Geologic Framework, Age, and Lithologic Characteristics of the North Park Formation in North Park, North-Central Colorado

Scientific Investigations Report 2016–5126

U.S. Department of the Interior
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COVER. View to the southeast looking toward the high peaks near the north end of the Never Summer Mountains. Highest peak on the skyline (right) is Mount Richthofen (12,940 feet [3,944 meters]), which is composed of 29.7-mega-annum (Ma, million years ago) granodiorite and monzonite of the Mount Richthofen stock. The serrate portion of the skyline to the left of Mount Richthofen, known as the Nokhu Crags, is composed of thermally metamorphosed Pierre Shale. Northeast-dipping rocks and sediments of the North Park Formation are locally exposed at Owl Ridge in the foreground. The base of the ledge-forming rocks in right foreground mark the base of the North Park Formation. The communications tower in left foreground is on the eroded top of the formation. A thin, 28.1-Ma ash-flow tuff, erupted from the Braddock Peak volcanic and intrusive complex in the north part of the Never Summer Mountains, is locally exposed slightly above the ledge-forming rocks in the right foreground. Photograph by R.R. Shroba, U.S. Geological Survey, August 6, 2011.

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By Ralph R. Shroba

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Conversion Factors, Symbols, and Abbreviations

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F–32)/1.8

Altitude, as used in this report, refers to distance above the vertical datum.

Symbols

°	degrees
′	minutes
≥	greater than or equal to
≤	less than or equal to

Divisions of Quaternary, Neogene, and Paleogene Time Used in This Report

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

Period or subperiod	Epoch		Age
Quaternary	Holocene		11.7–0 ka
	Pleistocene	late	126–11.7 ka
		middle	781–126 ka
		early	2.59 Ma–781 ka
Neogene	Pliocene		5.33–2.59 Ma
	Miocene		23.0–5.33 Ma
Paleogene	Oligocene		33.9–23.0 Ma
	Eocene		55.8–33.9 Ma
	Paleocene		65.5–55.8 Ma

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By Ralph R. Shroba

Abstract

Deposits of the North Park Formation of late Oligocene and Miocene age are locally exposed at small, widely spaced outcrops along the margins of the roughly northwest-trending North Park syncline in the southern part of North Park, a large intermontane topographic basin in Jackson County in north-central Colorado. These outcrops suggest that rocks and sediments of the North Park Formation consist chiefly of poorly consolidated sand, weakly cemented sandstone, and pebbly sandstone; subordinate amounts of pebble conglomerate; minor amounts of cobbly pebble gravel, siltstone, and sandy limestone; and rare beds of cobble conglomerate and altered tuff. These deposits partly filled North Park as well as a few small nearby valleys and half grabens. In North Park, deposits of the North Park Formation probably once formed a broad and relatively thick sedimentary apron composed chiefly of alluvial slope deposits (mostly sheetwash and stream-channel alluvium) that extended, over a distance of at least 150 kilometers (km), northwestward from the Never Summer Mountains and northward from the Rabbit Ears Range across North Park and extended farther northwestward into the valley of the North Platte River slightly north of the Colorado-Wyoming border. The maximum preserved thickness of the formation in North Park is about 550 meters near the southeastern end of the North Park syncline.

The deposition of the North Park Formation was coeval in part with local volcanism, extensional faulting, development of half grabens, and deposition of the Browns Park Formation and Troublesome Formation and was accompanied by post-Laramide regional epeirogenic uplift. Regional deposition of extensive eolian sand sheets and loess deposits, coeval with the deposition of the North Park Formation, suggests that semiarid climatic conditions prevailed during the deposition of the North Park Formation during the late Oligocene and Miocene.

The North Park Formation locally contains a 28.1-mega-annum (Ma, million years ago) ash-flow tuff near its base at Owl Ridge and is interbedded with 29-Ma rhyodacite lava flows and volcanic breccia at Owl Mountain. The formation locally contains vertebrate fossils at least as young as Barstovian age (about 15.9–12.6 Ma) and overlies rocks as young as the White River Formation, which contains vertebrate fossils of Chadronian age (about 37–33.8 Ma) in North Park and a bed of 36.0-Ma volcanic ash in the upper part of the Laramie River valley about 30 km northeast of Walden, Colorado. Based on the ages of the vertebrate fossils, folding of the rocks and sediments in the North Park syncline may be much younger than about 16 Ma.

Bedding characteristics of the North Park Formation suggest that (1) some or much of the sand, sandstone, and pebbly sandstone may have been deposited as sheetwash alluvium; (2) much of the siltstone may have been deposited as sheetwash alluvium or ephemeral pond or marsh deposits; (3) beds of sandy limestone probably were deposited as ephemeral pond or marsh deposits; and (4) altered tuff probably was deposited in ephemeral ponds or marshes. Most of the conglomerate and gravel in the North Park Formation are stream-channel deposits that were deposited by high-energy ephemeral or intermittent streams that issued from volcanic terrain rather than debris-flow deposits in relatively near-source fan deposits dominated by sediment gravity flow. Laccolithic doming, uplift, and tilting in the Never Summer Mountains near the Mount Richthofen stock, as well as the formation of volcanic edifices in the Never Summer Mountains and the Rabbit Ears Range during the late Oligocene and Miocene, significantly steepened stream gradients and greatly increased the erosive power and transport capacity of streams that transported large rock fragments and finer sediment eroded from volcanic and sedimentary sources and deposited them in the North Park Formation.

Much of the material that makes up the rocks and sediments of the North Park Formation was derived from the erosion of volcanic, intrusive, and sedimentary rocks. Clasts in the North Park Formation were derived chiefly from the erosion of volcanic and intrusive igneous rocks of late Oligocene and Miocene age that range in composition from rhyolite to trachybasalt. These rocks are locally exposed along the west flank of the Never Summer Mountains, the north flank of the Rabbit Ears Range, and the east flank of the Park Range at and near Rabbit Ears Peak. The minor amount of igneous and metamorphic clasts of Proterozoic age in the North Park Formation are commonly composed of durable rock types that are resistant to both physical and chemical weathering. Many of these clasts may have been derived from the erosion of conglomerate and

conglomeratic sandstone in the Coalmont Formation rather than from basement rocks currently at or near the ground surface in the Never Summer Mountains. Much of the sand and finer grained particles in the North Park Formation probably were derived from the erosion of sandstone, shale, and sandy claystone of the Coalmont Formation. Likewise, much of the abundant sand-sized quartz and feldspar in sand, sandstone, and pebbly sandstone of the North Park Formation probably was derived from the erosion of sandstone, conglomeratic sandstone, and conglomerate of the Coalmont Formation. Some of the fine sand, very fine sand, and silt in very fine grained sandstone and siltstone of the North Park Formation may be derived from the erosion of coeval eolian sand and loess in the Browns Park Formation that was transported across the Park Range by westerly or southwesterly winds.

