" pattern overprinted on the Dakota Group (Kd) rocks. Landslide debris deposits (NPls) composed of fragmented Dakota Group rocks overlie these intact block-glide masses in the northernmost exposure (fig. 12) and are considered part of the block-glide complex. These landslide deposits probably derived from incompetent rocks exposed upslope near the head of the landslide complex after initial detachment of the intact blocks below.

Miocene-Pliocene Uplift and River Incision

Middle Miocene time was marked by onset of significant renewed uplift of the Front Range in this area (Bolyard, 1997; Steven and others, 1997). Eaton (1986, 1987) assembled regional evidence to argue that this younger uplift was subcontinental in scale and most likely due to thermal rise of a welt of aesthenospheric mantle beneath the region and related lithospheric thinning (Alvarado Ridge of Eaton, 1986). The axis of this broad ridge is marked by the location of the Rio Grande rift, a north-south trending series of normal faults and deep local basins that formed along the extended crest of the regional uplift (Eaton, 1986; Chapin and Cather, 1994).

In the area of the Fort Collins quadrangle, this Miocene uplift is suggested by the persistent boulder gravel deposits (NPgy) in east- and northeast-trending paleocanyons of the early Cache la Poudre River drainage and Buckhorn Creek as discussed above (Scott and Taylor, 1986; fig. 12). These gravel deposits that mark the positions of paleocanyons define fairly straight drainages. Stream gradients may have been moderate to steep across the Oligocene-Miocene surface beveled over Proterozoic crystalline rocks or drainage may have followed planar faults and fractures within the basement rocks. Steven and others (1997) noted that these Miocene drainages cross the preexisting Oligocene drainages of the White River Group at a high angle and indicate regional post-Oligocene tilting of the Front Range block toward the east and northeast (that is, due to uplift south and west of this locale). Middle to late Miocene uplift and erosion of the modern Front Range and Laramie Mountains are recorded by the Miocene sand, gravel, and conglomerate of the Ogallala Formation (about 17 Ma to 6 Ma; Izett, 1975).

These high-level (high in the landscape) gravel deposits have been interpreted as paleovalley backfill along Oligocene to Miocene rivers that carried sediment to the alluvial fan complex of the Ogallala Formation (No) on the eastern plains of Colorado and Wyoming (Blackstone, 1975 ; Tweto, 1975; Scott and Taylor, 1986; Steven and others, 1997). The paleovalleys (North Fork Cache la Poudre paleovalley, Cache la Poudre paleovalley, and Buckhorn paleovalley on fig. 12) within the mountain blocks appear to grade close to the upslope limit of the preserved Ogallala, and the clast compositions are similar in the two deposits, but gravels as young as Pliocene not differentiated within the poorly exposed deposits may obscure any direct correlations. Absolute timing of most of these deposits remains highly uncertain. The gravel deposits on Green Ridge are interbedded with 28 Ma rhyolite ash-flow tuff, whereas the Ogallala is dated by faunal remains as about 17 Ma to about 5 Ma (Izett, 1975). The base of the gravelly deposits is likely to be time-transgressive from higher (older) to lower (younger) landscape positions and the drainage pattern may have evolved over a considerable span of time.

In any event, the modern stream courses of the Cache la Poudre drainage and (possibly) Buckhorn Creek probably developed on an aggraded alluvial surface linked to the Ogallala Formation on the Colorado Piedmont. The modern drainage displays significant, kilometer-scale meandering paths, even where the river flows through deep canyons cut into the Proterozoic basement (for example, the Big Narrows of the Cache la Poudre River along the northern edge of the Cache la Poudre Wilderness). Such large meanders suggest the drainage path was established on a low- to moderate-gradient surface prior to incision into the basement rock (Steven and others, 1997). The late Miocene to Pliocene alluvial surface of the Ogallala Formation probably merged with the Sherman surface in the Laramie Mountains straddling the state line where the Sherman Granite was deeply weathered to a uniform feldspathic grus (see summary in Eggler, 1973; Blackstone, 1975).

Erosion has dominated Front Range geomorphology since the end of Ogallala Formation deposition in middle Miocene (Blackstone, 1975; Steven and others, 1997; Leonard, 2002). The main drainages tied to the South Platte River removed almost all of the Oligocene and Miocene deposits east of the Continental Divide on the Colorado Piedmont (Steven and others, 1997). This erosion was certainly triggered in part by renewed uplift of the area. Cross-sectional forms of present canyons through the Proterozoic basement rocks show that the most recent deepening has occurred rapidly, leading to very steep inner-canyon walls (Bolyard, 1997; Steven and others, 1997). The entrenched meanders show that the rapid incision (post 5 Ma) did not allow time for streams to adjust to contrasts in canyon-wall fabric or rock types. Analysis of depositional gradients for the Ogallala Formation in the area immediately north of the Fort Collins quadrangle indicates that this part of the Colorado Piedmont has been tilted eastward since Ogallala deposition, due primarily to tectonic uplift of the Front Range and to lesser flexural rebound related to incision (McMillan and others, 2002).

The accelerated erosion during Pliocene time may also reflect the marked change to a cooler, wetter climate following the Miocene (Molnar and England, 1990; Crowley and North, 1991; Krantz, 1991; Bluemle and others, 2001). However, most studies conclude that climate-induced accelerated stream power alone is insufficient to explain the incision. Leonard (2002) examined the Pliocene and Quaternary incision of the North and South Platte River drainages and concluded that both tectonic uplift and flexural adjustment to erosion were required to account for the gradients of modern streams and post-depositional warping of the Ogallala.

Pliocene and younger faults that might have accommodated this tectonic uplift of the Front Range core have not been positively identified. Steven and others (1997) suggest that the Pliocene uplift involved diffuse adjustments in irregular fault-bounded blocks within the main ranges. North-trending fault zones in the upper Laramie River valley (Laramie River fault zone, fig. 12) may have also undergone Pliocene-Quaternary displacement, but more detailed study is necessary to test this possibility.

Economic Geology

The geologic resources of the Fort Collins quadrangle have supported commercial development and economic growth over the years. The mountain regions contain deposits of precious metals that were explored in the late 1800s, and diamonds have been recovered from kimberlite bodies along the Colorado-Wyoming State line in the last several decades. The foothills hogback zone has been extensively quarried for various rock and stone products over the years. The Denver-Cheyenne Basin area has been explored and developed for substantial resources of coal, oil, and natural gas. The valleys of the major rivers and streams have all produced substantial quantities of sand and gravel for building materials, and will continue to do so in the foreseeable future. Above all, water has been the most heavily developed natural resource of the region.

Manhattan District

Early Tertiary intrusive rocks (Pedp, Peap, and Peio) emplaced during the latter part of the Laramide orogeny provided heat sources and hosts for several minor mineral deposits in the Manhattan District north of Rustic (summarized from Pearson and others, 1981). Similar small-vein systems were explored southwest of the main district identified as the Home and Mayesville Districts located just west of Rustic along the Cache la Poudre River. Most of the weak mineralization consists of quartz veins with pyrite, chalcopyrite, and galena that show modest enrichment in gold. Very little ore was produced and most activity had ceased by 1900.

Diamonds of the State-Line Kimberlite District

Neoproterozoic and Devonian kimberlite pipes (DZk) have been found at several localities within the Proterozoic basement rocks west of Virginia Dale. Diamonds were first discovered in the kimberlite breccia in the 1970s and commercial-scale processing began in the 1990s. This area is known as the State Line District and it includes kimberlite pipes in northern Colorado and southern Wyoming, and is comprehensively summarized by Hausel (1998). More than 130,000 industrial-grade stones were recovered, as were several gem-quality diamonds larger than 28 carats raw weight. The largest mine at Kelsey Lake, about 14 km northwest of Virginia Dale, operated a mill between 1996 and 1999, and recovered nearly 1,000 carats of industrial and gem-quality diamonds. Operations had ceased by 2006.

Coal, Oil, and Gas

The marine deposits of the Cretaceous Western Interior Seaway contain abundant carbonaceous debris that serve as source rocks for significant hydrocarbon deposits of the region. Oil and gas resources in the Denver Basin are described and summarized by Higley and Cox (2005), and coal resources in the same area were summarized by Roberts (2005). Both reports form the primary sources for the following summary; additional information and extensive bibliographies are contained in these summary reports.

More than 245 million barrels of oil (MMBO) and more than 2.2 trillion cubic feet (TCFG) of natural gas have been produced by about 2,000 wells in the Denver Basin since early development began in the late 1800s. The principal source rocks are in the middle part of the South Platte Formation (upper Dakota Group, Kd) as well as the shaly formations of the Benton Group (Kbm) between the Dakota Group and the Niobrara Formation. Hydrocarbon production is greatest from sandstone bodies within the Dakota Group, at the base of the Niobrara Formation, and within the Upper Cretaceous Pierre Shale. The high rates of subsidence and sedimentation within the Denver Basin during Late Cretaceous time led to burial, heating, and the subsequent generation of oil and gas.

Most of the oil and gas production in the Denver Basin comes from the Muddy Sandstone (upper Dakota Group; equivalent to the first sandstone member of the South Platte Formation), also known in the petroleum literature as the “J” sandstone. It is well confined above and below by shale formations (both significant source rocks) and its high permeability enhances production. Traps are a combination of stratigraphic pinch-outs, up-dip stratigraphic truncations, and numerous anticlinal structural traps within the Laramide folds adjacent to the Front Range uplift. Oil- and gas-producing wells in the Fort Collins quadrangle are limited to the area west of Wellington where anticlinal folds provide the structural traps.

Minor coal was mined in this area between 1897 and 1942 from thin beds in the Laramie Formation.

Limestone and Gypsum

Limestone is extensively quarried for cement manufacture in the foothills hogback belt between Laporte and Livermore. These operations primarily exploit the Fort Hays Limestone Member of the Upper Cretaceous Niobrara Formation (Kn) and limestones within the Lower Permian Ingleside Formation (Pi).

Gypsum is interbedded at several stratigraphic levels within the Lower Triassic and Upper Permian Lykins Formation (TRPl) in the northeastern part of the Fort Collins quadrangle. Small-scale quarry operations have extracted gypsum stone over the years in the area near Table Mountain west of Wellington.

Gypsum, in the variety known as alabaster, is present in thick blocks and well-crystallized veins within the Lykins Formation. Alabaster has been quarried discontinuously for several decades by artisans in the Fort Collins area and fashioned into decorative and utilitarian objects on a small scale.

Sand and Gravel

Quaternary floodplain and fluvial terrace deposits of sand and gravel have been widely developed in the eastern part of the quadrangle for construction materials (Schwochow and others, 1974). The youngest terraces (Holocene valley-floor alluvium [Qa] and Broadway Alluvium [Qb]) have been most thoroughly developed because the clasts are freshest and post-depositional soils are relatively thin. Sand and gravel quarries are common along the floodplain of the Cache la Poudre River. Extensive sand and gravel deposits are present in the Laramie River valley, but currently they are too distant from markets to be economic.

Quarry Stone

Several quarries have been opened in the foothills hogback belt east of the Front Range to exploit resources of dimension stone and flagstone for building materials and landscaping rock. Sandstone of the Dakota Group (Kd) is quarried in a few locations along the range front where it hosts abundant lichen that produce an aesthetically pleasing appearance referred to as “moss rock.” Sandstone from the Ingleside Formation is crushed and sold for road ballast and landscaping purposes.

Proterozoic crystalline rock is quarried at a few sites in the area where it is crushed and sized, for example, along the Red Feather Lakes road west of Livermore. This material is chiefly for road base, rip-rap, and landscape dimension stone.

Water

The earliest western settlers in this region recognized that water was a critical commodity to develop and control. Some of the earliest development projects in this region were ditch systems and reservoirs constructed by settlers during the post-1849 California gold-rush migration. Every major stream that issues from the mountain front is diverted at numerous levels in privately owned ditches that convey the spring and summer flow to agricultural lands on the Colorado Piedmont.

Further water development began in the high mountain valleys during the late 1800s and early 1900s. These projects constructed dams, reservoirs, and conveyances for the purpose of storing winter snowpack so that meltwater could be released during the middle and late summer for irrigation on the piedmont (Cole, 2004a; Cole and Braddock, 2009, p. 46-47).

Local cities own most of these systems to provide fresh-water resources for their municipalities. The City of Fort Collins obtains some of its water from the North Platte River system by diversion of flow in the Michigan River headwaters just south of Cameron Pass. The Michigan Ditch conveys spring runoff to Cameron Pass and then to Joe Wright Creek that is operated to control summer-season flow for the city. The city also operates Eaton Reservoir and Halligan Reservoir on the North Fork Cache la Poudre River for seasonal water storage.

The City of Greeley also obtains North Platte River water by trans-mountain diversion. The Skyline Ditch system in the upper Laramie River valley conveys spring runoff to the Laramie-Poudre Tunnel (constructed 1909–1911) and then to the main branch of the Cache la Poudre River approximately 7 km southwest of Kinikinik. The City of Greeley also owns and operates six mountain reservoirs: Milton Seaman, Barnes Meadow, Peterson Lake, Comanche, Hourglass, and Twin Lakes Reservoirs.

Both municipalities obtain substantial water from the Colorado-Big Thompson (C-BT) Project, administered by the U.S. Bureau of Reclamation. The project was constructed in stages between 1938 and 1957 to meet numerous needs in northern Colorado (see Cole and Braddock, 2009, p. 46–47). It collects and diverts water from the Colorado River headwaters west of the Continental Divide and transmits it through the 21-km (13 mi)-long Alva B. Adams tunnel beneath Rocky Mountain National Park to a distribution system along the Big Thompson River drainage on the eastern slope. The C-BT Project spans 241 km (150 mi) of waterways and includes 12 reservoirs, 56 km (35 mi) of tunnels and siphons, and 6 hydroelectric power plants (Cole, 2004a). The project provides municipal water for 30 communities east of the Continental Divide and irrigation water for approximately 2,490 km^2 (615,000 square acres) along the Big Thompson, Cache la Poudre, and South Platte River drainages.

Environmental Geology

Geology is a fundamental consideration when any part of the landscape is evaluated for a particular use. The geology of the Fort Collins quadrangle is both diverse and complex. Different aspects of geology and topography are important in both the relatively populated areas of the Colorado Piedmont and the less populated, but frequently visited mountainous terrain.

This section of the report summarizes some of the geologic processes and conditions that can pose hazards in this area. This section of the report is not intended to be comprehensive, but rather to present geologic factors that have historically led to hazards or damage when they were ignored. Much of the information in this section regarding landslides and expansive soils is summarized from a 2004 field-trip guide covering environmental geology of the Denver metropolitan area (Abbott and Noe, 2004) and from several papers referenced in that guide. The Colorado Geological Survey has also published several papers and booklets on geologic hazards that are especially pertinent (Soule and others, 1976; Noe, 1997; Noe and Dodson, 1997; Noe and others, 1997, 1999).