Introduction

Deposits of the North Park Formation are locally preserved in an intermontane topographic basin in north-central Colorado known as North Park (fig. 1). North Park occupies the northern part of the North Park-Middle Park basin of Laramide age (Tweto, 1980), also informally known as the Colorado Headwaters basin (Cole and others, 2010), that formed during middle Paleocene through early Eocene time (Cole and Dechesne, 2013; Dechesne and others, 2013a). The main body of the North Park Formation is preserved in the North Park syncline (40 kilometers [km] long, 1–8 km wide, trending roughly N. 65° W.) in the southern part of North Park where it was mapped by Hail (1965, 1968), Kinney (1970a), Kinney and Hail (1970a), and Tweto (1976). Except for small, widely spaced exposures commonly observed along the southern margin of the North Park syncline, much of the North Park Formation is concealed beneath relatively thin surficial deposits, which consist of sheetwash alluvium, colluvium, and minor lag gravel that support a vegetative cover composed mainly of sagebrush, grasses, and herbs. These surficial deposits are formed chiefly by the disintegration and downslope transport of poorly consolidated sand and gravel and weakly cemented sandstone and conglomerate of the North Park Formation. At Peterson Ridge, the North Park Formation is locally exposed in small outcrops near the floodplain of the North Platte River and near Colorado Highway 14. At Owl Ridge, the formation is locally exposed in shallow road cuts and gullies near the floodplain of the Illinois River and in gullies on the south side of Owl Ridge about 1 km east of Jackson County Road 21 (fig. 2). The topographically highest deposits on the south limb of the syncline are typically cobbly pebble gravel of the North Park Formation and, locally, younger gravelly lag deposits formed by the erosion of gravelly deposits of the North Park Formation.

Prior to extensive erosion by the North Platte River and its tributaries during the Pliocene, or possibly during the latest Miocene, deposits of the North Park Formation once partly filled North Park to elevations of at least 3,200 meters (m) at Owl Mountain (Barnes, 1958), 2,835 m at Mexican Ridge and 2,815 m at Pole Mountain (Hail, 1968), and 2,760 m north of Kings Canyon near the headwaters of Camp Creek (Steven, 1960). Deposits of the North Park Formation also partly filled the upper part of the Laramie River valley (Camp, 1979), where they locally overlie poorly exposed fine-grained sediments of the White River Formation (fig. 3). Deposits of the North Park Formation accumulated in a shallow paleovalley(?) near Mountain Home, Wyoming (Blackstone, 1975), two small northwest-trending fault-bounded valleys (half grabens) on the east flank of the Sierra Madre near the Colorado-Wyoming border (Montagne, 1957, 1991; Hail, 1965; Izett, 1975; Mears, 1998), and the valley of the North Platte River from the east end of Independence Mountain northwestward to about 20 km north of Saratoga, Wyo. (Montagne, 1957, 1991). The spatial distribution of scattered outcrops suggests that deposits of the North Park Formation once covered at least 2,500 square kilometers (km^2) in North Park alone (Barnes, 1958; Steven, 1960; Hail, 1968). Maximum remaining thickness of the North Park Formation in North Park is about 340 m near the west end of the North Park syncline (Hail, 1965) and as much as about 550 m at Owl Mountain (Montagne and Barnes, 1957), where deposits of the North Park Formation are interbedded with lava flows and volcanic breccia 3–54 m thick (Barnes, 1958, p. 22) and about 29 million years (m.y.) old (table 1) that may have been deposited in a northwest-trending paleovalley. The original thickness of the North Park Formation is unknown because of extensive and widespread postdepositional erosion.

Gravelly deposits that may be temporally correlative with those of the North Park Formation, or younger, are preserved in Middle Park on Little Wolford Mountain, 9 km northwest of Kremmling, Colo. (fig. 1). Little Wolford Mountain is capped by ≤125 m of slightly bouldery, gravelly deposits that are rich in angular and very angular clasts composed of Tertiary intrusive and volcanic rocks chiefly of intermediate composition. These clasts probably were eroded from bedrock sources on the south flank of the Rabbit Ears Range, near and west of Hyannis Peak (Kinney and Hail, 1970b; Tweto, 1979). The thick sequence of gravelly deposits on Little Wolford Mountain overlies mainly siltstone and (or) very fine grained sandstone of the Troublesome Formation and may have been deposited in a paleovalley. The base of the gravelly material is ≥410 m above the modern channel of the Colorado River, which indicates that these gravelly deposits are considerably older than the oldest terrace deposits of Pleistocene age near Kremmling, which are 190 m above the Colorado River (Izett and Barclay, 1973). The gravelly deposits on Little Wolford Mountain probably predate the establishment of the Colorado River near Kremmling during the late Miocene or early Pliocene (Shroba and others, 2010) as well as an episode of major stream incision and drainage integration in the Rocky Mountain region, which began about 8–4 mega-annum (Ma, million years ago) (McMillan and others, 2006; Cather and others, 2012).

Thick (about 60–150 m), high-level deposits of bouldery gravel that may be temporally correlative with some of the older deposits of the North Park Formation are preserved southeast of North Park on and near Gravel Mountain (Izett, 1968; Cole and Braddock, 2009; Cole and others, 2011), where they probably mark the positions of two roughly north-trending paleovalleys