Landslides and Rockfalls

Landslides occur in several geologic settings in the Fort Collins quadrangle. The large-scale block-glide landslide complexes of the Dakota Group strata (Braddock, 1978) were described previously in the section on "Post-Laramide Structures," most are believed to be inactive, although excavation of the toe areas could lead to further earth movement. Mountain landslides involving Proterozoic crystalline rocks are known from the upper Laramie River valley and the southernmost Medicine Bow Mountains (Kellogg, Ruleman and others, 2008).

Landslides and slumps occur on the slopes below the Oligocene rhyolitic volcanic rocks in the southwestern corner of the quadrangle, perhaps due to underlying clay-rich, Tertiary sediment of the White River Group.

Rockfalls are fairly frequent in mountain canyons and disrupt and damage highways and trails. They are most common during the spring and summer months when rainfall and snowmelt raise the local water table. This increases soil pore-water pressure and can cause unstable rock masses to slide and fall.

Expansive Soils

Clay-rich expansive or swelling soils in the Colorado Piedmont section of the Fort Collins quadrangle have caused damage to foundations, structures, and roads due to expansion and contraction resulting from wetting and drying. Flat-lying and gently inclined beds of the Pierre Shale are most susceptible to this process due to the presence of zones rich in expansive clays. More steeply inclined beds are susceptible to bedrock heaving due to vertical variations in expansive clays within the section. Of particular concern are the lower (Kpl), middle (Kpm), and upper (Kpu) shale members which contain discrete bentonite layers as well as significant bentonitic claystones. The intervening sandstone-rich layers of the Pierre Shale (Kph and Kpr) pose a much lower risk. The Morrison Formation (Jm), Benton Group (Kbm), and Smokey Hill Shale Member of the Niobrara Formation (Kn) also pose moderate risk but development on these units is very sparse within the map area. Experience during the last 40 years has shown that these conditions can be mitigated with engineered systems in most cases, and all county building departments require soil testing and appropriate mitigation for new construction in areas east of the foothills hogback belt.

Floods

The mountainous terrain of the Front Range is drained by major rivers that flow through deeply incised, narrow canyons from about 1,676 m to 2,743 m (5,500 to 9,000 ft) elevation. Major summer thunderstorms concentrate their most intense rainfall between elevations of about 2,134 m to 2,743 m (7,000 to 9,000 ft) due to orographic conditions, and so the potential for mountain-valley flash flooding is both high and persistent (Cole, 2004a). Buckhorn Creek and the South Fork and main stem of the Cache la Poudre River are uncontrolled below this potential high-rainfall zone down to the mouth of the canyons where they empty onto the Colorado Piedmont. The North Fork Cache la Poudre River is controlled by Halligan Reservoir and Seaman Reservoir, but the terrain along the North Fork is neither as high nor as steep as the terrain farther south in the quadrangle (thus, less susceptible to orographically enhanced rainfall).

The City of Fort Collins has undergone occasional minor to severe flooding through the years (following information summarized from City of Fort Collins website, accessed May 2008 at http://www.fcgov.com). Although the Cache la Poudre River flows along the northeast side of the old historic downtown area, most of this area has escaped significant damage because it sits on Slocum Alluvium, 10 to 30 ft above the floodway. The original Camp Collins was located on the floodway and was largely destroyed in 1864 when a severe spring rainstorm in the mountains caused a major flood surge that swept through the mountain canyon and discharged through Laporte and the settlers′ colony. A similar spring flood (caused by heavy mountain rain combined with rapid snowmelt) in 1904 also swept away numerous structures that had been built in the floodway.

The flood of June 9, 1891, initiated by the failure of one of the dams that impounded Chambers Lake, may have affected developed areas of Fort Collins. This flood destroyed bridges across the Cache la Poudre River between the junction with Joe Wright Creek and Fort Collins. Very fresh, boulder alluvium deposited during this flood now underlies the area that is now Aspen Glen Campground along Colorado State Highway 14 in the Roosevelt National Forest.

Subsequent flooding events affected developed areas of Fort Collins in 1938, 1951, 1977, and 1992, and were caused by the heavy rains of persistent and slow-moving summer storms in the piedmont area, not in the mountains. The 1997 Spring Creek flood was one of the most damaging of these piedmont-storm events. Heavy rain on the night of July 27 (about 100 mm to 150 mm or 4 to 6 inches [in]) was followed by nearly 254 mm (10 in) of rain during a 5-hour span on the night of July 28, and the resulting discharge in Spring Creek exceeded the estimated 500-year event by more than 30 percent.

Every major stream on the east slope of the Front Range has undergone moderate to significant flooding at one time or another in recorded history and the likelihood of future flooding is high. As modern development encroaches further on floodplains and floodways, the potential for damage continues to rise.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

[Surficial deposits in the Fort Collins quadrangle record the alluvial, mass-movement, glacial, and eolian processes during the Quaternary and late Neogene. Many of the surficial deposits in these areas are poorly exposed. Deposits that are of limited extent (less than about 200 m wide), including (1) small earth-fill dams, (2) waste rock, commercial rock products, and fill material at quarries such as near La Porte and Livermore, and (3) small organic-rich deposits (Qo) in glaciated areas, were not mapped. Also, thin deposits (less than about 1.5 m thick), including (1) some mass-movement deposits above treeline (such as block-stream and some block-slope deposits) and (2) some sheetwash deposits (Qsw) that locally mantle gently sloping bedrock and surficial map units, were not mapped.

Most of the surficial units on this map are informal allostratigraphic units (discontinuity-bound sequences) of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005), whereas the other Phanerozoic bedrock units are informal or formal lithostratigraphic units. For this reason, subdivisions of stratigraphic units use time terms “late” and “early” where applied to surficial units, but use position terms “upper” and “lower” where applied to lithostratigraphic units. Formal names used for fluvial and pediment deposits east of the mountain front are those established by Scott (1960, 1963). Tentative correlation of surficial deposits east of the mountain front with those formally established by Scott in the Denver area is based on the mapping of Colton (1978) near Fort Collins and on relative height above present stream level, physical properties, and genesis in the piedmont north of Fort Collins determined by Shroba.

A fractional map symbol (No/Na) is used on the cross sections where individual units are too thin to show separately. The units occur from top to bottom as listed. This fractional unit is not described here; instead refer to descriptions of individual units. Fractional map units are not shown on the Correlation of Map Units diagram on the map sheet.

Informal names (such as terrace alluvium of Pinedale age, Qgp, and pediment deposits) are applied to fluvial and pediment deposits in the Laramie River valley and in other areas west of the mountain front.

The mapped distribution of surficial units on the Round Butte, Buckeye, Wellington, Crazy Mountain, Glendevey, and Rawah Lakes 7.5' quadrangles and parts of the Deadman, Kinikinik, Boston Peak, Chambers Lake, and Fort Collins 7.5' quadrangles is based primarily on interpretation by Shroba of 1:40,000-scale, black-and-white aerial photographs (NAPP, National Aerial Photography Program images accessed in 1999 at https://lta.cr.usgs.gov/NAPP) . Surficial deposits in other areas are compiled from existing mapping (fig. 4). Age assignments for surficial deposits within the quadrangle are based chiefly on the relative degree of modification of inferred original surface morphology and relative heights above present stream channels. Degree of soil development and clast weathering were used to distinguish till of Pinedale age (Qtp) from till of Bull Lake age (Qtb). Soil-horizon designations are based on those of the Soil Survey Staff (1999) and Birkeland (1999).

Grain or particle sizes of surficial deposits are field estimates. Size limits for sand (0.05–2 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) are those of the Soil Survey Staff (1951). In descriptions of surficial map units, the term “clasts” refers to granules and larger particles (>2 mm in diameter), whereas the term “matrix” refers to sand and finer particles (≤2 mm in diameter).

In this report, the terms “alluvium” and “alluvial” refer to material transported by running water confined to channels (stream alluvium) as well as by running water not confined to channels (sheetwash). The term “colluvium” refers to all rock and sediment transported downslope chiefly by gravity (Hilgard, 1892; Merrill, 1897). Colluvial material on slopes is transported chiefly by mass-movement (gravity-driven) processes—such as creep, sliding, debris flow, and rock fall—locally aided by sheetwash.

Surficial map units that include debris-flow deposits probably also include hyperconcentrated-flow deposits. These latter deposits are intermediate in character between stream-flow and debris-flow deposits (Pierson and Costa, 1987; Meyer and Wells, 1997).

In this report the terms “soil” and “soils” refer to pedogenic soils formed in surficial deposits (for example, Birkeland, 1999)]

ARTIFICIAL-FILL DEPOSIT

af **Artificial-fill (latest Holocene)**—Engineered, compacted fill material composed of rock fragments and finer material in four large earth-fill dams at Horsetooth Reservoir near Fort Collins, and in three smaller earth-fill dams at Eaton, Panhandle, and Long Draw Reservoirs in the western part of the map area. Estimated thickness is 3–60 m

ALLUVIAL DEPOSITS

Qa **Valley-floor alluvium (Holocene)**—Sand and gravel in stream channels as well as sand, sandy and clayey silt, and gravel underlying floodplains and adjacent low terraces less than 4.5 m above major streams and their major tributaries east of the foothills hogback belt of the Front Range. Unit includes post-Piney Creek alluvium and Piney Creek Alluvium (Colton, 1978). The younger alluvium commonly lies within stream channels cut in the older alluvium. Unit Qa locally includes small fan deposits (Qf) and sheetwash aprons (Qsw) along the margins of major valleys, and overlies Broadway Alluvium (Qb) in major valleys. The abundance of silty and clayey sediment, particularly along Boxelder Creek and its major tributaries, suggests that unit Qa was derived in part from sediments eroded from silty and clayey bedrock units such as the Pierre Shale and probably from loess deposits (Qlo). Low-lying deposits are prone to periodic stream flooding. Estimated thickness is 1–5 m

Qva **Mountain valley alluvium (Holocene and late Pleistocene)**—Pebbly to bouldery gravel, sand, and minor deposits of silty alluvium in stream channels, floodplains, and low terraces along courses of major and tributary streams in the mountains west of the foothills hogback belt and along the Laramie River near the northwest corner of the quadrangle. Unit Qva locally includes outwash deposits (Qgp) downstream from till of Pinedale age (Qtp), small fans deposits (Qf) and minor deposits of colluvium (Qc) along valley margins, as well as organic-rich sediments (Qo) in bogs, fens, marshes, and meadows. Deposits of unit Qva, near cirques in the Medicine Bow Mountains, locally may include outwash deposits of post-Pinedale age. Unit is chiefly present along the Cache la Poudre River, Laramie River, and their tributaries. Outwash deposits are a potential source of coarse aggregate. Low-lying deposits are prone to periodic flooding. Estimated thickness is 3–9 m

Qsw **Sheetwash alluvium (Holocene and late Pleistocene)**—Mostly slightly pebbly to pebbly, slightly silty to silty sand that is commonly deposited on gentle slopes. Low-lying areas of unit Qsw are susceptible to sheet flooding due to unconfined overland flow, and locally to stream flooding and gullying. Recently disturbed areas of unit Qsw may be susceptible to minor wind erosion. Estimated thickness is 1–4.5 m

Qb **Broadway Alluvium (late Pleistocene)**—Mostly cobbly pebble gravel and pebble gravel in terrace and valley-fill deposits along the Cache la Poudre River and its major tributary streams east of the foothills hogback belt. Deposits of unit Qb underlie unit Qa in floodplains along major streams as well as terraces about 7.5 m above the Cache la Poudre River and about 3–7.5 m above major tributary streams. Unit Qb also forms gravelly alluvial aprons along Sand Creek and the upper reaches of Rawhide Creek and Spottlewood Creek, near the northeast corner of the quadrangle. Deposition is considered to be broadly coeval with Pinedale glaciation, about 30–12 ka (Madole and Shroba, 1979; Nelson and others, 1979; Madole, 1986, 1991). The upper part of the Broadway probably was deposited after Pinedale-age glaciers reached their maximum extent about 21 ka (Madole, 1986), and ceased deposition by about 10–11 ka (Holliday, 1987). Unit Qb may be locally overlain by thin, unmapped loess deposits (Qlo). Unit Qb in the floodplain of the Cache la Poudre River near Fort Collins is a major source of coarse aggregate. Thickness of valley-fill deposits beneath unit Qa in the Cache la Poudre River valley is typically 3–6 m (Schwochow and others, 1974); estimated thickness of terrace deposits along the Cache la Poudre River and Boxelder Creek near Fort Collins is 7.5–15 m

Qgp **Terrace alluvium of Pinedale age (late Pleistocene)**—Fluvial deposits composed chiefly of cobbly pebble gravel rich in granitic clasts. Deposits underlie one and locally two terraces and terrace remnants about 3–6 and 12–15 m above the Laramie River downstream of Four Corners; about 9 m above McIntyre Creek downstream of Glendevey; about 3–6 m above Joe Wright Creek downstream of Chambers Lake; about 3–12 m above the Cache la Poudre River downstream of the confluence with Joe Wright Creek; and about 12 m above the Michigan River and North Fork Canadian River near the southwest corner of the map area. The proximity of moraines composed of till of the Pinedale glaciation (Qtp) to terraces underlain by unit Qgp suggests that much of unit Qgp is outwash deposited by glacial meltwater during the Pinedale glaciation, about 12–30 ka (Nelson and others, 1979; Madole, 1986; Schildgen and others, 2002; Benson and others, 2004, 2005, 2007). Deposits along Cache la Poudre River downstream of Kinikinik, and probably those along the Laramie River and McIntyre Creek, locally include alluvium derived from tributary drainages that were not glaciated, but probably were subject to periglacial processes. Unit Qgp locally includes small bodies of valley-floor alluvium (Qva) and till of Pinedale age (Qtp) as well as sheetwash alluvium (Qsw) and fan deposits (Qf) along valley margins. Unit also includes bouldery flood gravel along Joe Wright Creek that is too narrow to map separately. The gravel contains boulders as large as 120×140×210 cm^3, and may have been deposited during the flood of June 9, 1891, that flowed from the failed dam at Chambers Lake. Deposits of unit Qtp are a potential source of coarse aggregate. Estimated thickness is 3–15 m; possibly as much as 90 m on the up-valley sides of Pinedale terminal moraines (Madole and others, 1998)