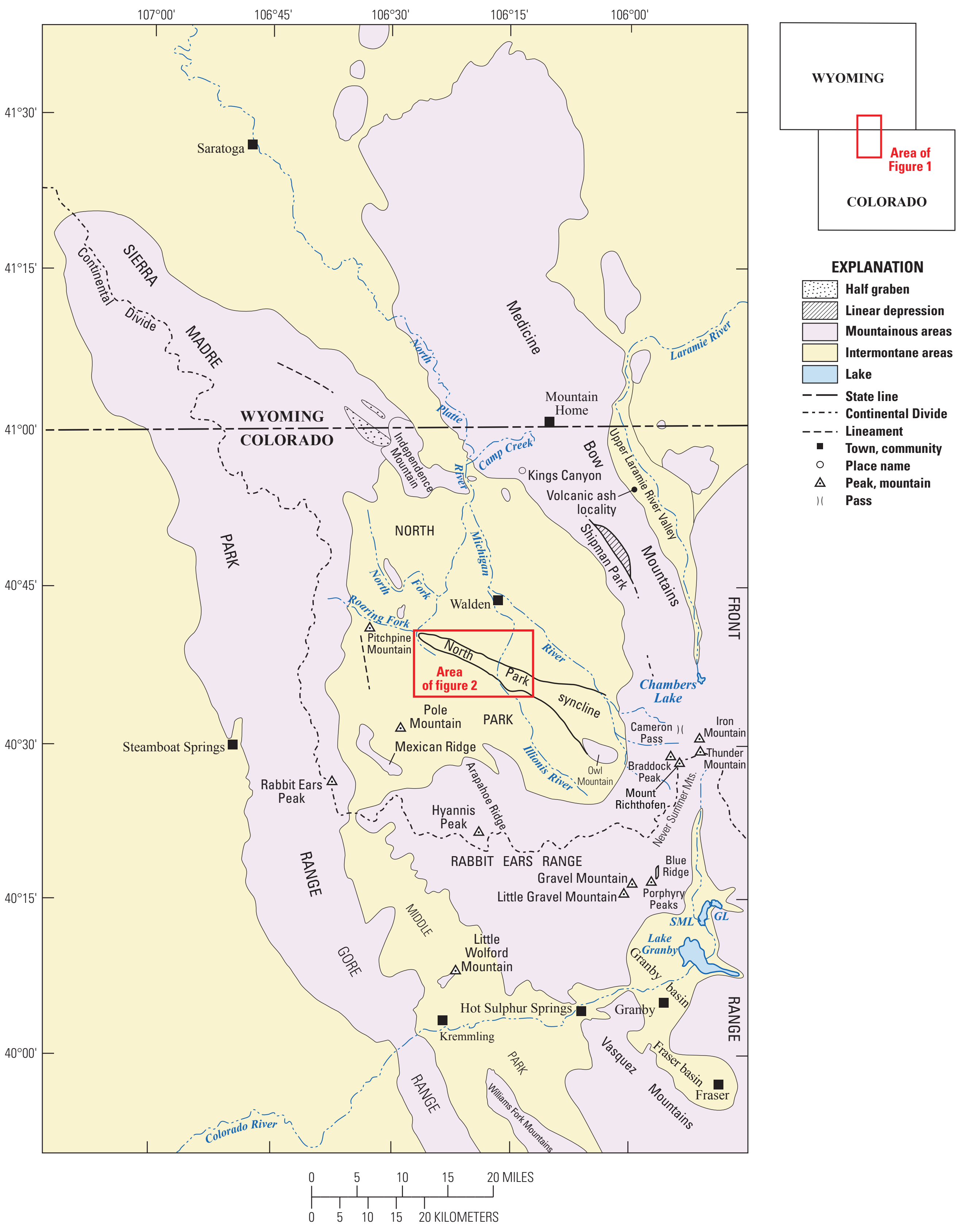


Figure 1. Geographic setting of North Park, Colorado. Sketch map showing mountainous areas, intermontane areas, and major waterbodies, as well as geologic and topographic features, streams, towns, and place names referred to in the text. Dashed lines indicate lineaments visible on National Agriculture Imagery Program imagery. (GL, Grand Lake; SML, Shadow Mountain Lake)

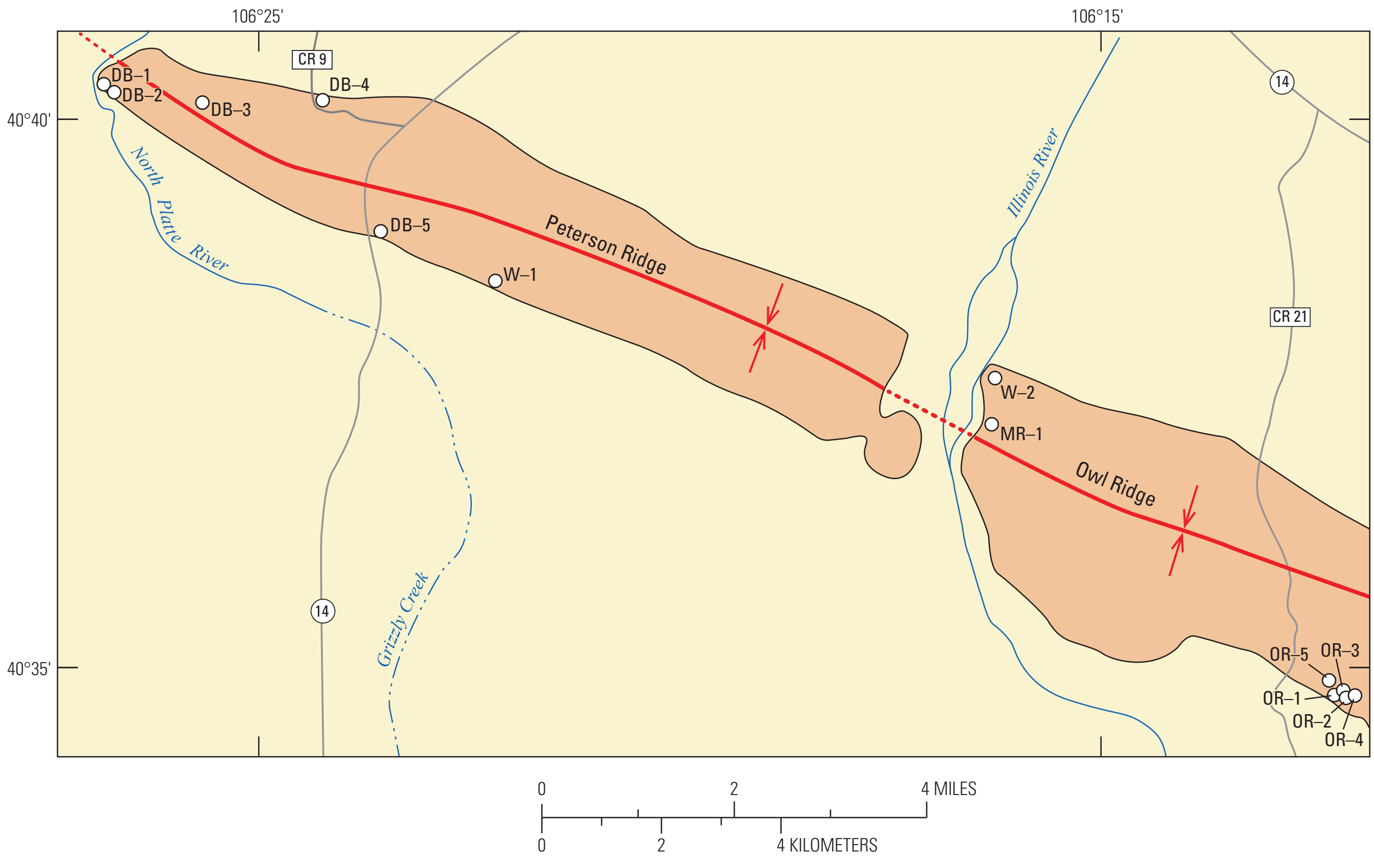
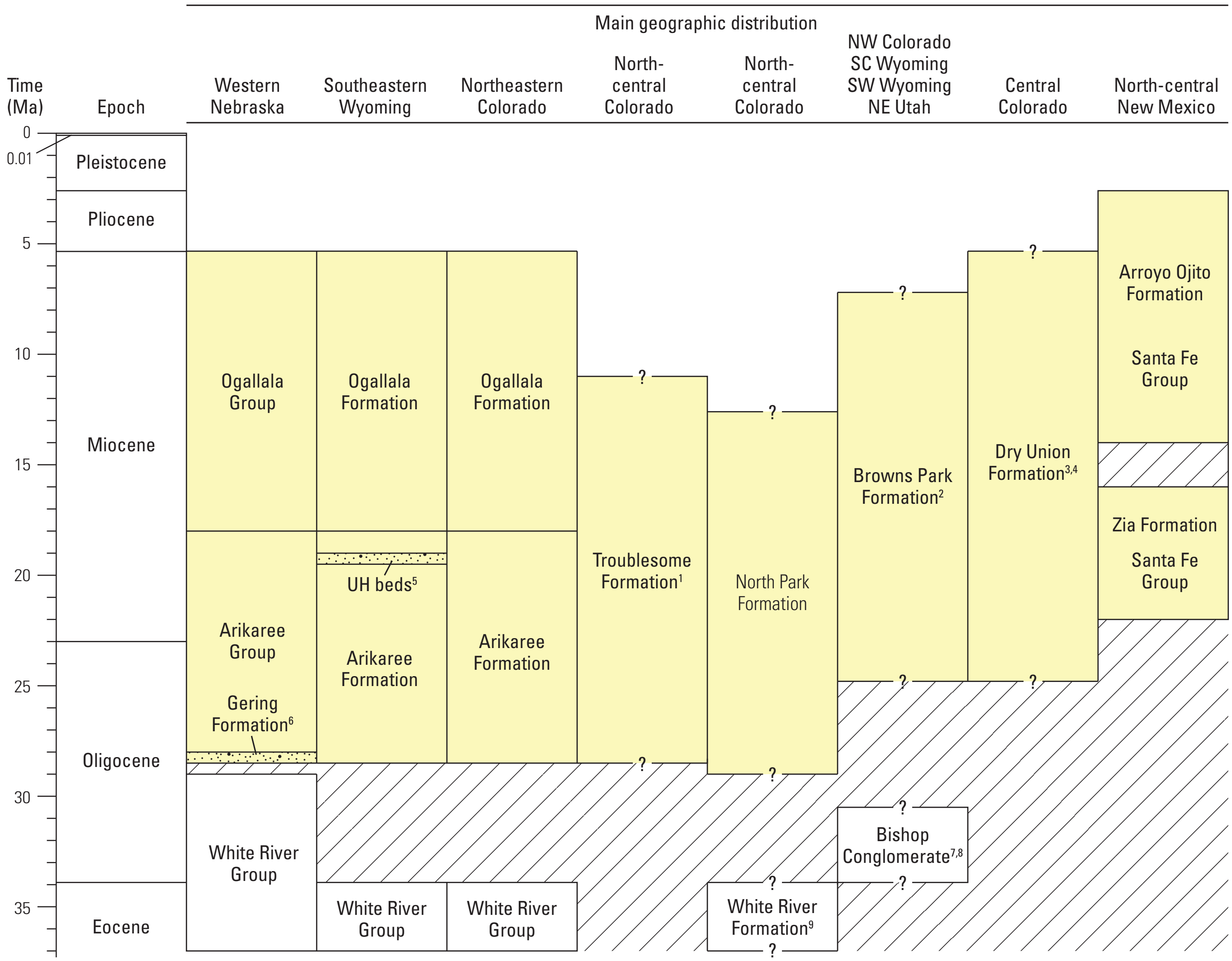


Figure 2. Locations of partial measured sections at Peterson Ridge and Owl Ridge on the northern and southern flanks of the North Park syncline. Site identifiers (for example, DB–1) correspond to partial measured sections described in tables 5–17. Light brown shading indicates areas where the North Park Formation is at or near the ground surface in the North Park syncline (based on geologic mapping by Madole, 1991). Surficial deposits and the Coalmont Formation are not shown. Beds of the North Park Formation in the area of the syncline commonly strike about N. 65° W., and dips commonly range from about 15° to 30° to the northeast and southwest. Axis of syncline is shown in red, dotted where deposits of the North Park Formation are concealed beneath surficial deposits (yellow shading).

at and near the southern end of the Never Summer Mountains (fig. 1). Gravelly deposits on Gravel Mountain and on nearby Little Gravel Mountain are essentially unconsolidated, poorly sorted, and without bedding. They consist of rounded, granule- to boulder-sized clasts as much as 4.3 m in diameter set in a coarse, sandy matrix. These clasts are chiefly composed of Proterozoic basement rocks and porphyritic andesite pebbles (Izett, 1968); the latter probably were derived from conglomerate of Paleocene age (Dechesne and others, 2013b) near the base of the Middle Park Formation. Nearby deposits of bouldery gravel on Blue Ridge and on the east side of the Porphyry Peaks are similar in grain size and somewhat similar in clast lithology to those at Gravel Mountain and Little Gravel Mountain, although the former deposits (1) lack clasts composed of porphyritic andesite (Cole and others, 2011) and (2) contain some clasts that closely resemble nearby outcrops of quartz latite of Apiatan Mountain (Cole and Braddock, 2009) that was intruded at 28.4±2.3 Ma (whole-rock potassium-argon [K-Ar] age; Marvin and others, 1974). Deposits of high-level bouldery gravel on Gravel Mountain and Little Gravel Mountain, as well as those on Blue Ridge and on the east side of Porphyry Peaks, lack volcanic or intrusive clasts eroded from the late Oligocene (about 29.6–26 Ma) Braddock Peak complex sourced in the northern part of the Never Summer Mountains (Cole and others, 2008; Cole and Braddock, 2009). The clasts in these bouldery deposits possibly were derived from a drainage basin or basins that did not include rocks of the Braddock Peak complex.

Usage of the name North Park Formation began with Beekly (1915), who restricted the name North Park to the topmost beds in North Park, which are characterized by calcareous sandstone and ash beds. Later work by Montagne and Barnes (1957) along the flanks of the North Park syncline revealed that the lowest part of the North Park Formation, as established by Beekly (1915), locally contains vertebrate fossil-bearing beds typically assigned to the White River Formation. Geologic mapping in and near the syncline by Hail (1965), Kinney (1970a), Kinney and Hail (1970a), and Tweto (1976) assigned light-colored, tuffaceous claystone, siltstone, and minor fine-grained sandstone beds, which locally contain titanothere bones of Chadronian age (table 2) (Montagne and Barnes, 1957), to the White River Formation and the overlying coarser grained sandstone and conglomerate to the North Park Formation. The North Park Formation typically contains sparse to abundant volcanic clasts (Hail, 1965); locally contains a thin, poorly



[1]The Troublesome Formation probably is older than 28.4 Ma because a latite porphyry intrusion, with a zircon ission-track age of 28.4±2.3 Ma, probably intruded beds of the Troublesome Formation at the north end of the Granby basin (Izett, 1974).

[2]Locally, beds of the Browns Park Formation in northwestern Colorado are cut by a lamprophyre dike and latite porphyry intrusion that yielded potassium-argon (K-Ar) ages on biotite of 11.4±0.5 Ma and 7.8±0.4 Ma, respectively (Buffler, 2003). Ages are corrected using conversion factors of Dalrymple (1979).

[3]The Dry Union Formation contains fossil mammals as young as 6–5 Ma (Hopkins, 2005).

[4]Sediments of the Dry Union Formation probably are younger than 30.4 or 28.9 Ma (Shroba and others, 2014, and references cited therein).

[5]The Upper Harrison beds of Peterson (1907, 1909) contain a volcanic ash that yielded a fission-track age on zircon of 19.2±0.5 Ma (Tedford and others, 2004).

[6]In western Nebraska, the Gering Formation is the oldest formation of the Arikaree Group.

[7]The Bishop Conglomerate is only recognized in northeastern Utah and southwestern Wyoming (Hansen, 1986).

[8]Two ash beds in the Bishop Conglomerate in northeastern Utah yielded weighted-mean $^{40}Ar/^{39}Ar$ ages on sanidine of 30.54±0.22 Ma and 34.03±0.04 Ma (Kowallis and others, 2005).

[9]Volcanic ash from an ash bed in the White River Formation in the upper part of the Laramie River valley yielded an $^{40}Ar/^{39}Ar$ age on sanidine of 36.0±0.3 Ma (table 3).

Figure 3. Generalized stratigraphic relations for sediments and rocks of Neogene and late Paleogene age mentioned in this report. Younger deposits are not shown. The range in age of most of the sediments and rocks depicted in this figure are based chiefly on ages shown in table 1 and those cited elsewhere in this report. Ranges in age for the Ogallala Group, Ogallala Formation, Gering Formation, and Upper Harrison (UH) beds of Peterson (1907, 1909) are from Tedford and others (2004). The range in age for the White River Formation is from Lillegraven (1993), Larson and Evanoff (1998), Prothero and Emry (2004), and Tedford and others (2004); that for the Bishop Conglomerate is from Kowallis and others (2005); and those of the Arroyo Ojito Formation and the Zia Formation are from Tedford and Barghoorn (1999). Minimum age for the Dry Union Formation is based on ages of fossil mammals (Hopkins, 2005). Dotted pattern indicates a formation within a group or a unit within a formation, and diagonal lines indicate nondeposition or a missing section and associated unconformity. Yellow shading indicates range in age of North Park Formation and of correlative stratigraphic units mentioned in this report. (Ma, mega-annum [million years ago]; NE, northeastern; NW, northwestern; SC, south-central; SW, southwestern)

Table 1. Radiometric ages of lava flows, tuffs, and other volcanic deposits within or interbedded with the North Park Formation, Troublesome Formation, and main unit of Browns Park Formation above basal conglomerate in Colorado, Wyoming, and Utah.