Qgb **Terrace alluvium of Bull Lake age (late and middle Pleistocene)**—Fluvial deposits composed chiefly of bouldery to slightly bouldery, cobbly pebble gravel rich in granitic rocks of the Rawah batholith (XgR) that underlies terrace remnants along the Laramie River and locally along McIntyre Creek near the northwest corner of the quadrangle. Terrace remnants are about 37–43 m above the Laramie River downstream of Four Corners. Terrace remnants along McIntyre Creek are about 30 m above stream level downstream of Glendevey. A few terrace remnants along the Cache la Poudre near Stove Prairie Landing are about 24–40 m above stream level. Deposits of unit Qgb are about 30 m above the North Fork Canadian River near the southwest corner of the map area. Deposits along the Laramie River near the down-valley limit of glaciation contain boulders about 30–70 cm in diameter. Large pebbles, cobbles, and boulders commonly are subangular to subrounded. Deposits 5.5 km farther downstream near Four Corners are composed of cobbly pebble gravel that contains lenses of slightly bouldery gravel. The proximity of moraines composed of till of the Bull Lake glaciation (Qtb) to terrace remnants underlain by unit Qgb suggests that much of unit Qgb is outwash deposited by glacial meltwater during the Bull Lake glaciation (about 120–170 ka; Sharp and others, 2003; Pierce, 2004). Unit Qgb is a potential source of coarse aggregate. Estimated thickness is 3–15 m

Qg **Gravelly stream alluvium (late and middle Pleistocene)**—Small deposits of poorly sorted and poorly to well stratified stream gravel and probably finer-grained sediment in valleys, west of the Dakota hogback, in the eastern part of the map area. Clasts are commonly of Precambrian rock, but locally are derived from nearby sedimentary rocks; many of the clasts are weathered. Calcium carbonate cement is locally abundant (Braddock, Wohlford, and Connor, 1988; Courtwright and Braddock, 1989). Deposits near Table Mountain are about 18 m and locally 24 m above Boxelder Creek and about 12 m above some of its tributary streams. Deposits west of Livermore, Colo., are about 24 m and 37 m above the North Fork Cache la Poudre River and about 24, 37, 60, and 85 m above some of its tributary streams. Unit locally includes fan deposits (Qf) and pediment deposits (Qp). Deposits of unit Qg are a potential source of fill and road subbase material. Estimated thickness is 3–15 m

Qs **Slocum Alluvium (middle Pleistocene)**—Unit was deposited by streams and probably locally by debris flows in the piedmont east of the foothills hogback belt where it commonly consists of widespread deposits of slightly cobbly, pebble gravel interbedded with pebbly sand and slightly pebbly silty sand. The Slocum consists of pediment and valley-fill or terrace deposits at two levels. Lower (younger) deposits are commonly pediment deposits about 9–15 m above stream level. Higher (older) deposits are pediment and valley-fill or terrace deposits about 15–18 m above stream level. The latter deposits typically cap small hills. Slocum Alluvium in the Denver area is considered to be about 240 ka (Madole, 1991), based on a uranium-series age of 190±50 ka near Canon City, Colo. (Szabo, 1980). Terrace or valley-fill deposits of unit Qs are a potential source of fill and road subbase material. Estimated thickness is 2–9 m

Qv **Verdos Alluvium (middle Pleistocene)**—Unit was deposited by streams and probably locally by debris flows in the piedmont east of the foothills hogback belt where it consists of non-cobbly to very slightly cobbly, pebble gravel. Locally, the gravel is interbedded with pebbly sand and slightly pebbly silty sand. Unit Qv consists of pediment and, locally, valley-fill or terrace deposits at one and locally two levels. Lower (younger) deposits are about 34–37 m above stream level and a small, higher (older) deposit east of Rawhide Creek is about 45 m above stream level. Beds and lenses of water-laid Lava Creek B tephra (about 640 ka; Lanphere and others, 2002) are present at several localities in the Denver area. The tephra locally occurs at the base of higher (older) pediment deposits of Verdos Alluvium (Scott, 1963), and is present within or at the top of higher (older) main-stream fluvial deposits of the Verdos in and near Denver (Hunt, 1954; Scott, 1972; Baker, 1973; Van Horn, 1976; Kirkham, 1977). Terrace or valley-fill deposits of unit Qv are a potential source of fill and road subbase material. Estimated thickness is 2–9 m

ALLUVIAL AND MASS-MOVEMENT DEPOSITS

Qac **Alluvium and colluvium, undivided (Holocene to middle? Pleistocene)**—Chiefly undifferentiated valley-floor alluvium (Qa), mountain-valley alluvium (Qva), sheetwash alluvium (Qsw), fan deposits (Qf), colluvium (Qc), and locally other mass-movement deposits along minor streams and on adjacent lower (toe) slopes. Low-lying areas of unit adjacent to stream channels may be subject to periodic stream flooding and debris-flow deposition. The adjacent toe slopes may be susceptible to local sheet flooding due to unconfined overland flow, and locally to gullying. Estimated thickness is 3–15 m

Qsc **Sheetwash alluvium and colluvium, undivided (Holocene to middle? Pleistocene)**—Thin mantle composed chiefly of slightly pebbly to pebbly, silty sand and sandy silt that overlies the North Park Formation (N₱n) in the Laramie River valley near Glendevey. Unit Qsc locally includes small outcrops of the North Park Formation (N₱n), and locally may include pebbly lag deposits. Deposited chiefly by unconfined overland flow on gentle slopes and by mass-movement processes on moderate slopes. Low-lying areas of unit are susceptible locally to sheet flooding due to unconfined overland flow, and locally to stream flooding and gullying. Estimated thickness is 1–1.5 m

Qf **Fan deposits (Holocene and late Pleistocene)**—Mostly poorly sorted, slightly bouldery pebble and cobble gravel and locally pebbly and cobbly silty sand. Deposited chiefly by streams and debris flows in fan- and tongue-shaped accumulations near base of moderate to steep slopes along valley sides west of the foothills hogback belt where unit commonly overlies unit Qgp. Lower limits of deposits are about 3–12 m above stream level. Unit locally may include sheetwash alluvium (Qsw), colluvium (Qc), and probably hyperconcentrated-flow deposits. Low-lying areas on the unit may be subject to stream flooding and debris-flow deposition. Estimated thickness is 3–9 m

Qp **Pediment deposits (late and middle Pleistocene)**—Gravelly and sandy alluvium that overlies gently sloping surfaces cut on sedimentary rocks in the foothills hogback belt and locally on sedimentary rocks and granite in the mountains. Unit Qp also includes gravelly alluvium and debris-flow deposits that overlies gently sloping surfaces cut on sediments and sedimentary rocks in the Laramie River valley. Deposits consist chiefly of crudely stratified and non-sorted to poorly sorted, clast- and locally matrix-supported sediment. Deposits southeast of Virginia Dale are composed chiefly of slightly cobbly, pebble gravel that contains abundant granules and resembles grus weathered from the Sherman Granite (Eggler and others, 1969; Braddock, Eggler, and Courtright, 1989). Deposits north of Eaton Reservoir that overlie the Sherman Granite (YgSH) are composed of granite-rich pebble gravel and pebbly sand derived from the Sherman Granite. Those that overlie the Fountain Formation (PIPf) are composed of arkosic, conglomerate- and sandstone-rich gravel and pebbly sand derived from the Fountain Formation. Deposits north of Bull Mountain are composed of sandstone-rich gravel and non-pebbly to pebbly silty sand. Deposits in the Laramie River valley are composed of non-bouldery to slightly bouldery, cobbly, pebble gravel as well as matrix-supported small boulders to granules. Bouldery debris-flow deposits locally contain sandstone casts eroded from the Dakota Group (Kd) that are as large as 30×45×45 cm^3. Unit Qp locally may include small unmapped bodies of sheetwash alluvium (Qsw), colluvium (Qc), and probably hyperconcentrated-flow deposits. The approximate heights above stream level of the lower (downslope) limits of pediment deposits are 37 m near Virginia Dale, 18 m near Eaton Reservoir and Bull Mountain, and 12–18, 37–55, and 64–73 m above stream level in the Laramie River valley as it flows northward near the northwest corner of the quadrangle. Deposits near their lower limits in the Laramie River valley may be graded to, and locally may include, fluvial gravel deposited by the Laramie River. Low-lying areas on unit Qp may be subject to stream flooding and locally to debris-flow deposition. Estimated thickness is 1–4.5 m

MASS-MOVEMENT DEPOSITS

Qc **Colluvium (Holocene to middle? Pleistocene)**—Non-sorted deposits that consist of clay, silt, sand, and clasts that range in size from granules to large boulders, formed by a variety of mass-movement processes. Unit Qc chiefly includes small deposits in and near the foothills hogback belt and on slopes in montane areas, as well as extensive areas of block-slope deposits near and above present day treeline at about 3,475 m where freeze-thaw action has promoted mass-movement and downslope transport. The composition of the deposits reflect that of the bedrock or sediment from which the colluvium was derived. Unit Qc includes material transported by frost creep, solifluction, nivation and other periglacial processes, sheetwash, landslide, debris flow, hyperconcentrated flow, and rock fall. Unit Qc locally includes small bodies of undifferentiated valley-floor alluvium (Qa), mountain-valley alluvium (Qva), pediment deposits (Qp), sheetwash alluvium (Qsw), landslide deposits (Qls), and talus deposits (Qta). Estimated thickness is 3–15 m

Qls **Landslide deposits (Holocene to middle? Pleistocene)**—Deposits of unsorted and unstratified debris, on slopes at or near the base of slopes. These deposits commonly have hummocky topography. Many of the landslides and landslide deposits form on unstable slopes that are underlain by shale, siltstone, and claystone near the eastern and western boundary of the quadrangle. An extensive hummocky mass west of Chambers Lake consists mainly of blocks of Proterozoic granite of Rawah batholith and is interpreted to be a landslide complex that likely blocked the Joe Wright Creek-upper Laramie River drainage (Kiver, 1968) and formed a large lake (at the present site of Chambers Lake) after the retreat of Pinedale ice upvalley of the landslide complex. The original dam formed by the landslide complex lead to diversion of Joe Wright Creek into the Cache la Poudre River system. Large landslide complexes flank the hogbacks west of Fort Collins and the margins of Bull Mountain near the northwestern corner of the quadrangle where the Dakota Group (Kd) sandstone caprock has slid over weaker, less competent sedimentary rock (Braddock and Eicher, 1962; Braddock, 1978; Courtright and Braddock, 1989). Younger landslide deposits are commonly bounded upslope by crescent-shaped headwall scarps (hachured line symbol) and downslope by lobate toes. The unit locally includes material displaced chiefly by rotational rockslides, rotational earth slides, debris slides, debris flows, earth flows, and earth slide-earth flows as defined by Varnes and Cruden (1996). Some deposits probably are formed by translational slides and rock or earth creep. The sizes and lithologies of the clasts and the grain-size distributions of the matrices of these deposits reflect those of the displaced bedrock units and surficial deposits. Landslide deposits are prone to continued movement or reactivation due to both natural and human-induced processes. Deposits on gentle slopes along and east of the foothills hogback belt locally include minor bodies of sheetwash (Qsw) and creep-deformed deposits. Deposits in the mountains locally include small rock-fall deposits. Some of the landslide deposits composed of material derived from the Dakota Group (Kd) on the east flank of the foothills hogback belt and the margins of Bull Mountain may be of middle Pleistocene age. Estimated thickness is 5–45 m

Qta **Talus deposits (Holocene to middle? Pleistocene)**—Large angular boulders and smaller rock fragments deposited chiefly by rock and snow avalanche, rock fall, rock slide, and debris flow at the base of cliffs and steep slopes where debris forms aprons, cones, and fan-shaped deposits. Unit locally includes rubbly scree deposits and probably tills of Holocene age near cirque headwalls (for example, Benedict, 1973a; Benson and others, 2007). Much of the talus in glaciated valleys and cirques postdates the retreat of Pinedale ice. Unit Qta is mapped chiefly in alpine and subalpine areas along the crest of the Medicine Bow Mountains and Never Summer Mountains, and in the upper part of the Cache la Poudre River valley upstream of Kinikinik. Small talus deposits adjacent or surrounded by colluvium (Qc) are mapped as colluvium. Estimated thickness is 3–15 m

GLACIAL DEPOSITS

Qr **Rock-glacier deposits (Holocene and latest Pleistocene)**—Lobate and tongue-shaped masses of boulder- to silt-sized rock debris that commonly have steep fronts, and flanks and form in cirques, along valley walls, and on valley floors above an elevation of 2,900 m commonly in areas of high talus production. Deposits consist of a veneer of angular boulders that overlies a thick mass of smaller debris. Rock material accumulated chiefly as talus that is mobilized downslope by flowage that is probably due to the deformation of interstitial ice or an ice core (Braddock and Cole, 1990). The lower part of the unit is ice cemented or has an ice core. Lobate rock glaciers form along valley walls, and are ice cemented. Tongue-shaped rock glaciers resemble glaciers, form on valley floors, and commonly have debris-covered ice cores (Benedict, 1973b; White, 1976). Ice-cemented rock glaciers likely formed under periglacial conditions (Barsch, 1987), whereas ice-cored rock glaciers probably are debris-covered glaciers (Janke, 2007). Inactive ice-cored rock glaciers commonly have depressions adjacent to headwall cliffs (where glacial ice melted), longitudinal marginal-and-central meandering furrows, and collapse pits. Ice-cemented rock glaciers commonly lack these surface features (White, 1976). Rock fragments on and within rock-glacier deposits are derived from steep slopes chiefly by rockfall and locally by sliding and avalanche. Unit Qr locally may include minor talus deposits (Qta) displaced by post-depositional creep or flowage, colluvium (Qc), other mass-movement deposits, and probably tills of Holocene age near cirque headwalls (for example, Benedict, 1973a; Benson and others, 2007). Many of the rock-glacier deposits in Colorado are of latest Pleistocene or early Holocene age (Meierding and Birkeland, 1980). Estimated maximum thickness is 45 m

Qtpp **Till of post-Pinedale age (latest Pleistocene)**—Non-sorted and non-stratified, ice-deposited angular boulders to granules in a sandy matrix that commonly forms two or more small moraines as much as 0.5–2.2 km beyond cirque headwalls (Kiver, 1968) at elevations as low as 3,220–3,415 m near present timberline on the east flank of the Medicine Bow Mountains. The unit probably is correlative with deposits that form the paired moraines of the Satanta Peak advance of Benedict (1973a, 1985) in the Arapahoe Pass area of the Front Range, about 50 km south of the quadrangle. Deposits of the Satanta Peak advance have minimum-limiting radiocarbon (^{14}C) ages of 9,915±380 years before present (before A.D. 1950 [B.P.]) and 9,700±215 yr B.P. (Benedict, 1973a), and probably date from 12–10 ka B.P. (Benedict, 1985). These deposits probably are coeval with glacial deposits formed during the Younger Dryas climatic event (11,000–10,000 ^{14}C yr B.P.) in northwestern North America and northern Europe (Menounos and Reasoner, 1997). Surface soils formed in deposits of the Satanta Peak advance have either thin (1525 cm) cambic (Bw) or argillic (Bt) horizons that contain 5–9 percent clay in the <2 mm-sized fraction (Birkeland and others, 1987). Unit locally may include till of Pinedale age (Qtp), talus deposits (Qta), and younger tills of late Holocene age. Deposits of unit Qtpp that are too small to map separately, such as those near Iceberg Lake, are combined with and mapped as till of Pinedale age (Qtp). Estimated thickness is 1.5–15 m