[Abbreviations: an, anorthoclase; Ar, argon; b, basalt; bt, biotite; BP, Browns Park Formation; BPv, Browns Park valley near northeastern corner of Utah; BPl, Browns Park Formation lower sequence of Montagne (1991); BPu, Browns Park Formation upper sequence of Montagne (1991) also referred to by Montagne as the North Park Formation equivalent; Fb, Fraser basin; FT, fission track; Gb, Granby basin; gl, glass; GMB, Grouse Mountain Basalt; GM, Grouse Mountain near Hot Sulphur Springs, Colo.; K, potassium; MP, Middle Park near Kremmling, Colo.; NP, North Park Formation; NS, Never Summer Mountains; OM, Owl Mountain; OR, Owl Ridge; p, pumice; pl, plagioclase; PR, area west of Park Range in northwestern Colorado; rd, rhyodacite lava flow; san, sanidine; SM, valley on east side of Sierra Madre Range near Saratoga, Wyo.; t, tuff; TR, Troublesome Formation; wGR, west side of Gore Range; wr, whole rock; zr, zircon]

Geologic unit	Location	Dating method	Deposit dated	Material dated	Age (Ma)	Reference
BP	PR	FT	t	gl[1]	7.2±0.6	Naeser and others (1980)
BP	PR	FT	t	gl[1]	8.2±1.4	Izett (1975)
BP	PR	FT	t	zr	8.3±0.7	Luft (1985)
BP	PR	FT	t	zr	8.6±0.8	Luft (1985)
BP	PR	FT	t	zr	9.0±2.1	Snyder (1980a)
BP	PR	FT	t	zr	9.1±1.0	Izett (1975)
BP	PR	FT	t	zr	9.2±1.7	Snyder (1980a)
BP	PR	FT	t	zr	9.8±0.4	Naeser and others (1980)
BP	PR	FT	t	zr	9.9±0.4	Naeser and others (1980)
TR	MP	$^{40}Ar/^{39}Ar$	t	san, pl	[2]11.0±0.05	Izett and Obradovich (2001)
BP	PR	FT	t	zr	11.3±0.8	Honey and Izett (1988)
BP	BPv	K-Ar	t[3]	gl	11.8±0.4	Damon (1970)
BPu	SM	$^{40}Ar/^{39}Ar$	p	an	[2]14.5±0.04	Montagne (1991)
TR	MP	$^{40}Ar/^{39}Ar$	t	san	[2]15.2±0.04	Izett and Obradovich (2001)
TR	MP	$^{40}Ar/^{39}Ar$	t	san	[2]15.6±0.05	Izett and Obradovich (2001)
TR	MP	$^{40}Ar/^{39}Ar$	t	san, pl	[2]15.8±0.10	Izett and Obradovich (2001)
BP	PR	FT	t	zr	15.8±2.6	Snyder (1980a)
BPu	SM	$^{40}Ar/^{39}Ar$	p	bt	[2]15.9±0.04	Montagne (1991)
TR	MP	$^{40}Ar/^{39}Ar$	t	san	[2]17.1±0.06	Izett and Obradovich (2001)
TR	MP	$^{40}Ar/^{39}Ar$	t	san	[2]18.3±0.07	Izett and Obradovich (2001)
TR	MP	$^{40}Ar/^{39}Ar$	t	san	18.9±0.22	Izett and Obradovich (2001)
GMB	GM	K-Ar	b[4]	wr	20.1±0.4	Izett (1975)
BP	PR	FT	t	zr	20.2±1.9	Snyder (1980b)
BPl	SM	$^{40}Ar/^{39}Ar$	p	bt	[2]23.0±0.15	Montagne (1991)
BP	PR	FT	t	zr	23.3±3.7	Izett (1975)
TR	MP	$^{40}Ar/^{39}Ar$	t	san	[2]23.5±0.06	Izett and Obradovich (2001)
BP	PR	FT	t	zr	23.5±2.5	Izett (1975)
BP	wGR	$^{40}Ar/^{39}Ar$	b[5]	wr	23.97±0.29	Kunk and others (2002)
BP	PR	K-Ar	t	bt	24.8±0.8	Izett and others (1970)
TR	Gb	K-Ar	b[6]	wr	[7]26.7±0.9	Marvin and others (1974)
TR	Fb	$^{40}Ar/^{39}Ar$	t[8]	san	[9]27.3±0.1	E.E. Larsen[10], written comun., 2009
NP	NS, OR	$^{40}Ar/^{39}Ar$	p[11]	san	[2]28.1±0.06	E.E. Larsen, written comun., 2013
NP	OM	$^{40}Ar/^{39}Ar$	rd[12, 13]	bt	28.8±0.2	J.C. Cole, USGS, oral comun., 2013
NP	OM	$^{40}Ar/^{39}Ar$	rd[14]	bt	29.0±0.4	J.C. Cole, USGS, oral comun., 2013

[1]Fission-track ages on glass may be minimum ages; basalt flows that overlie the Browns Park Formation have K-Ar ages of 10.7±0.5 Ma and 9.5±0.05 Ma (Buffler, 1967).

[2]Mean age.

[3]Tuff was collected by Winkler (1970) and K-Ar age was determined by Damon (1970).

[4]East of Kremmling, basaltic flows are interbedded with sediments of the Troublesome Formation (Izett, 1975).

[5]Lowest of three, dated basalt flows at Yarmony Mountain (Kunk and others, 2002), about 30 km southwest of Kremmling, Colo.

[6]Lowest of two basalt flows in Troublesome Formation in Granby basin near Granby, Colo. (Izett, 1974).

[7]K-Ar age was corrected using decay constants of Steiger and Jäger (1977); uncorrected age is 25.9±0.4 Ma (Izett, 1974).

[8]Rhyolite tuff is in the lower part of the Troublesome Formation or may underlie the formation.

[9]Age reported by Knox (2005) and corrected by E.E. Larson.

[10]Professor Emeritus, University of Colorado at Boulder.

[11]Pumice from an ash-flow tuff in North Park Formation in North Park syncline.

[12]Lava flow beneath highest lava flow at Owl Mountain.

[13]Highest lava flow at Owl Mountain has $^{40}Ar/^{39}Ar$ age of 29.35±0.09, which is greater than that of the underlying older dated flow (J.C. Cole, oral commun., 2013).

[14]Lava flow on west side of county road 27 between Owl Ridge and Owl Mountain.

Table 2. North American land mammal ages used in this report.

[Ages of time boundaries are those of Tedford and others (2004) except for the Chadronian, which is that of Prothero and Emry (2004). Ma, mega-annum (million years ago)]

Land mammal age	Age
Barstovian	15.9–12.6 Ma
Hemingfordian	19.0–15.9 Ma
Arikareean	30.0–19.0 Ma
Chadronian	37–33.8 Ma

welded, pumice-rich, rhyolitic tuff near its base at Owl Ridge (Kinney, 1970a); and is interlayered with rhyodacite lava flows and volcanic breccia at Owl Mountain (Montagne and Barnes, 1957; Barnes, 1958; Cole and others, 2010). The North Park Formation disconformably overlies deposits of the White River Formation and, locally, those of the Coalmont Formation (Steven, 1960; Hail, 1965; Kinney, 1970a; Tweto, 1976). The deposition of the White River Formation followed a major episode of erosion and stream incision (Evanoff, 1990) at about 42–37 Ma (Lillegraven, 1993; Cather and others, 2012). This episode of regional erosion and stream incision postdates the Laramide uplift of the Sierra Madre and Park Range at about 79–49 Ma and 75–45 Ma, respectively (Kelley, 2005). Major uplift of the Medicine Bow Mountains, Park Range, and possibly the Sierra Madre, however, postdates the deposition of the Coalmont Formation and is likely younger than early Eocene in age (Dechesne and others, 2013a). Major uplift and attendant erosion of these basement-cored uplifts after early Eocene time may account for the accumulation of poorly sorted, locally bouldery basal conglomerate of the Browns Park Formation along the west flank of the Park Range (Buffler, 1967, 2003) and the east flank of the Sierra Madre (Montagne, 1991).

The uniformly fine-grain, silt-rich tuffaceous character and the relatively insignificant content of locally derived material in deposits of the White River Formation in and near North Park (Montagne and Barnes, 1957; Steven, 1960; Hail, 1965), as well as in adjacent and nearby parts of southeastern Wyoming, northeastern Colorado, and western Nebraska (Denson and Bergendahl, 1961), suggest that sediments of the White River Formation accumulated in low-energy environments that received a considerable amount of airborne volcanic ash (Denson and Chisholm, 1971) with minimal input from local bedrock sources and little or no influence from any local tectonic activity (Blackstone, 1975).

Geologic Framework

Key factors that contribute to the understanding of the geologic framework of the North Park Formation are (1) the structural setting of the North Park syncline, (2) the geologic setting and depositional environment of the North Park Formation, and (3) the inferred climatic conditions during the deposition of the North Park Formation.

Structural Setting of the North Park Syncline

In North Park, the North Park Formation is mainly preserved in, but is only locally exposed in, a northwest-trending structure known as the North Park syncline. Exposed beds on the southern limb of the syncline dip 12°–32° NE.; dip values average 23° (Hail, 1965; Kinney, 1970a; Kinney and Hail, 1970a; this study). Exposed beds on the northern limb of the syncline dip 14°–33° SW.; dip values average 23° (Hail, 1965; Kinney, 1970a; Kinney and Hail, 1970a; this study). Dip values measured on both limbs of the syncline do not show any obvious relation between dip value and stratigraphic position within the North Park Formation. Attitudes measured in beds of the North Park Formation in the North Park syncline are similar to those of nearby beds of the Coalmont Formation (Hail 1965; Kinney and Hail, 1970a), which suggests that little or no folding occurred in the area of the North Park syncline between the deposition of the Coalmont Formation and the deposition of the North Park Formation. Folding may be due to movement on either (1) a major, southwest-dipping normal fault on the north flank of the syncline (Behrendt and others, 1969; Kinney, 1970a, Kinney and Hail, 1970a; Izett, 1975) or (2) a concealed, northeast-dipping thrust fault or transpressive structure on the south flank of the syncline (D.S. Stone, written commun., 1999, as cited in Erslev and others, 1999). A recent paleomagnetic investigation in the eastern part of the North Park syncline indicates that folding occurred after the deposition of the 28.1-Ma ash-flow tuff near the base of the North Park Formation (West and others, 2015).

Folds formed in rocks and sediments that are similar in age to those of the North Park Formation are also present in Middle Park and on the west side of the Park Range. Three north- to northwest-trending synclines with gently to locally steeply dipping beds in Middle Park near Kremmling, Colo., are formed in the Troublesome Formation on the east side of a down-to-east Neogene normal fault that locally displaces the Troublesome Formation (Izett and Barclay, 1973; Izett, 1975). A few north- to northeast-trending anticlines and locally overturned synclines, north and northwest of Steamboat Springs, Colo., locally deform the Browns Park Formation (Buffler, 1967, 2003; Snyder, 1980c).

Geologic Setting and Depositional Environment of the North Park Formation

The deposition of the North Park Formation was coeval in part with local volcanism, extensional faulting, and the development of half grabens (Cole and others, 2008, 2010) and was accompanied by post-Laramide regional epeirogenic uplift driven, in part, by heating and thinning of the lithosphere as well as by inflation of the crust produced by the intrusion of extensive, relatively low-density batholiths and stocks of middle Tertiary age (Eaton, 2008). Regional epeirogenic uplift promoted eastward tilting and erosion of the Front Range (Steven and others, 1997), which led to the deposition of extensive gravel units in the upper part of the

Ogallala Formation in northeastern Colorado and the Ogallala Group in western Nebraska (Heller and others, 2003) between about 13.5 and 6 or 5 Ma (Tedford, 2004; Duller and others, 2012) and to canyon cutting after 6 or 5 Ma. Depth of canyon cutting probably was proportional to amount of uplift (Steven and others, 1995). Some of the post-Miocene uplift, tilting, and warping in northeastern Colorado and western Nebraska, as well as the current elevation of this region, may be driven by mantle processes (Leonard, 2002; McMillan and others, 2006) such as mantle convection (Karlstrom and others, 2012).

The deposition of the lower part of the North Park Formation may have been coeval, in part, with the deposition of the thick (≤90 m), pre-24.8-Ma (Izett and others, 1970), locally derived, basal conglomerate of the Browns Park Formation. The latter probably accumulated as debris-flow, sheetflood, and stream-channel deposits on an erosion surface (possibly 42–37 Ma; Cather and others, 2012) formed along the west flank of the Park Range (Buffler, 1967, 2003) and the east flank of the Sierra Madre (Montagne, 1991). The deposition of the basal conglomerate of the Browns Park Formation is probably due to tectonic uplift of these ranges (Izett, 1975). Extensional faulting and development of synvolcanic half grabens, formed predominantly along northwesterly trends, accompanied volcanism at the Braddock Peak volcanic and intrusive complex in the Never Summer Mountains and adjacent parts of the southern Medicine Bow Mountains and western Front Range. As much as 150 m of 28.8- to 28.2-Ma andesite flows and volcanic breccia, rhyolite tuff, and dacite flows accumulated at the Braddock Peak complex (Cole and others, 2008). These rocks dip about 35°–50° NE. into a major northwest-trending fault and are overlain by 28.1-Ma tuff (informally known as the Thunder Mountain tuff) that dips about 15°–20° into the fault (Cole and others, 2008). Pumice clasts eroded from either the Braddock Peak complex or the Rabbit Ears Range were transported by streams as far east as western Nebraska, where pumice clasts from the basal part of the Gering Formation of the Arikaree Group yielded a $^{40}Ar/^{39}Ar$ weighted mean age on sanidine of 28.3±0.03 Ma (Swisher, 1995).

Normal (extensional) faulting, possibly related to intrusions and eruptions in the Braddock Peak complex, also likely played a key role in the alignment of the upper part of the Laramie River valley north of Chambers Lake (Izett, 1975; Camp, 1979; McCallum and others, 1983) as well as the upper part of the Colorado River valley south of Cameron Pass (Izett, 1975). Normal faulting likely accounts for the northwest-trending linear depression near the crest of the Medicine Bow Mountains known as Shipman Park (Dechesne and others, 2013b) and those on the west side of Independence Mountain (Montagne, 1957). A few discontinuous, northwest-trending lineaments (visible on imagery from the National Agriculture Imagery Program) in the western part of the Medicine Bow Mountains, in the eastern part of the Sierra Madre, and on the western margin of North Park southwest of Pitchpine Mountain (fig. 1) may be due in part to extensional faulting during the Neogene. Normal faults showing major movement during the Neogene and those inferred to have major movement during the Neogene have been mapped along the linear, north-south-trending eastern margin of the Park Range, along the north side of the North Park syncline, and along and near the southern margin of Independence Mountain at the north end of North Park (Hail, 1965; Tweto, 1978; Colman, 1985; Dechesne and others, 2013b). The lineament southwest of Pitchpine Mountain (roughly 9 km long, trending N. 10° W.) suggests that, locally, faulting has displaced surficial deposits, some as young as the till of the Pinedale glaciation of late Pleistocene age.