Qtp **Till of Pinedale age (late Pleistocene)**—Mostly non-sorted and non-stratified, subangular to subrounded boulders to granules in a silty sand to sandy silt matrix. Material <2 mm in diameter is estimated to be 20–50 percent of the unit. This matrix consists chiefly of poorly sorted sand and a minor to moderate amount of silt and clay. The unit locally may contain a significant amount of silt down valley of the Chambers Lake area where glaciers have eroded small, unmapped deposits that consist in part of weakly consolidated siltstone and sandstone that probably are of Oligocene age (Izett, 1975; Braddock and Cole, 1990). End moraines near the down-valley limit of glaciation are probably composed, in part, of outwash (Madole and others, 1998). Unit Qtp commonly forms large prominent, sharp-crested lateral and end moraines that are very bouldery and have distinct constructional morphology. Deposits locally have unfilled and undrained kettles, moraine-dammed lakes, and swamps (Braddock and Cole, 1990; Madole and others, 1998). Surface soils formed in till of Pinedale age (Qtp) have either thin (10–40 cm) cambic (Bw) or weakly developed argillic (Btj) horizons or they lack B horizons and have A/Cox profiles. Soil B horizons formed in till of Pinedale age in the Front Range, south of the map area, commonly contain 7–8 percent clay in the <2 mm-sized fraction (Shroba, 1977). Most of the biotite-rich granitic and gneissic clasts within the soil are unweathered and disintegrated clasts are rare. Unit locally includes deposits of stratified drift deposited by glacial meltwater, till of Bull Lake age, colluvium (Qc), other mass-movement deposits, and valley-floor alluvium (Qva); unit locally may include till of pre-Bull Lake age. As mapped in the Laramie River valley, unit Qtp includes deposits of younger and older till. The younger till forms terminal and lateral moraines south of Stubb Creek, 3 km southeast of Glendevey. The top of the outwash gravel graded to the younger till is about 3–6 m above the Laramie River. Deposits of older till form remnants of lateral moraines as much as 2.4 km down valley of the maximum down-valley extent of the younger till near Glendevey. The top of the outwash gravel graded to the older till is about 40 m above the Laramie River just downstream of the older till, but decreases in height to about 12–15 m above the Laramie River 8–19 km downstream of the older till. Radiocarbon and cosmogenic-exposure ages indicate that till of unit Qtp is about 12–30 ka (Nelson and others, 1979; Madole, 1986; Schildgen and Dethier, 2000; Benson and others, 2004, 2005, 2007). Much of the till of unit Qtp within the map area probably is similar in age. The older till of unit Qtp near Glendevey may be much older, because the higher outwash gravel graded to the older till (1) is substantially higher than the lower outwash gravel graded to the younger till and (2) the higher outwash lacks well preserved bar-and-channel topography characteristic of the lower outwash graded to the younger till. The older till near Glendevey may be correlative with an early advance of Pinedale ice about 34–47 ka (Sturchio and others, 1994), or it may be early Wisconsin in age (about 55–70 ka; Lisiecki and Raymo, 2005). During the Pinedale glaciation, the largest ice mass in the quadrangle formed in the headwaters of the Cache la Poudre River, Joe Wright Creek, and the Laramie River (Madole and others, 1998). The ice mass was as much as 600 m thick and flowed 45 km down the valley of the Cache la Poudre River to an altitude of about 2,325 m (Madole and others, 1998) and 23 km down the Laramie River valley to an altitude of about 2,540 m. Glaciers on the west flank of the Medicine Bow Mountains flowed about 2–7 km down-valley to altitudes of about 2,720–2,915 m. Estimated thickness is 1.5–30 m

Qtb **Till of Bull Lake age (late and middle Pleistocene)**—Mostly non-sorted and non-stratified, subangular to subrounded boulders to granules in a silty sand matrix. Material <2 mm in diameter estimated to be 20–40 percent of the unit. Unit Qtb commonly forms prominent lateral moraines that have rounded crests beyond the down-valley limit of till of Pinedale age (Qtp) in the Laramie River valley near Glendevey and south of Kelley Creek on the west flank of Medicine Bow Mountains. Undrained depressions are uncommon (Madole and others, 1998). Surface boulders typically are less abundant on moraines of the Bull Lake glaciation than on those of the Pinedale glaciation. Surface soils formed in till of

Bull Lake age (Qtb) have clay-enriched argillic (Bt) horizons that are thicker and contain more clay than those formed in till of Pinedale age (Qtp). Soil B horizons formed in till of Bull Lake age in the Front Range, south of the map area, commonly are 50 cm thick and contain 11–19 percent clay in the <2 mm-sized fraction (Shroba, 1977). Many of the biotite-rich granitic and gneissic pebbles and cobbles within the soil are weathered and are partly to completely disintegrated. ^{230}Th/U analyses that constrain the ages of glacio-fluvial deposits near the type area for the Bull Lake glaciation along the north flank of the Wind River Range, Wyo., and ages of glacial deposits near West Yellowstone indicate that the Bull Lake glaciation probably began prior to 167±6.4 ka (possibly 190 ka) and may have continued until about 122±10 ka (Sharp and others, 2003; Pierce, 2004). ^{10}Be and ^{26}Al analyses of surface boulders on moraines composed of till of Bull Lake age (Qtb) near Nederland, Colo., yielded minimum age estimates of 101±21 and 122±26 ka (Schildgen and others, 2002). These age estimates are in accord with a uranium-trend age estimate of 130±40 ka for till of Bull Lake age (Shroba and others, 1983) near Allens Park, Colo. Unit locally includes deposits of stratified drift deposited by glacial meltwater, till of Pinedale age (Qtp), colluvium (Qc), and other mass-movement deposits; near the down-valley limit of glaciation, unit locally may include till of pre-Bull Lake age that lacks depositional morphology. Ice during the Bull Lake glaciation flowed 24 km down the Laramie River valley to an altitude of about 2,530 m and 5 km down Kelley Creek valley to an altitude of about 2,780 m. The extent of ice during the Bull Lake glaciation in the valley of the Cache la Poudre River is unknown, but was less than that during the Pinedale glaciation. Estimated thickness is 1.5–15 m

ORGANIC-RICH DEPOSIT

Qo **Organic-rich sediment (Holocene and latest Pleistocene)**—Bog, fen, and marsh deposits associated with high or fluctuating water tables and frequent or continuous saturation in formerly glaciated terrain underlain by till of Pinedale age (Qtp) near the southwest corner of the quadrangle. Plant remains in these deposits are partly to completely decomposed. Unit Qo locally includes muck, peat, and organic-rich mud as well as layers of mineral-rich sediment. Peat and organic-rich mud locally overlie mineral-rich lacustrine or pond deposits. Organic-rich deposits are prone to significant compression under load owing to the very low density of organic material and high water content. Fen deposits in the Laramie River valley southwest of Boston Peak were studied during the 1980s as an example of sediment-hosted uranium deposits related to biological, geochemical, and hydrologic controls on the deposition of uranium from uranium-enriched ground waters (Schumann, 1990; Zielinski, 1990). Estimated thickness is 1–4.5 m

EOLIAN DEPOSIT

Qlo **Loess (late and late middle? Pleistocene)**—Non-stratified, well-sorted, wind-deposited, plastic to very plastic, sandy silt and locally sandy, clayey silt derived by wind erosion from floodplains and possibly Cretaceous bedrock sources by northwesterly or westerly paleowinds. Loess overlies deposits as young as Broadway Alluvium (Qb) near the northeast corner of the quadrangle. Deposits of sandy silt, too small to show at map scale, locally mantles Slocum Alluvium (Qs) on the west side of Boxelder Creek near Buckeye. Thin (≤50 cm) layers of pebbly, clayey, sandy silt that locally mantle other deposits of Slocum Alluvium (Qs) and Verdos Alluvium (Qv) in the piedmont east of the foothills hogback belt may consist in part of loess that that was mixed with the underlying gravelly alluvium by biotic processes. Deposits of unit Qlo locally reworked by unconfined overland flow contain a minor amount of coarse sand and granules, and locally a few pebbles. Unit Qlo locally may contain small deposits of silty eolian sand. Loess in northeastern Colorado records two episodes of deposition at about 20–14 ka and 13–10 ka (Muhs and others, 1999). Holocene loess is locally extensive in the eastern part of Colorado (Madole, 1995), but none has been recognized within or near the quadrangle. Unit Qlo locally overlies and locally may include deposits of older loess. These deposits of older loess are correlative with the older loess mapped by Scott (1960, 1963) in the southern part of the Denver area. The deposits of older loess within the quadrangle and those mapped by Scott may be as old as 120–170 ka. They may be correlative with eolian silt and sand about 65 km southeast of the Fort Collins quadrangle that yielded thermoluminescence age estimates of about 150 ka (Forman and others, 1995). Some of the closed depressions on till of Pinedale age (Qtp) may locally contain thin (≤50 cm) deposits of loess or silty sheetwash alluvium (Qsw) derived chiefly from loess. Thin silty sheetwash deposits (Qsw) may locally overlie unit Qlo. West of Boxelder Creek near Fort Collins and Wellington, unit Qlo has a few linear dune-like features. They are as much as 10 m high, commonly trend N.52°W., and are composed of sandy silt. Estimated thickness is 3–11 m

POST-LARAMIDE SEDIMENTARY ROCKS

No **Ogallala Formation (lowermost Pliocene? to middle Miocene)**—Reddish-brown to brown, poorly sorted, medium- to coarse-grained arkosic sandstone and conglomerate rich in granite clasts, minor siltstone, and rare calcrete or limestone beds preserved east of the Front Range near the northeastern corner of the quadrangle. Clasts include rounded pebbles to boulders, as large as 1 m in diameter, of flow-banded, slightly porphyritic rhyolite (Moore, 1959), which was probably eroded from rhyolite flows in the headwaters of the Cache la Poudre River and transported by large streams northeastward into extreme northern Colorado and across southeastern Wyoming into Nebraska (Swinehart and others, 1985). Northeast of the quadrangle in eastern Wyoming, the conglomerate-rich facies of the Ogallala grades eastward into beds of siltstone, sandstone, volcanic ash, and limestone (Flanagan and Montagne, 1993). The Ogallala disconformably overlies the Arikaree(?) Formation (Na?) and Brule Formation of the White River Group (₽wr) and its depositional top is not exposed (Moore, 1959; Courtwright and Braddock, 1989). Possible Pliocene age is based on fission-track age from zircon (4.6±1.0 Ma) for ash bed near the preserved top of the Ogallala in Nebraska; oldest included ash beds are about 17 Ma (Izett, 1975). Unit is combined with Arikaree Formation (Na?) on cross sections and designated as No/Na?. Thickness of Ogallala Formation is greater than 90 m and is locally as much as 140 m

Na? **Arikaree(?) Formation (Miocene)**—Light-brown or very pale brown massive siltstone; silty, very fine grained sandstone; and minor arkosic gravel. Slightly cobbly, granite-rich pebble gravel as much as 12 m thick is locally present at the base. Preserved underneath Ogallala Formation (No) near the northeast corner of the quadrangle. Correlation uncertain due to lack of outcrop continuity with Miocene rocks farther east (Courtwright and Braddock, 1989); however, a fragment of an oredont jaw bone considered to be of Miocene age was collected just east of the quadrangle (sec. 26, T. 12 N., R. 68 W.; Moore, 1959). Northeast of the Fort Collins quadrangle in eastern Wyoming, the Arikaree Formation consists of siltstone, fine-grained sandstone, limestone, and volcanic ash (Flanagan and Montagne, 1993). Thickness ranges from 0 to 79 m

N₽ls **Landslide debris deposits (lower Miocene or Oligocene)**—Irregular, slope-mantling deposits consisting of massive blocks of sandstone and fragmented shale of the Dakota Group (Kd) that were formed by slope collapse on the margins of extensive, tabular, largely intact slide blocks of the Dakota Group that overlie the Oligocene and Eocene White River Group (₽wr) (Braddock and Eicher, 1962; Braddock, 1978); landslide debris deposits are unconformably overlain by Pliocene(?) and Miocene Ogallala Formation (No) (Courtwright and Braddock, 1989). Maximum preserved thickness is about 36.5 m

N₽n **North Park Formation (Miocene and upper Oligocene?)**—Light-tan to white, calcareous sandstone and conglomerate, with lesser amounts of white, light-gray, and pink calcareous siltstone. Camp (1979) described five distinct lithologies. They are, in approximate descending order: (1) pink, fine-grained calcareous sandstone and siltstone composed of poorly sorted quartz and feldspar cemented by calcite; (2) interbedded buff to white, coarse-grained, locally trough cross-bedded, calcareous sandstone and conglomerate containing pebbles to small boulders composed of pink to lavender, flow-banded rhyolite and porphyritic volcanic rocks (intermediate composition) and, locally, Proterozoic granite and gneiss in a medium- to coarse-grained sandstone matrix cemented by coarse-grained calcite; (3) white, very fine-grained, calcareous, tuffaceous sandstone containing fine-grained quartz, feldspar, and as much as 15 percent glass shards; (4) white calcareous sandy mudstone containing poorly sorted fine- to medium-grained quartz, chert, and biotite; and (5) a basal cherty limestone, which we reassign to the basal unit of the Permian and Pennsylvanian Fountain Formation (PIPf) based on correlation with exposures east of Bull Mountain. Exposures are generally small and discontinuous, so exact relationship of these lithologies is unclear, although the lower units appear to be composed of finer-grained sediments that interfinger up-section with the coarser-grained units (Camp, 1979, p. 64). No fossils have been recovered from the Laramie River valley. The unit is correlated by Camp (1979) with the North Park Formation (NPn) to the west (Hail and Lewis, 1960; Izett, 1975) of middle and late Miocene age, with which we agree, although Beckwith (1942) and Knight (1953) correlated deposits surrounding North Middle Mountain with Miocene and Oligocene rocks in Wyoming and Colorado. Without better age control, we cannot rule out an upper Oligocene age. Unit may contain some undifferentiated Pliocene gravel deposits. Contains clasts of rhyolite tuff (Pr) dated at 27.7±0.05 Ma (^{40}Ar/^{39}Ar age for sanidine; Knox, 2005). Total thickness probably as much as 200 m