After the deposition of the North Park Formation, tectonic activity produced the North Park syncline as well as minor normal faults that displace the North Park Formation at three localities near Independence Mountain, near the north end of North Park (Hail, 1965; Izett, 1975). Folding of the rocks and sediments in the North Park syncline is younger than about 16 Ma and may be much younger, based on the ages of fossil mammals preserved in deformed rocks (see "Age of the North Park Formation," p. 9). Folding may be due to faulting near the syncline (Kinney, 1970a, Kinney and Hail, 1970a; Izett, 1975; Tweto, 1978) or beneath the syncline (Behrendt and others, 1969). The minor faults near the north end of North Park are parallel to the normal fault on the south margin of Independence Mountain (Izett, 1975; Dechesne and others, 2013b) and postdate the deposition of the North Park Formation (Izett, 1975). Neogene faults in the North Park area commonly are high-angle, en echelon structures that strike northwest to west-northwest and form linear half grabens and transtensional rhomboid grabens and, locally, form tight transpressional folds (Workman, 2013). On the east side of North Park, at the north end of the Never Summer Mountains, intrusive igneous rocks of the 29.7-Ma Mount Richthofen stock are cut by north-trending, steeply dipping, strike-slip faults that were later reactivated as extensional dip-slip faults (Erslev and others, 1999). This episode of strike-slip faulting postdates Laramide contraction and uplift of the nearby Sierra Madre and Park Range, but it may be related to major uplift of the Medicine Bow Mountains and Park Range mostly after early Eocene time (Dechesne and others, 2013a).

Bedding characteristics of the North Park Formation suggest that some or much of the sand, sandstone, and pebbly sandstone may have been deposited as sheetwash alluvium, and much of the siltstone may have been deposited as sheetwash alluvium or ephemeral pond or marsh deposits. The presence of channel-fill (stream-channel) deposits with well-defined margins and scoured bases (Smith, 2000; Kuhle and Smith, 2001), as well as the lack of nonsorted debris-flow deposits or sheetflood deposits (the latter with their characteristic thin couplets composed of relatively fine over coarse-grained sediments [Blair, 1987; Blair and McPherson, 1994]), suggests that many of the pebbly deposits in the North Park Formation at Peterson Ridge and Owl Ridge are streamflow-dominated alluvial slope deposits rather than relatively near-source fan deposits dominated by sediment gravity flow. Stream-channel deposits in the North Park Formation commonly consist of parallel, planar-bedded, well-stratified cobbly pebble gravel, pebble conglomerate, and sandy pebble conglomerate overlain by pebbly sandstone that locally contains lenses of pebble conglomerate. These deposits are rich in volcanic clasts, and probably were deposited by high-energy ephemeral or intermittent streams that issued from volcanic terrain. Laccolithic uplift, doming, and tilting of the area at and near the Never Summer thrust during the emplacement of the Mount Richthofen stock (Cole and others, 2008), as well as formation of volcanic edifices mainly in the Never Summer Mountains and the Rabbit Ears Range, significantly steepened stream gradients and greatly increased the erosive power and transport capacity of streams. These high-energy streams transported volcanic and sedimentary detritus eroded from these ranges and deposited it in the North Park Formation. Owing to the high-energy depositional environment of these streams, fine- to medium-grained sand, sandy silt, or silt overbank and stream-channel deposits were not observed.

Deposits of the North Park Formation probably once formed a broad and relatively thick sedimentary apron composed chiefly of alluvial slope deposits (mostly sheetwash alluvium and stream-channel alluvium) that extended northwestward from the Never Summer Mountains and northward from the Rabbit Ears Range across North Park and northwestward into the valley of the North Platte River to at least 20 km north of Saratoga, Wyo. (Steven, 1960; Montagne, 1991), a distance of at least 150 km.

Inferred Climatic Conditions during the Deposition of the North Park Formation

Deposition of extensive eolian sand sheets and loess deposits of the Browns Park Formation (24.8–7.2 Ma) in northwestern Colorado (Luft, 1985; Buffler, 2003), sandy loess of the Upper Harrison beds of Peterson (1907, 1909) of latest Arikareean age (Hunt, 2002; Tedford and others, 2004) in southeastern Wyoming and western Nebraska (Hunt, 1990), and thick eolian deposits of the Zia Formation (22–16 Ma) of the Santa Fe Group in the Rio Grande rift of north-central New Mexico (table 3) (Tedford and Barghoorn, 1999; Williams and Cole, 2007) suggests that semiarid climatic conditions prevailed regionally during the deposition of the North Park Formation during the late Oligocene and Miocene. However, the pollen assemblages in two samples of fine-grained carbonaceous sediments from the Troublesome Formation, collected about 11 and 13 km northeast of Kremmling, Colo. (U.S. Geological Survey botanical localities D1905 and D3493), suggest that climatic conditions during the time of deposition of these pollen-bearing sediments may not have been much drier than those of the present (about 30 centimeters [cm] mean annual precipitation) (Shroba and others, 2010).

Age of the North Park Formation

The age of the North Park Formation is not well constrained. The North Park Formation in North Park disconfomably overlies beds of the White River Formation, which locally contains titanothere bones of Chadronian (late Eocene) age (Montagne and Barnes, 1957). This North American land mammal age is in accord with an isotopic age recently determined for a white vitric volcanic ash bed within fine-grained sediments of the White River Formation in the west-central part of the Laramie River valley (volcanic ash locality in fig. 1), where the North Park Formation directly overlies beds of the White River Formation. This vitric volcanic ash yielded a $^{40}Ar/^{39}Ar$ age on biotite of 36.0±0.3 Ma (table 3).

The North Park Formation commonly contains lenses as well as scattered fragments composed chiefly of dark, relatively fine grained volcanic clasts and, locally, those composed of rhyolitic clasts. At Owl Ridge, the North Park Formation locally contains a thin, poorly welded, pumice-rich, rhyolitic ash-flow tuff near its base. Based on its chemistry and mineralogy, this tuff is considered to be an outflow phase erupted during a pyroclastic event at the Braddock Peak complex (Cole and others, 2008), about 15 km southeast of the mapped extent of the North Park syncline. Three samples of this tuff, including one sample collected from the tuff bed near the base of the North Park Formation in the North Park syncline at Owl Ridge, have a $^{40}Ar/^{39}Ar$ mean age on sanidine of 28.1±0.06 Ma (table 1). The oldest volcanic rock interbedded with sediments of the North Park Formation at Owl Mountain is rhyodacite that has a $^{40}Ar/^{39}Ar$ age on biotite of 29.0±0.4 Ma (table 1).

The dark volcanic and rhyolitic clasts in the North Park Formation may have been eroded from trachybasalt flows and rhyolite tuffs, respectively, exposed at and near the Braddock Peak complex. These trachybasalt flows range in age from 29.6 to 28.5 Ma, whereas the rhyolite tuffs range in age from

Table 3. Isotopic age of volcanic ash in the Laramie River valley.