NPgy **Younger high-level fluvial gravel (Miocene? and Oligocene)**—Unsorted unstratified deposits of boulders (as large as 1.25 m), cobbles, and pebbles in a dominantly coarse sandy matrix with some silt; numerous clasts derived from underlying rhyolite tuff (Pr) dated at 27.7±0.05 Ma (^{40}Ar/^{39}Ar age for sanidine; Knox, 2005). Madole (1982) concluded similar deposits to the south of the map area formed in ancient valley systems that were subsequently disrupted by Neogene uplift of the Front Range. These high-level gravel deposits mark the trace of paleo-valleys of the early North Fork Cache la Poudre River from the Green Ridge area north and east through Prairie Divide to Livermore. Similar gravel deposits mark the courses of the early Michigan River west of Cameron Pass (Braddock and Cole, 1990; Kellogg, Ruleman and others, 2008), the main Cache la Poudre River east of the Big Narrows area, and the early Buckhorn Creek drainage in the south-central area of the quadrangle. Generally poorly exposed with lag gravel and younger colluvial cover that obscures deposit and basal contact. Western exposures may correlate with parts of the North Park Formation (NPn) in Laramie River valley or lateral equivalent. Deposits west of Livermore on eastern edge of Front Range may contain significant amounts of younger undifferentiated gravel as young as Pliocene where deposits grade slightly above Quaternary stream terrace deposits. Unit thickness is highly variable and difficult to estimate due to inferred relief on basal contact (Cole and others, 2008). Thickest exposure is above Cache la Poudre River on Green Mountain where at least 100 m thick (Abbott, 1976) but may exceed 200 m above axis of paleovalley

Pwr **White River Group, undivided (lower Oligocene and upper Eocene)**—Mapped in the northeastern corner of the map area where unit unconformably overlies deformed and eroded Upper Cretaceous Fox Hills Sandstone (Kfh) and Pierre Shale. Total minimum thickness approximately 76 m. Includes:

Lower Oligocene Brule Formation of upper part of White River Group—Consists of white, olive-gray, or pink, massive, clayey siltstone with thin beds of arkose, pebble gravel, silicic volcanic ash, and minor expansive claystone. Siltstone in the Brule Formation locally contains abundant calcareous concretions.

Upper Eocene Chadron Formation of lower part of White River Group—Underlies the Brule, and is red, purplish-red, or gray siltstone and minor sandstone interbedded with silicic volcanic ash and very poorly sorted fluvial gravel and conglomerate containing cobbles of Proterozoic crystalline rock and boulders of Paleozoic sandstone (as large as 60×65×120 cm^3), and minor very coarse arkose.). Gravel and conglomerate are more abundant in the lower part of the Chadron Formation than in the upper part. Volcanic ash beds in the White River Group range in age from about 35.5 Ma to 30 Ma (Prothero and Swisher, 1992; Larson and Evanoff, 1998).

₽s **Sedimentary rocks, undivided (Oligocene and Eocene?)**—Small exposures of sedimentary rocks that interfinger with or underlie Oligocene volcanic deposits in Pearson Park and just northwest of Long Draw Reservoir in southern part of quadrangle. Also includes small exposures of sediments surrounding Chambers Lake. Include blocky-weathering, orange-pink, tan, or light-gray tuffaceous mudstone, conglomeratic sandstone containing pebbles and cobbles of Oligocene volcanic rocks from the Braddock Peak volcanic complex, and fine-grained vitric tuff. Tentatively correlated with The White River Group (₽wr) exposed east of the Front Range. Similar deposits exposed below the North Park Formation (N₽n) west of the map area in the Laramie River valley produced an $^{40}Ar/^{39}Ar$ age from biotite of 36.0±0.3 Ma (Shroba, 2016). Thickness not known

₽bs **Tuffaceous sandstone and basalt (Oligocene)**—Massive, very poorly indurated, fine-grained, well-sorted, pale tan tuffaceous sandstone containing quartz, feldspar, glassy shards, and a few percent lithic grains. Sandstone overlies dark gray-brown, breccia of scoriaceous basalt that contains about 8 percent plagioclase and 15 percent olivine phenocrysts (both 1 to 2 mm); scoria vesicles partially filled with pale yellow zeolite(?). Deposit only exposed on the east slope of Laramie River valley about 1 km north of Chambers Lake; sandstone is probably equivalent to upper part of Oligocene and Eocene? Sedimentary rocks (₽s) and basalt is probably equivalent to Oligocene basalt (₽b) mapped farther south in the headwaters of the Cache la Poudre River (Braddock and Cole, 1990; Knox, 2005). Sandstone is about 30.5 m thick (top not exposed)

₽go **Older high-level fluvial gravel (Oligocene)**—Unsorted, unstratified deposits of cobbles (as large as 38 cm) and pebbles in sandy matrix that appear to underlie rhyolite tuff (₽r) dated at 27.73±0.05 Ma ($^{40}Ar/^{39}Ar$ age for sanidine; Knox, 2005). Contains porphyritic clasts of dacitic and andesitic(?) volcanic material of uncertain age, as well as more common clasts of durable Proterozoic igneous and metamorphic rocks. Deposit only mapped in the Green Ridge area near Nunn Creek Basin where relationship with rhyolite tuff is inferred. Thickness not known

POST-LARAMIDE VOLCANIC ROCKS

₽r **Rhyolite tuff (upper Oligocene)**—Combined unit consisting of two ash-flow units that were erupted coeval with emplacement of the Mount Cumulus stock in the Never Summer Mountains. Well exposed to the north and east of Iron Mountain. Isolated exposures located on Green Ridge near Nunn Creek suggest that unit underlies younger paleochannel gravel deposits (N₽gy) and overlies older gravel deposits (₽go). Lower ash flow is light-gray and brownish-gray with conspicuous phenocrysts of smoky-brown quartz, sanidine, and minor biotite in a devitrified matrix. Knox (2005) determined an $^{40}Ar/^{39}Ar$ age for sanidine of 27.73±0.05 Ma from exposures on Green Ridge. The younger tuff is gray, stony, massive, and contains phenocrysts of sanidine (4–5 percent), plagioclase (4–5 percent), biotite (3–5 percent), and about one percent of hornblende and pyroxene, but no quartz. Combined thickness of both units at least 152 m at Bald Mountain (northeast of Cameron Pass)

₽rw **Rhyolite welded tuff (upper Oligocene)**—Strongly welded, weakly layered gray, black, or brown crystal-rich tuff distinguished by brown, euhedral smoky quartz phenocrysts; probably coeval with granite and rhyolite porphyry of Mount Cumulus stock (O′Neill, 1981; Cole and Braddock, 2009). Unit represents welded zone of rhyolite ash-flow tuff (₽r; 27.73±0.05 Ma from $^{40}Ar/^{39}Ar$ on sanidine; Knox, 2005) in vicinity of Iron Mountain

₽v **Volcanic rocks, undivided (Oligocene)**—Undifferentiated rhyolite, dacite, trachyte, and andesite flows west of Cameron Pass near Gould Mountain. Porphyritic rhyolite resembles upper flow unit of Iron Mountain rhyolite tuff (₽r); lacks quartz phenocrysts. Knox (2005) determined $^{40}Ar/^{39}Ar$ ages for sanidine of 28.46±0.08 Ma from the rhyolite and 28.52±0.02 Ma from the thick dacite porphyry flow that caps Gould Mountain. Several undifferentiated flows of dacite, trachyte, and andesite underlie the main dacite flow north of Gould Mountain which are probably of similar age to the trachybasalt flows (₽b) east of Cameron Pass. Thickness of the younger rhyolite unit just south of the map area is about 366 m, possibly thickened by rheomorphic folding (O’Neill, 1981;

Kellogg, Ruleman and others, 2008). Thickness of main dacite flow is unknown. At least 100 m thick section of flows below main dacite north of Gould Mountain

₽b **Basalt (Oligocene)**—Black, aphanitic, massive, dense trachybasalt flows that weather dark brown. Rock consists of "small interlocking labradorite laths, slightly larger sanidine crystals, considerable interstitial augite, and a small amount of glass" (Gorton, 1953, p. 91) with small phenocrysts of feldspar, hornblende, and augite (Corbett, 1968). Exposed along Highway 14 near Joe Wright Reservoir and on the flanks of Iron Mountain as high as about 3,400 m. Described as trachyandesite (Pearson and others, 1982; Corbett, 1968), but chemical analysis indicates basaltic composition (Kellogg, Ruleman and others, 2008). $^{40}Ar/^{39}Ar$ whole-rock age is 29.58±0.22 Ma from exposure near Joe Wright Reservoir and 28.52±0.15 Ma from exposure on west side of Iron Mountain (Knox, 2005). Top and bottom not exposed, and orientation uncertain due to lack of internal flow layering; thickness unknown. Includes small area of andesite welded tuff just northeast of Flat Top Mountain which occupies similar stratigraphic position below Iron Mountain rhyolite flows

POST-LARAMIDE INTRUSIVE ROCKS

Located primarily in the Braddock Peak volcanic complex near Cameron Pass (southwestern corner of the quadrangle) with minor occurrences in the Manhattan mining district north of Rustic (Cache la Poudre River canyon)

₽rp **Rhyolite porphyry and felsite (Oligocene)**—Dikes and small plugs of white, tan, or light-reddish-brown porphyritic rock containing variable amounts of phenocrysts (quartz, sanidine, oligoclase, biotite and brown hornblende) in an aphanitic matrix. Small stock in the Manhattan district is leucocratic, sparsely porphyritic, flow-banded, and internally brecciated; zircon fission-track ages are 33–37 Ma (McCallum and Naeser, 1977; Shaver and others, 1988)

₽iy **Younger intrusive rocks, undivided (Oligocene)**—Small dikes or plugs of various colors and compositions, typically altered to the extent that phenocryst minerals not identifiable. Includes felsic rocks of late Oligocene age in the Cameron Pass area

LARAMIDE INTRUSIVE ROCKS

Located primarily in the Manhattan mining district north of Rustic (Cache la Poudre River canyon)

₽dp **Dacite porphyry (Eocene)**—Dikes and small plugs of gray, dense, porphyritic rock containing common phenocrysts of hornblende and plagioclase, plagioclase and biotite, or biotite alone, with sparse resorbed quartz (Shaver and others, 1988) in the Manhattan district. Zircon fission-track ages range between about 53 and 60 Ma (McCallum and Naeser, 1977)

₽ap **Andesite porphyry (Eocene)**—Dikes of gray, porphyritic rock with abundant hornblende phenocrysts in a very fine grained matrix of feldspar, hornblende, and minor quartz (Shaver and others, 1988) in the Manhattan district. Zircon fission-track ages range between about 53 and 55 Ma (McCallum and Naeser, 1977)

₽io **Older intrusive rocks, undivided (Eocene)**—Small dikes or plugs of various colors and compositions, typically altered to the point that phenocryst minerals not identifiable. Includes felsic and intermediate rocks of Eocene age in the Manhattan district

LARAMIDE SEDIMENTARY ROCK

₽c **Coalmont Formation (Eocene and Paleocene)**—Fluvial sedimentary unit preserved on the margin of the North Park Basin (west of Cameron Pass) where it lies on Upper and Lower Cretaceous Benton Group (Kb). Gray, brownish-gray, and brown, fine- to coarse-grained arkose, dark-gray carbonaceous mudstone, and lenses of coarse conglomerate with clasts of Proterozoic rocks as large as 1.5 m and clasts of intermediate volcanic rocks; thickness exceeds 518 m here (O'Neill, 1981; Braddock and Cole, 1990; Kellogg, Ruleman and others, 2008), but exceeds 2,740 m in North Park west of this quadrangle (Hail, 1968); top eroded everywhere

PRE-CENOZOIC SEDIMENTARY ROCKS

Kfh **Fox Hills Sandstone (Upper Cretaceous)**—Upper part of formation consists of cross-bedded tan sandstone; grades downward into brown, fine-grained silty sandstone and gray shale. Fox Hills formed in strand-line and delta-front environments during withdrawal of the Late Cretaceous Western Interior Seaway (Roberts, 2005); consists of several overlapping tabular sand bodies. Preserved beneath Oligocene and Eocene White River Group (₱wr) deposits near the northeast corner of the quadrangle. Thickness variable, but locally as much as 24 m

Kp **Pierre Shale, undivided (Upper Cretaceous)**—Thick, monotonous black shale in the Denver Basin, east of the Front Range. Subunits are well described by Scott and Cobban (1965; 1986); total thickness about 2,297 m. Unit Kp in cross section *D–D′* only. Subdivided for this map into five units

Kpu **Upper shale member**—Friable sandstone and soft shaly sandstone (upper transition member) and gray concretionary silty shale (unnamed upper shale member); thickness about 1,012 m

Kpr **Richard Sandstone Member, Larimer Sandstone Member, Rocky Ridge Sandstone Member and two intervening unnamed shale members**—Light-brown or brownish-yellow, micaceous or glauconitic sandstone interlayered with gray shale; thickness about 160 m

Kpm **Middle shale member**—Claystone and sandy siltstone; light-gray or yellowish-gray calcareous sandstone (Terry Sandstone Member) poorly exposed near center of unit; thickness about 259 m

Kph **Hygiene Sandstone Member**—An upper hard, glauconitic, ridge-forming sandstone separated from a lower friable sandstone by a shale; thickness about 74.5 m

Kpl **Lower shale member**—Mostly dark olive-gray bentonitic shale (Mitten Member and local Sharon Springs Member and unnamed lower shale member); thickness about 792.5 m

Kmv **Mesaverde Formation (Upper Cretaceous)—**Transitional marine and nonmarine beds in the Laramie Basin west of the Front Range; dark-gray, calcareous marine shale and siltstone interbedded with ledge-forming marine sandstone with ironstone concretions (Beckwith, 1942; Camp, 1979). Contains local carbonaceous beds, but no commercially exploited coal deposits. Conformably overlies Steele Shale (Kss); base is defined by the lowest prominent marine sandstone ledge above the Steele Shale (Kss). Total thickness about 610 m (top eroded) in this area

Kss **Steele Shale (Upper Cretaceous)—**Thick, monotonous, black to dark-gray, marine shale and mudstone in the southern Laramie Basin west of the Front Range; conformably overlies the Niobrara Formation (Kn); correlates with the lower and middle parts of the Pierre Shale. Steele contains zones of thin bedded sandstone about 305 m above the base (unnamed) and 518–580 m above the base (Shannon Sandstone Member; Beckwith, 1942). A white sandstone near the top of the preserved section contains *Baculites reesidei Elias* ammonites, indicating equivalence to the upper middle sandy unit of the Pierre Shale (Scott and Cobban, 1986). Total thickness about 731.5 m

Kn **Niobrara Formation (Upper Cretaceous)—**Gray, calcareous marine shale and biomicrite beds; thinly laminated; typically weathers to light-gray or buff near top; commonly contains oyster fossils (*Inoceramus* sp.); conformably overlies Benton Group (Kbm). East of Front Range, Niobrara consists of Smoky Hill Shale Member in upper part and the basal, thin Fort Hays Limestone Member (extensively quarried for cement manufacture; Scott and Cobban, 1986). West of Front Range, Niobrara consists of the upper chalky member, upper shale member, lower chalky member, and the basal Sage Breaks Shale Member (Cobban and Reeside, 1952; Camp, 1979). Thickness of combined units varies from about 106.7 m (southeast) to 88.4 m (northeast) to 140.2 m (northwest) across the quadrangle

Kbm **Benton Group (Upper and Lower Cretaceous)**—Includes several marine shale, calcareous shale, bentonite, and limestone units that lie conformably above the Dakota Group (Kd) and conformably below the Niobrara Formation (Kn); exposure is typically poor. The Benton Group is locally subdivided east of the Front Range (from top to bottom) into the olive-gray, silty-sandy Carlile Shale, dark-gray to olive-gray Greenhorn Limestone, dark-gray Graneros Shale, and underlying Mowry Shale (Scott and Cobban, 1986). West of the Front Range, the Benton Group has been subdivided into (from top to bottom) the Wall Creek Sandstone Member and the shaly member of the Frontier Formation and the underlying Mowry Shale (Shaw, 1957; Camp, 1979). Mowry Shale is wavy-bedded, rusty, siliceous shale that contains fish scales, weathers light gray, and is locally absent east of the Front Range. Thickness of combined units varies from about 147.8 m (southeast) to 173.7 m (northeast) to 115.8 m (northwest) across the quadrangle

Kd **Dakota Group (Lower Cretaceous)**—Light-gray to brown-gray, fine-grained, ripple-marked sandstone and interbedded gray carbonaceous shale in upper part, and chert-pebble conglomerate and sandstone in lower part; base is major regional unconformity. In eastern foothill belt, the Dakota consists of South Platte Formation in upper part and Lytle Formation in lower part. Sandstones are strongly cemented with silica and form prominent ridges; blocks of weathered Dakota sandstone litter slopes surrounding outcrops. The Dakota was deposited in fluvial and swamp environments during a major marine transgression. Thickness ranges from about 88.4 m (southeast) to 74.7 m (northeast) to 76.2 m (northwest) to 75 m (southwest) across the quadrangle

Jm **Morrison Formation (Upper Jurassic)**—Green, red, yellow, and white, blocky-weathering claystone and siltstone, gray micrite, and gray, fine- to medium-grained, cross-bedded sandstone. Morrison Formation deposited by low gradient rivers in floodplains and in freshwater lakes and swamps. Thickness varies from about 97.5 m along the eastern foothills belt to 85.3 m (northwest) to 90 m (southwest) across the quadrangle

Jms **Morrison Formation (Upper Jurassic) and Sundance Formation (Upper and Middle Jurassic), undivided**—Mapped in the southwest corner of the map area where unit is predominantly Morrison Formation (Jm), but poor exposure along the flanks of the Medicine Bow Mountains makes it difficult to differentiate contact between Morrison and underlying Sundance Formations. Base of map unit locally includes about 3 m of light-orange, medium-grained, cross-bedded sandstone that may be equivalent to southern trailing edge of Upper Triassic Jelm Formation (Kellogg, Ruleman and others, 2008). Thickness of combined units about 134 m

J₮msj **Morrison (Upper Jurassic), Sundance (Upper and Middle Jurassic), and Jelm (Upper Triassic) Formations, undivided**—Shown on cross sections only. Includes all of mapped units Jm and J₮sj

J₮sj **Sundance (Upper and Middle Jurassic) and Jelm (Upper Triassic) Formations, undivided**—The Sundance Formation, in upper part of unit, dominantly consists of fine- to very fine-grained, tabular-bedded, variably colored sandstone that weathers yellowish tan; base is a regional unconformity. Sundance Formation deposited in shallow, near-shore marine environments (Pipiringos and O′Sullivan, 1976). The underlying Jelm Formation (only the Red Draw Member is present) consists of orange-pink or reddish-brown, fine-grained, cross-bedded, calcareous sandstone and local red-brown shale and limestone-pebble conglomerate; pinches out southwestward near Cameron Pass (Kellogg, Ruleman and others, 2008), and southeastward in the foothills hogback belt about 48 km south of this quadrangle. Thickness of combined units varies from 42.7 m (southeast) to 56.4 (northeast) to 118.9 m (northwest) across the quadrangle

₮Pl **Lykins Formation (Lower Triassic and Upper Permian)—**Thick sequence of dominantly red and red-brown siltstone and fine-grained sandstone that forms a valley or subdued slope between the Lyons Sandstone and the Jelm Formation on the east side of the Front Range. Persistent limestone sequences present at several stratigraphic levels, including the Forelle Limestone Member (Upper Permian) in the lower third of the Lykins; gypsum beds are conspicuous in the lowermost Lykins and are locally quarried in the Table Mountain quadrangle (Broin, 1957; Courtright and Braddock, 1989). Unit generally correlates with, in descending order, the Red Peak Formation and upper part of Goose Egg Formation (₮Prgu) and Forelle Limestone Member and uppermost shale (Glendo Shale of Burk and Thomas, 1956) of the Satanka Shale Member of the Goose Egg Formation (Pgfsu) west of the Front Range. Thickness varies from 183 m (southeast) to 152 m (northeast)

Pl **Lyons Sandstone (Lower Permian)**—Unit exposed east of the Front Range. Moderate orange, pink, or pinkish-gray, fine- to medium-grained, well-sorted, cross-stratified, eolian quartz sandstone (firmly cemented with silica and local calcite), and tan, gray, and red laminated siltstone. Lyons Sandstone deposited in widespread eolian dune complexes that graded northward to coastal sabkhas and mudflats (Walker and Harms, 1976; Berman, 1979); unconformably overlies the Owl Canyon Formation (Po). Unit not mapped west of the Front Range in this quadrangle, but Maughan and Wilson (1963) suggest that the unnamed sandstone at the top of the lower part of the Satanka Shale Member of Goose Egg Formation (Pgsl) is equivalent to the Lyons Sandstone. Unit thins from 15 m in the southeast corner of the map to 1–9 m north of Bellvue, Colo., where the unit is generally mapped as a linear 'key bed' between the overlying Lykins Formation (ŦPl) and underlying Owl Canyon Formation (Po)

Pu **Lyons Sandstone and Owl Canyon and Ingleside Formations, undivided (Lower Permian)**—Mapped only to the south of the Fletcher Hill fault along Buckhorn Creek on the southern edge of the quadrangle, where the Permian section is folded near vertical and attenuated against the fault

Po **Owl Canyon Formation (Lower Permian)**—Red siltstone and fine-grained, red, ripple-laminated sandstone; interbedded locally with the Ingleside Formation below and with the Lyons Sandstone above; not mapped west of the Front Range. Owl Canyon was deposited in tidal flats and estuaries and possibly in large desert lake environments (Pearson, 1976; Berman, 1979). Unit generally correlates with the base of the Satanka Shale Member of Goose Egg Formation (lower part of unit Pgsl) west of the Front Range; thickness varies from 70 m (southeast) to 84 m (northeast)

Pi **Ingleside Formation (Lower Permian)**—Pink to light-red, fine-grained quartzose sandstone; commonly well cemented with quartz or calcite; thin to very thick bedded, locally cross-bedded; limestones present at several stratigraphic levels; exposed only east of the Front Range. Ingleside Formation was deposited in coastal sabkhas and shallow marine lagoons (Berman, 1979). Limestones are unusually thick east of Livermore where they have been extensively quarried for cement production. Thickness varies from 46 m (southeast) to 67 m (northeast); mapped as a linear 'key bed' between overlying Owl Canyon Formation (Po) and underlying Fountain Formation (PIPf) south of Fletcher Hill and Redstone Creek faults where unit is folded near vertical and attenuated against the fault

ŦPrgu **Red Peak Formation (Lower Triassic) and upper part of Goose Egg Formation (Lower Triassic and Upper Permian), undivided**—Unit exposed west of the Front Range. Red to red-brown, planar laminated, ripple-marked, cross-bedded siltstone and micaceous shale interbedded with gypsum near base. Thin carbonate bed defines top of Goose Egg Formation, but entire unit is poorly exposed and generally underlies valleys, so formational contact is not mapped. Unit was deposited in shallow-water, hypersaline marine environments. Mapped in two small areas near the southwestern corner of quadrangle west of Cameron Pass includes 1–2 m of light gray, laminated algal limestone near the base (Forelle? Limestone Member of Goose Egg Formation) as well as a few meters of underlying red sandy shale (Satanka? Shale Member of Goose Egg Formation) which may correlate to the top of the lower Goose Egg Formation (Pgfsu) (Ward, 1957; Braddock and Cole, 1990). Map unit rests unconformably on Proterozoic basement in southwestern part of quadrangle (Berman, 1979) and conformably above lower Goose Egg Formation in northwestern part of quadrangle (Pgfsu). Unit ŦPrgu generally correlates with the middle and upper parts of the Lykins Formation (ŦPl) east of the Front Range. Total thickness ranges from about 243.8 m (southwest) to 176.8 m (northwest)

Pgl **Lower part of Goose Egg Formation (Upper and Lower Permian)**—Unit exposed west of the Front Range. Consists of the Forelle Limestone and Satanka Shale Members. Shown undivided on cross sections only. On map, divided into two subunits as follows:

Pgfsu **Forelle Limestone Member (Upper Permian) and upper part of Satanka Shale Member (Upper and Lower Permian), undivided**—The overlying Forelle Limestone Member consists of two beds of gray, microcrystalline, wavy laminated, algal limestone (each about 2.1 m thick) separated by about 3 m of purple and tan laminated shaly dolomite. The underlying upper part of the Satanka Shale Member consists of red sandy shale and siltstone interlayered with lesser amounts of fine-grained sandstone, blocky gypsum, and wavy-laminated dolomitic limestone near base of unit. Base of unit defined by thin gray dolomitic limestone with white to gray chert nodules. Workman and Braddock (2010) correlate this basal limestone to the base of the Minnekahta Limestone Member of the Goose Egg Formation of Burk and Thomas (1956). Unit Pgfsu is the lateral equivalent of the lower part of the Lykins Formation (T̄RPl) east of the Front Range (Broin, 1957; Rascoe and Baars, 1972). Total thickness of the two units is about 60 m

Pgsl **Lower part of Satanka Shale Member (Lower Permian)**—Reddish-orange to dark maroon, thin laminated, sandstone and siltstone with increasing interbedded dolomitic sandstone and gypsum near top of section. Percentage of sandstone increases to south across map area. Workman and Braddock (2010) correlate unit with Opeche Shale Member of Goose Egg Formation of Burk and Thomas (1956); Pearson (1972) correlates the upper part of the unit with the Lyons Sandstone (Pl) and Maughan and Wilson (1963) correlate the lower part of unit Pgsl with the Owl Canyon Formation (Po) both mapped on the east side of the Front Range; the regional unconformity described by Cole and Braddock (2009) below the Lyons Sandstone is inferred to exist within unit Pgsl based upon these correlations. Camp (1979) included this unit as part of the underlying Casper Formation (Pℙc) which we restrict here to exposures of “festoon” cross-bedded sandstones and interbedded limestones which pinch out near the northern edge of the quadrangle; within Laramie River valley unit may include thin exposures of unmapped Casper Formation at the base. Interfingers with underlying Fountain Formation (Pℙf) to south (Pederson, 1953). Thickness about 35 m at Sand Creek Pass (northwest)

Pℙc **Casper Formation (Lower Permian to Middle Pennsylvanian)**—White to buff, yellow-weathering, fine- to medium-grained, well-sorted, carbonate cemented quartzose sandstone and interbedded thin lenses of freshwater limestone; sandstones display prominent ripple marks and large-scale trough (festoon) cross-bedding accompanied by significant soft-sediment deformation; mapped only in the vicinity of Sand Creek in the northwestern part of the quadrangle. Formation thins markedly southward and pinches out just north of Sand Creek Pass (Workman and Braddock, 2010). The Casper Formation was deposited in a coastal dune complex (Steidtmann, 1976) and the upper part is the approximate lateral equivalent of the marine shelf and sabkha deposits of the Ingleside Formation (Pi) east of the Front Range. Thickness is about 29 m at Chimney Rock; mapped as a linear ‘key bed’ between overlying Goose Egg Formation (Pgsl) and underlying Fountain Formation (Pℙf) where exposures are too thin to map, but outcrops form prominent, readily identified low cliffs and mesas east of Bull Mountain

Pℙf **Fountain Formation (Lower Permian to Lower Pennsylvanian)**—Reddish-brown, purplish-gray, and light greenish-gray, arkosic conglomerate; medium- to coarse-grained, feldspathic sandstone; dark-reddish-brown and pale green micaceous siltstone and shale; and minor thin limestone; unconformably overlies Proterozoic crystalline rocks. The Fountain Formation contains material eroded from the uplifted Proterozoic basement of the Ancestral Rocky Mountains; sediments were deposited in rapidly subsiding basins by braided stream systems and (locally) by eolian transport (Berman, 1979). Thickness varies from about 198 m (northeast) to 210 m (northwest) to 268 m (southeast) across the quadrangle; thins south along Laramie River valley and absent in southwestern part of quadrangle where inferred Ancestral Rocky Mountain uplift occurred; includes Casper Formation (Pℙc) where too thin to show in cross section *A–A′*

PALEOZOIC AND PROTEROZOIC INTRUSIVE ROCK

DZk **Kimberlite (Devonian? and Neoproterozoic)—**Dark-gray or dark-olive-green, altered kimberlite breccia, carbonatitic kimberlite, and porphyritic kimberlite; typically contains olivine, chromian pyroxene, pyrope garnet, ilmenite, chromite, and phlogopite, variably altered to serpentine and carbonate minerals (McCallum and Eggler, 1979; Hausel, 1998). Kimberlite forms irregular dikes and deeply eroded diatremes that contain nodules of lower crustal granulite, peridotite, and pyroxenite. Outcrop is poor, but kimberlite soil shows characteristic blue color and correlates with grassy vegetation anomalies in otherwise forested land. Kimberlites are clustered in several small groups across the Fort Collins quadrangle and in adjoining areas north in Wyoming; thousands of carats of industrial-grade stones and some gem-quality diamonds have been recovered by commercial extraction (Carlson and Marsh, 1986; Hausel, 1998). Radiometric studies confirm both Devonian and Neoproterozoic emplacement ages in this quadrangle and across the Front Range (Naeser and McCallum, 1977; Lester and others, 2001)

PROTEROZOIC INTRUSIVE AND METAMORPHIC ROCKS

Proterozoic intrusive rocks in the Fort Collins quadrangle were emplaced during two principal time periods, based on radiometric age determinations by several methods. Rocks formed during these major intrusive periods were recognized and formalized by Tweto (1987) as the Mesoproterozoic Berthoud Plutonic Suite (approximately 1,350 to 1,440 Ma; DeWitt and others, 2010) and the Paleoproterozoic Routt Plutonic Suite (approximately 1,690 to 1,725 Ma; Premo and others, 2010a). Batholith-sized intrusions have long been designated with a geographic place-name that has served as a type locality for a named lithodemic unit (for example, Boulder Creek batholith consisting primarily of Boulder Creek Granodiorite) and rocks of similar composition, texture, and ages have been correlated with the named lithodemic units (see Tweto, 1987). Later isotopic studies have shown that some of these correlations were not valid (Premo and Van Schmus, 1989). The nomenclature and symbology for Proterozoic intrusive rocks in this quadrangle (and adjoining areas) are based on age, composition, and a local intrusive-body name, rather than on inferred correlation to the type of a named lithodemic unit. Map-unit symbol is composed as follows:

Intrusion age: Y = Mesoproterozoic (1,600 to 1,000 Ma); X = Paleoproterozoic (2,500 to 1,600 Ma)
Composition: d, diorite, diabasic mafic rock; g, granite; gb, gabbro; gd, granodiorite; j, trondhjemite; qd, quartz diorite
Intrusive body (where named): H, granite of Hagues Peak; LC, Log Cabin batholith; LP, Longs Peak batholith; R, Rawah batholith; SH, Sherman batholith; T, Thompson Canyon sills; V, Virginia Dale ring-dike complex
Textural and (or) mineralogical descriptors (where appropriate): h, hornblende-bearing; p, porphyritic; e, equigranular; a, aplitic
Temporal or spatial descriptors (where appropriate): y, younger; o, older or outer; i, inner

MESOPROTEROZOIC INTRUSIVE ROCKS

Ygb **Gabbro of the Iron dike**—Dark-gray to black ferrogabbro; weathers dark brown to orange brown with prominent limonite stains along joint surfaces; very fine grained along dike margins, and medium-grained in centers of thicker dike segments (as wide as 15 m). Intruded 1,316±50 Ma (Rb-Sr isochron age; Braddock and Peterman, 1989). Iron Dike forms a narrow north-northwest trending swarm along the eastern front of the Medicine Bow Mountains (Pearson and others, 1982) and in the Mummy Range just north of Long Draw Reservoir; this distinctive dike swarm has been traced as far north as the Wyoming State line (Tweto, 1987) and as far south as Boulder, Colo. (Cole and Braddock, 2009), over a total distance of about 120 km

Ygay **Younger aplite dikes and plugs**—Exposed in the central and southern parts of the quadrangle; unit includes light-gray to buff, very fine- to medium-grained, xenomorphic granular alkali-feldspar syenogranite to monzogranite with variable accessory biotite and muscovite that grades into pegmatite; large bodies just north of the Cache la Poudre River contain sparse garnet and intrude biotite granite (Yg and Yge); north-northwest striking dikes exposed south of Greyrock Mountain are porphyritic, biotite-rich, and intrude mafic dikes (Yd). Whole-rock Rb-Sr age from correlative rocks to south of quadrangle is 1,361±30 Ma (Peterman and others, 1968); probably related to intrusion of Silver Plume-type granites (Braddock, Abbott, and others, 1988)

Yg **Biotite granite**—Gray to buff, fine- to medium-grained, equigranular to seriate porphyritic biotite syenogranite to monzogranite, correlated with granite of Log Cabin batholith and other Silver Plume-type granites throughout the Front Range (Eggler and Braddock, 1988; Shaver and others, 1988); associated with smaller unnamed intrusive bodies and dikes. Color index generally 2 to 5. To the north of the Log Cabin batholith, unit forms an oval, irregular plug intruded into the Sherman Granite phases of the Virginia Dale ring-dike complex; intrusion age established as 1,390±30 Ma (Rb-Sr isochron; recalculated from Peterman and others, 1968). To the south and east of the Log Cabin batholith, unit includes numerous irregular shaped intrusive bodies and dikes along the 1.2 Ga (Abbott, 1972) Skin Gulch shear zone which might be displaced or satellitic bodies of the main Log Cabin batholith or may be separate plugs and dikes intruded between the Log Cabin and Longs Peak-St. Vrain batholiths. Unit is primarily porphyritic to south where equigranular phase (Yge) is mapped separately; includes mafic quartz monzonite of Abbott (1976)

Yge **Equigranular biotite granite**—Gray, equigranular to slightly porphyritic, fine- to medium-grained biotite syenogranite to monzogranite mapped to south and east of the Log Cabin batholith; weathers to pink or tan; correlated with granite of Log Cabin batholith and other Silver Plume-type granites throughout the Front Range (Shaver and others, 1988)

Granite of Log Cabin batholith—Light-gray, grayish-orange, pale pink, or tan monzogranite to syenogranite that contains 1–8 percent biotite; texture ranges from equigranular to seriate porphyritic to distinctly porphyritic, and grainsize ranges from fine to coarse. Coarse-grained, porphyritic phase is prominent along the western and southern batholith margins and in the Red Feather Lakes area and displays a flow alignment of microcline phenocrysts that dips steeply outward. Mylonitic foliation is locally present in the vicinity of the Skin Gulch shear zone. Granite of Log Cabin batholith typically weathers tan and light orange-brown and forms a landscape of rounded tors surrounded by grus aprons. Age of intrusion is similar to granite of Longs Peak (YgLP) and other Silver Plume-type granites of the Front Range; U-Pb SHRIMP age on zircon grains from the coarse, porphyritic phase is 1,407±13 Ma, and from the medium-grained, equigranular phase is 1,408±15 Ma (DeWitt and others, 2010; Premo and others, 2012). Along southern margin of batholith, porphyritic and equigranular phases have been mapped separately

YgLC **Granite of Log Cabin batholith, undivided**—Mapped north of the Elkhorn Creek shear zone through most of the Log Cabin batholith where coarse-grained, porphyritic phase is predominant, but lack of detailed mapping does not allow differentiation of phases

YgLCe **Equigranular granite of Log Cabin batholith**—Mapped separately south of the Elkhorn Creek shear zone and along the western edge of the batholith where more detailed mapping exists (Abbott, 1976; Shaver and others, 1988); gray, equigranular to slightly porphyritic, fine- to medium-grained biotite syenogranite to monzogranite; flow foliation defined by alignment of biotite is common; weathers to pink or tan

YgLCp **Porphyritic granite of Log Cabin batholith**—Mapped south of the Elkhorn Creek shear zone where detailed mapping exists (Abbott, 1976; Shaver and others, 1988); gray to buff, coarse-grained, porphyritic to seriate porphyritic biotite syenogranite to monzogranite; 2–4 cm-long subhedral phenocrysts of perthitic microcline and sparse oligoclase are commonly aligned to form flow foliation; weathers to tan and light orange-brown

YgLP **Granite of Longs Peak**—Light- to medium-gray, grayish-orange, orange-pink, or red-purple syenogranite to monzogranite that contains characteristic tabular microcline phenocrysts. Biotite is the principal dark mineral, locally accompanied by magmatic sillimanite and (or) garnet plus minor accessory minerals. Equigranular matrix is locally fine, medium or coarse grained and weakly foliated by aligned biotite grains. Color index generally 5 to 8. Granite intruded the Longs Peak-St. Vrain batholith as a viscous magma that extensively deformed metamorphic wall-rocks (Cole, 1977; Braddock and Cole, 1979, 1990; Cole, 2004b; Cole and Braddock, 2009); only the northernmost part of the batholith is exposed in this quadrangle. Age of intrusion is established as 1,420±25 Ma (Rb-Sr isochron; Peterman and others, 1968) and 1,393±25 Ma (U-Pb zircon discordia; Plymate and others, 2005). Secondary muscovite (non-oriented, porphyroblastic) is locally conspicuous, particularly in small satellite intrusions; formed by subsolidus hydration of sillimanite+potassium feldspar or breakdown of primary biotite to muscovite+magnetite

Yd **Mafic dikes and plugs**—Black, greenish-black, or dark-gray, fine- to medium-grained diabasic rocks of basaltic or andesitic composition that form a north- to northeast-trending dike swarm throughout much of northern Front Range. Plagioclase forms phenocrysts in most dikes and matrix consists of finer-grained feldspar, hornblende, pyroxene, and magnetite, or secondary minerals related to contact metamorphism or hydration alteration. The dike swarm cuts 1,433 Ma-old Sherman Granite (YgSH) (Frost and others, 1999) and is cut and deformed by 1,395 Ma-old granite of Longs Peak (YgLP) (Cole, 1977; Plymate and others, 2005) and 1,406 Ma-old granite of the Log Cabin batholith (YgLC) (Shaver and others, 1988)

Ygao **Older aplite dikes and plugs**—Exposed in the northern part of the quadrangle; unit includes pinkish-gray to red, fine- to medium-grained, xenomorphic to hypidiomorphic granular biotite monzogranite that forms dikes and small slightly porphyritic plugs that parallel the margins of the Virginia Dale ring dike structure; some dikes contain hornblende; intrudes rocks of the Virginia Dale ring dike complex (YgVi and YgVo) and is intruded by mafic dikes (Yd)

Virginia Dale ring-dike complex—A roughly circular composite intrusion, about 9 mi in diameter, is exposed in the northern part of the Fort Collins quadrangle and extends northward into Wyoming. As summarized from Eggler (1968), the ring-dike complex is a distinct structural and magmatic element of the Sherman Granite batholith, based on geochemical similarities, intrusive relationships, and the merging of the outer ring-dike with the main Sherman Granite batholith. The Virginia Dale ring-dike complex is intruded by biotite monzogranite (Ygao) and by mafic dikes (Yd). The age of intrusion is established by the emplacement of the Sherman Granite (YgSH) at 1,433±1.5 Ma (U-Pb zircon;Frost and others, 1999) and 1,430±20 Ma (Rb-Sr isochron; Zielinski and others, 1981)

YgVi **Inner cap rock monzogranite of the Virginia Dale ring-dike complex**—Pinkish-gray, medium-grained, porphyritic biotite monzogranite that displays flow foliation defined by aligned microcline phenocrysts, biotite-rich streaks, and aligned dioritic inclusions; color index generally 6 to 8. Contact with outer cap rock monzogranite (YgVo) is gradational

YgVo **Outer cap rock monzogranite of the Virginia Dale ring-dike complex**—Pinkish-gray, medium-grained, porphyritic biotite monzogranite, similar in all respects to inner cap rock monzogranite (YgVi) except that phenocrysts are smaller and better aligned, and biotite-rich streaks are more common; color index generally 7 to 9. Contact with inner cap rock monzogranite is gradational

YdV **Dioritic and hybrid rocks of the Virginia Dale ring-dike complex**—Fragmental and magmatically mixed rocks (Vasek and Kolker, 1999), ranging from diorite to monzogranite, that form a partial annular zone between the cap rock monzogranites (YgVi and YgVo) and the Sherman Granite (YgSH) outer ring-dike of the Virginia Dale ring-dike complex. Eggler (1968) interprets the hybrid zone as evidence of simultaneous intrusion of dioritic and monzogranitic magmas. Irregular blocks of metamorphic country rock are also contained within the hybrid zone

YgSH **Sherman Granite**—Red-weathering, coarse-grained, equigranular, subalkalic syenogranite with hornblende and biotite forming clotted aggregates (color index generally 6 to 11 in the Virginia Dale ring-dike complex; somewhat higher in the main Sherman batholith). Small amounts of accessory fluorite are typical. Sherman Granite characteristically weathers to thick quartz-feldspar grus and is poorly exposed (Eggler and others, 1969). Age of crystallization is determined at 1,433±1.5 Ma (U-Pb from zircon; Frost and others, 1999) from a sample in the Laramie Mountains north of the map area

Yghp **Hornblende granite porphyry**—Orange-weathering, yellowish-gray, fine-grained, massive, xenomorphic granular granite porphyry with conspicuous rounded phenocrysts of gray quartz, equant feldspar, and minute prismatic hornblende (color index about 5); typically weathers to smooth rounded forms. Present west of the Virginia Dale ring-dike complex; locally includes abundant inclusions of metamorphic wall rock; crosscut by mafic dikes and plugs (Yd) and by Sherman Granite (YgSH) (Eggler and Braddock, 1988; Braddock, Cole and Eggler, 1989)

Ygbh **Hornblende gabbro**—Black, medium-grained, massive rock consisting of hornblende, calcic plagioclase, and a little biotite and pyrite. Mapped only in the country rock northeast of the Virginia Dale ring-dike complex where it intrudes felsic gneiss (Xfl) and amphibolite (Xh). Gabbro is intruded by Sherman Granite (YgSH), but is interpreted to belong to the Berthoud Plutonic Suite because it lacks dimensional fabric and because it is geochemically related to the mafic intrusive rocks of the Virginia Dale complex (Eggler, 1968; Braddock, Eggler, and Courtright, 1989)

YgH **Granite of Hagues Peak**—Tan, coarse-grained to very coarse grained, porphyritic biotite-rich monzogranite and granodiorite. Contains conspicuous flow-aligned phenocrysts of microcline 2 to 6 cm long. Color index generally 10 to 15. The granite of Hagues Peak is intruded by the granite of Longs Peak (YgLP), and yields a whole-rock Rb-Sr isochron age of approximately 1,480 Ma (Braddock and Cole, 1990). Plymate and others (2005) indicate bulk geochemistry of this unit strongly resembles the granite of the Mt. Evans batholith (exposed 100 km south of the map area) intruded at 1,442±2 Ma (U-Pb on zircon; Aleinikoff and others, 1993)

Yqd **Quartz diorite**—Dark-gray, medium-grained, massive, biotite-hornblende quartz diorite and diorite; forms several small bodies along the southern quadrangle boundary contained within the granite of Hagues Peak (YgH) (Nesse and Braddock, 1989; Braddock and Cole, 1990; Plymate and others, 2005); may represent a mafic precursor to the granite of Hagues Peak

MESOPROTEROZOIC AND (OR) PALEOPROTEROZOIC INTRUSIVE AND METAMORPHIC ROCK

YXp **Pegmatite**—White, medium-grained to very coarse grained pegmatite with accessory biotite, muscovite, garnet, and (or) tourmaline. Pegmatites are widespread in the metamorphic rocks and likely formed during emplacement of both the Routt (approximately 1,690 to 1,725 Ma; Premo and others, 2010a) and Berthoud (approximately 1,350 to 1,440 Ma; DeWitt and others, 2010) Plutonic Suites; reliable field criteria for distinguishing pegmatite ages have not been established

YXu **Undivided intrusive and metamorphic rocks—**Undivided crystalline basement rocks shown beneath Phanerozoic sedimentary deposits in cross sections only. May include any Proterozoic intrusive and (or) metamorphic rocks included on the map as well as other unidentified crystalline rocks not exposed at the surface. No internal relationships are shown within unit

PALEOPROTEROZOIC INTRUSIVE ROCKS

Xgd **Granodiorite—**Light- to medium-gray, medium- to coarse-grained, weakly to strongly foliated granodiorite and monzogranite containing biotite and variable amounts of hornblende and local feldspar phenocrysts. These rocks are physically and mineralogically similar to the Boulder Creek Granodiorite of the Boulder Creek batholith 45 km south (Gable, 1980), but were intruded in discrete plutons. Emplacement age inferred to be similar to Boulder Creek batholith (1,713±4 Ma mean age from U-Pb SHRIMP on zircon from multiple samples in and south of the map area; Premo and others, 2010a) because these granodiorites intruded during main stage of regional folding, which is typical of the Boulder Creek Granodiorite (Braddock and Cole, 1979)

Xgdp **Porphyritic granodiorite**—Gray to dark brown, medium- to coarse-grained, porphyritic hornblende-biotite granodiorite with conspicuous lensoid microcline phenocrysts as large as a few centimeters; color index varies between 10 and 25. Forms bladed outcrops with steeply plunging mineral-segregation lineation. Unit occurs in and near the Cache la Poudre canyon between Rustic and Kinikinik. Age unknown, but assumed to be related to Boulder Creek-type granodiorite (Xgd; 1,713±4 from U-Pb SHRIMP zircon data; Premo and others, 2010a) based upon similar composition and structural relationships

Xgbh **Hornblende gabbro**—Dark-gray to greenish-black, medium-grained, equigranular, massive hornblende gabbro, consisting largely of plagioclase, hornblende, and minor pyroxene and iron-titanium (Fe-Ti) oxides. Forms a roughly circular pluton (1 km wide) near North Bald Mountain and a smaller body in the Cache la Poudre canyon west of Kinikinik. Considered youngest phase of Rawah batholith which intrudes main granite phase (XgR) based upon 1,715 Ma U-Pb SHRIMP zircon age from North Bald Mountain exposure (Premo and others, 2010a)

XgR **Granite of the Rawah batholith**—Pink to gray, fine- to medium-grained, xenomorphic equigranular biotite granite; mineral foliation and compositional banding uncommon. Contains sparse accessory biotite and (or) hornblende and minor sphene, apatite, zircon, allanite, and rare sillimanite, rutile, and garnet. Biotite percentage varies significantly (gradationally and in schlieren) and biotite-poor varieties are generally not foliated. Unit contains abundant inclusions of older metamorphic rocks. Hornblende gneiss (Xh) inclusions are commonly rotated relative to regional metamorphic foliation (Burch, 1983). Biotite gneiss (Xb) inclusions are far less common and generally smaller in size. Inclusions of leucocratic felsic gneiss (Xfl) may be common, but are hard to distinguish from Rawah due to similar composition and texture; exposures in the southern Medicine Bow Mountains are suspected to be largely older felsic gneisses based upon an older age reported by Kellogg, Ruleman and others (2008) and a change in geophysical signature to the south of Kelly Lake (Zietz and Kirby, 1972), but no mappable contact has been found. Burch (1983) describes coarser-grained, biotite-rich, foliated porphyritic granitic rocks as a separate phase of the Rawah; we reinterpret these rocks as inclusions of older felsic gneiss (Xfl) based on parallel foliation and interlayering with adjacent hornblende gneiss (Xh) inclusions. The Rawah batholith, proper, spans across the Laramie Mountains west of the Log Cabin batholith (YgLC) and the Medicine Bow Mountains; the northern boundary in the Laramie Mountains is marked by the Cornelius Creek shear zone of cataclasis and breccia (probably post-Proterozoic deformation). The smaller, isolated, northeast-southwest elongate intrusive body in the northern Mummy Range is correlated with the Rawah batholith based upon geochemistry and mineralogy (Plymate and others, 2005), but the exact relationship of these rocks to the Rawah batholith, proper, are still unclear. McCallum and Hedge (1976) report a whole-rock Rb-Sr age of 1,710 Ma; preferred age of batholith intrusion determined from U-Pb SHRIMP on zircon grains from several locations is 1,724–1,715 Ma with a mean age of 1718±4 Ma (Premo and others, 2010a). Plymate and others (2005) obtained an approximate crystallization age of 1,695±20 Ma by composite regression of discordant U-Pb isotope dilution-thermal ionization mass spectrometry (ID-TIMS) zircon-isochron data from three samples in the southern intrusive body

XjT **Trondhjemite of Thompson Canyon**—Light-gray, very fine-grained porphyritic to medium-grained equigranular, biotite-bearing leucocratic trondhjemite; forms thick tabular intrusions that are largely concordant to relict bedding in enclosing metasedimentary rocks; some locales display weak igneous biotite foliation parallel to trends of younger cross-folds in the region (Braddock and Cole, 1979). U-Pb discordia age is 1,726±15 Ma (Barovich, 1986) in the Big Thompson Canyon south of this quadrangle; Plymate and others (2005) obtained a zircon-isochron age from U-Pb TIMS-ID analysis of 1,702±6 Ma from a single body in the northern Mummy Range and correlate these rocks to the rocks in Big Thompson Canyon

Xp **Gneissic pegmatite**—White to pink, fine- to very coarse-grained, foliated granitic rocks composed of quartz, plagioclase, and microcline; exposed in the southern wall rocks of the Virginia Dale ring-dike complex where they are interlayered, folded and foliated parallel to the older metavolcanic and metasedimentary rocks (Xh, Xfb and Xbq) which they intrude; unit is intruded by granite of Log Cabin batholith (YgLC) and by younger pegmatite dikes (YXp)

PALEOPROTEROZOIC METAMORPHIC ROCKS

Biotite-bearing schist and gneiss units (Xb, Xbq, Xbk, Xbp, Xbg) and calc-silicate gneiss units (Xcg) are probably metasedimentary rocks; hornblende gneiss units (Xh) and felsic gneiss units (Xf, Xfl, Xfb) are probably metavolcanic rocks; mixed lithology units (Xbh, Xbqh, Xbkh) are probably interbedded metavolcanic and metasedimentary rocks. The biotite-bearing schists vary in metamorphic grade and minerology as shown by the metamorphic zone boundaries. Metasedimentary lithologies are notably sparse north of (approximately) the Skin Gulch shear zone, just as metavolcanic rocks are relatively sparse to the south (fig. 7). The age of regional metamorphism is 1,713±30 Ma (whole-rock Rb-Sr age of Peterman and others, 1968, recalculated by Braddock, Cole, and Eggler, 1989), similar to the emplacement age for widespread granodiorite (Xgd) equivalent to the Boulder Creek Granodiorite (1714.4±4.6 Ma [weighted mean of multiple SHRIMP and ID-TIMS U-Pb zircon ages]; Premo and Fanning, 2000), although some recrystallization may have continued later to about 1,693±5 Ma (SHRIMP U-Pb zircon age from migmatitic melt phase; Premo and others, 2007b). The age of deposition is inferred to be as old as 1,780 Ma based on comparison with primary volcanic ages, consistent with samarium-neodymium (Sm-Nd) model age of 1,800 Ma for the formation of continental crust in Colorado (DePaolo, 1981)

Xb **Biotite schist and gneiss**—Conspicuously banded rock marked by alternating layers of contrasting composition that probably reflect original sedimentary layering, as well as effects of metamorphic segregation and partial melting. This unit is typical of the highest grade metamorphic terranes, where coarse sillimanite is common and partial-melt textures are widespread. Dark-gray to black, medium- to coarse-grained layers are rich in biotite, sillimanite, and magnetite, and locally contain high-grade cordierite and (or) garnet (Gable and Sims, 1969; Cole, 1977, 2004b). Irregular quartzofeldspathic layers, bordered by selvages rich in biotite, sillimanite, and oxide minerals, formed in place in the rock during partial melting at the peak of metamorphism. Unit is subdivided as follows in areas of more detailed mapping and (or) better exposure (Cole, 1977; Braddock and Cole, 1990)

Xbq **Quartzofeldspathic mica schist**—Mica-poor schist interbedded with quartzofeldspathic metasandstone; typically shows identifiable sillimanite, and garnet is locally prominent. Unit contains interbedded knotted mica schist (Xbk) and sparse, thin beds of granule-sized metaconglomerate

Xbk **Knotted mica schist**—Biotite-rich schist that displays 3–10 mm porphyroblasts or clots of metamorphic minerals that exhibit a lumpy or knotted outcrop appearance. Contains interbedded quartzofeldspathic mica schist (Xbq) and sparse, thin beds of granule-sized metaconglomerate

Xbp **Porphyroblastic biotite schist**—Biotite- or sillimanite-rich variety of knotted mica schist that is characterized by large biotite porphyroblasts, typically about 0.635 cm (0.25 in) diameter. Unit forms an important stratigraphic marker symmetrically disposed about the axial surface of a major first-generation syncline in the Estes Park quadrangle to the south (Cole and Braddock, 2009)

Xbg **Granoblastic quartzofeldspathic biotite gneiss**—Medium- to dark-gray, fine-grained, thickly bedded to finely laminated, granoblastic gneiss consisting mainly of quartz, plagioclase, and biotite with smaller amounts of epidote, hornblende, or potassium feldspar; locally contains small calc-silicate clots that are flattened in the plane of compositional layering; typically interlayered with quartzofeldspathic mica schist (Xbq) and calc-silicate gneiss (Xcg)

Xbh **Biotite gneiss and hornblende gneiss, undivided**—Light- to dark-gray, medium-grained, layered to massive, moderately foliated gneiss consisting of interlayered bands of hornblende gneiss and amphibolite (Xh), biotite schist and gneiss (Xb), and lesser amounts of felsic gneiss (Xf) and calc-silicate gneiss (Xcg); felsic layers locally contain as much as 10 percent microcline. Unit mapped where exposure is poor and heterogeneity of layering makes mapping individual units difficult. Interpreted as interlayered metavolcanic and metasedimentary rocks. Forms an extensive part of the metavolcanic terrane intruded by the Rawah batholith (XgR) south of the Cache la Poudre River between about Rustic and Cameron Pass, and occurs as widespread blocky inclusions in the batholith within the Medicine Bow Mountains and Laramie

River valley. Primary age of deposition determined as 1,735±14 Ma (U-Pb SHRIMP from zircon; Kellogg, Ruleman, and others, 2008) from a sample near Kinikinik along the Cache la Poudre canyon

Xbqh **Quartzofeldspathic mica schist and hornblende gneiss, undivided**—Mapped north of Poudre Park where quartzofeldspathic mica schist is the predominant rock type, but multiple bands of hornblende gneiss and amphibolite (Xh), too thin to show at map scale, are interlayered parallel to foliation composing a significant percentage of the overall map unit

Xbkh **Knotted mica schist and hornblende gneiss, undivided**—Mapped north of Poudre Park where knotted mica schist (Xbk) is the predominant rock type, but multiple bands of hornblende gneiss and amphibolite (Xh), too thin to show at map scale, are interlayered parallel to foliation comprising a significant percentage of the overall map unit

Xh **Hornblende gneiss and amphibolite**—Dark-gray, greenish-gray, fine- to medium-grained, weakly to strongly layered hornblende-plagioclase gneiss and hornblende-biotite schist, locally interlayered with massive amphibolite. Chiefly consists of hornblende with variable amounts of plagioclase and magnetite, with minor amounts of biotite and (or) quartz. Contains thin layers and pods of white to light-green calc-silicate gneiss (Xcg); typically interlayered with granitic metavolcanic units and locally with metasedimentary biotite gneiss units. Age determined as 1,779±5 Ma (U-Pb SHRIMP from zircon; Workman, 2008) from a sample south of Eaton Reservoir in the northwestern part of the map

Xcg **Calc-silicate gneiss**—Greenish gray, gray, and white, moderately to strongly layered rock with granoblastic texture; consists mainly of plagioclase, epidote, diopside, calcite, and quartz with minor hornblende, garnet, or biotite; typically interlayered with hornblende gneiss (Xh) or with biotite gneiss (Xb)

Xf **Felsic gneiss**—Gray to pinkish-gray, medium- to coarse-grained, banded and moderately to strongly foliated felsic gneiss of monzogranitic to tonalitic composition. Contains common layers and lenses rich in biotite or biotite and hornblende that are elongate parallel to regional mineral foliation; typically interlayered with hornblende gneiss (Xh) and leucocratic granitic gneiss (Xfl). May be metamorphosed volcanic or intrusive felsic rocks. Primary ages of crystallization determined as 1,763±6 Ma and 1,755±23 Ma (U-Pb SHRIMP from zircon; Kellogg, Ruleman, and others, 2008) and 1,764±12 Ma (U-Pb TIMS-ID from zircon; Plymate and others, 2005). Where color index is low, this unit is difficult to distinguish from the younger granite of the Rawah batholith (XgR) which intruded about 50 million years later

Xfl **Leucocratic felsic gneiss**—Light- to medium-gray, pink- and orange-weathering, fine- to coarse-grained, weakly to moderately foliated rock composed primarily of quartz, oligoclase, microcline, and biotite; hornblende, garnet, and rare sillimanite locally present. Rocks have been described as gneissic granite, gneissic alaskite, gneissic quartz monzonite, or gneissic granodiorite. Compositional banding defined by changes in grain size or mineral proportions is typical in outcrop on the scale of inches to several feet. Unit typically interlayered with hornblende gneiss and other metavolcanic units. Primary age of volcanism is indicated by U-Pb SHRIMP age on zircon grains of 1766.6±8.3 Ma (Workman, 2008)

Xfb **Biotite felsic gneiss**—Dark-gray to pinkish-gray, medium- to coarse-grained, foliated and strongly lineated granodioritic rock with conspicuous microcline augen and aggregates that measure 1 to 2 in diameter; garnet and biotite are typical, and hornblende is locally present. Unit is intimately interlayered with hornblende gneiss (Xh) and with leucocratic felsic gneiss (Xfl), consistent with all three units comprising a compositionally diverse volcanic terrane. Primary age of volcanism is indicated by U-Pb SHRIMP age from zircon grains of 1,775.5±4.0 Ma (Workman, 2008)

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