[$^{40}Ar/^{39}Ar$ analysis performed in Denver, Colorado, by M.A. Cosca, U.S. Geological Survey. Datum: North America 1927. Ar, argon; Ma, mega-annum (million years ago); UTM, Universal Transverse Mercator]

Sample number	Rock name	Geologic unit	Location (UTM)	Mineral analyzed	Technique	Age
2012–08–11–1	Volcanic ash	White River Formation[1]	0416645E 4527680N	Biotite	$^{40}Ar/^{39}Ar$	36.0±0.3 Ma[2]

[1]Poorly exposed sediments that make up the formation near sample number 2012–08–11–1 appear to be composed chiefly of siltstone, very fine grained sandstone, and one or more ash beds.

[2]This ash is similar in age and may be equivalent to Ash B of Emry (1973), a white vitric ash exposed in the lower part of the White River Formation at Flagstaff Rim in central Wyoming about 190 kilometers northwest of sample number 2012–08–11–1, which yielded a $^{40}Ar/^{39}Ar$ age on biotite of 35.92±0.34 Ma (Swisher and Prothero, 1990).

28.6 to 28.2 Ma, (Cole and others, 2008). The ages of volcanic rock of similar composition exposed in the Rabbit Ears Range and on the east flank of the Park Range at and near Rabbit Ears Peak are not known, although rhyolite in the Rabbit Ears Volcanics on the south flank of the Rabbit Ears Range has been radiometrically dated. A sanidine separate (contaminated by microcline) collected from a rhyolite-welded tuff breccia in the middle part of the Rabbit Ears Volcanics, about 9 km northwest of Hot Sulphur Springs, Colo., yielded a K-Ar age on sanidine of 33±3 Ma (Izett, 1966, 1968). The Grouse Mountain Basalt commonly overlies the Rabbit Ears Volcanics and, locally, overlies the Troublesome Formation and older rocks (Izett, 1968). East of Kremmling, Colo., flows of the Grouse Mountain Basalt are interbedded with sediments of the Troublesome Formation (Izett, 1975). A whole-rock sample collected from the Grouse Mountain Basalt, northwest of Hot Sulphur Springs, Colo., yielded a K-Ar age of 20.1±0.4 Ma (Izett, 1975). The North Park Formation locally contains fossil mammals of late Hemingfordian age (Hail and Lewis, 1960) and Barstovian age (Montagne and Barnes, 1957; Montagne, 1991; Steven and others, 1997). However, some of the sediments of the North Park Formation may be younger than Barstovian age because fragments of fossil horse teeth collected by W.J. Hail, Jr., from sediments of the North Park Formation, in the North Park syncline about 12 km southeast of Walden, Colo. (U.S. Geological Survey vertebrate fossil locality F-59-16D), are similar to those in sediments of the Ogallala Group of western Nebraska and the Ogallala Formation in northeastern Colorado, which were deposited between about 18 and 6 Ma (Duller and others, 2012) or 5 Ma (Tedford, 2004). The $^{40}Ar/^{39}Ar$ ages on sanidine and biotite for volcanic rocks within and interbedded with the North Park Formation (table 1), the $^{40}Ar/^{39}Ar$ age on sanidine of the volcanic ash bed in the White River Formation beneath the North Park Formation (table 3), and the North American land mammal ages for fossil mammals in the North Park Formation suggest that the North Park Formation is less than 36 Ma, locally is at least as old as 29 Ma, and may be much younger than about 16 Ma.

Units similar in age to the North Park Formation in northern and central Colorado locally contain air-fall tuffs of late Oligocene to late Miocene age, such as those in the Troublesome Formation (23.5–11.0 Ma; table 1), Browns Park Formation (24.8–7.2 Ma; table 1), and Dry Union Formation (14.2–8.5 Ma; Hubbard and others, 2001; Xu and others, 2001). In contrast, few tuffs and altered tuffs have been observed in the North Park Formation in and near North Park (Hail, 1965; Montagne, 1991). However, one air-fall ash that was observed and collected from the North Park Formation, at Peterson Ridge near Colorado Highway 14 (SE¼NE¼ sec. 18, T. 8 N., R. 80 W.) about 150 m above the base of the formation, is very similar in chemistry and mineralogy to the chalky white ash in the Troublesome Formation in Middle Park (Izett, 1968) that has a $^{40}Ar/^{39}Ar$ age on sanidine of 18.9±0.22 Ma (Izett and Obradovich, 2001). Despite their similarity in chemistry and mineralogy, these ashes may not be from the same ash-fall event (Izett, 1968) because ash falls of different eruptive events from the same source can be similar in chemistry and mineralogy. Although very fine to medium-grained sandstone near the west end of the North Park syncline commonly contains volcanic ash in the matrix (Hail, 1965), the paucity of exposed tuff beds in the North Park Formation may be due to very limited exposure of the formation, redeposition and dilution of airborne volcanic ash with detrital material, and erosion and long-distance transport by high-energy streams.

Two pumice-rich deposits collected from the upper sequence of the Browns Park Formation (North Park Formation equivalent of Montagne, 1991) near Saratoga, Wyo., have $^{40}Ar/^{39}Ar$ mean ages of 14.5±0.04 on anorthoclase and 15.9±0.04 Ma on biotite (table 1). These ages are in accord with the presence of vertebrate fossils of Barstovian age identified at various localities in beds of the upper sequence of the Browns Park Formation of Montagne (1991) near Saratoga. A pumice-rich deposit collected from the lower sequence of the Browns Park Formation of Montagne (1991) near Saratoga has a $^{40}Ar/^{39}Ar$ mean age on biotite of 23.0±0.15 Ma (table 1). This age is similar to the $^{40}Ar/^{39}Ar$ mean age on sanidine of 23.5±0.06 Ma reported by Izett and Obradovich (2001) for their oldest dated tuff in the Troublesome Formation in Middle Park 7 km southeast of Kremmling, Colo., but it is younger than a K-Ar age on biotite of 24.8±0.08 Ma reported by Izett and others (1970) (table 1) for a tuff in the lower part of the Browns Park Formation in northwestern Colorado, about 30 m above either the basal conglomerate of the Browns Park Formation (Izett and others, 1970) or the Bishop Conglomerate (Hansen, 1986) in northwestern Colorado, about 155 km west of the North Park syncline.

Lithologic Characteristics of the North Park Formation

The main lithologic characteristics of the North Park Formation are clast composition and lithology and particle size of rocks and sediments.

Clast Composition of the North Park Formation

Much of the material that makes up the rocks and sediments of the North Park Formation was derived from the erosion of volcanic, intrusive, and sedimentary rocks. Clasts in the North Park Formation were derived chiefly from the erosion of volcanic and intrusive igneous rocks of late Oligocene and Miocene age that are locally exposed along the west flank of the Never Summer Mountains, the north flank of the Rabbit Ears Range, and probably the east flank of the Park Range at and near Rabbit Ears Peak (Montagne and Barnes, 1957; Hail, 1965; Snyder 1980b; Montagne, 1991). These rocks range in composition from rhyolite to trachybasalt (Hail, 1968; Kinney, 1970b; Kinney and Hail 1970b; Tweto, 1976; Snyder 1980b; O'Neill, 1981; Cole and

Braddock, 2009). The presence of rhyolitic and basaltic rock fragments in pebbly sandstone, conglomerate, and gravel is one of the main characteristics used to distinguish deposits of the North Park Formation from those of the underlying White River Formation or Coalmont Formation (Montagne and Barnes, 1957). Some of the clasts of porphyritic andesite and other volcanic rocks in the North Park Formation may be derived from the erosion of volcanic-pebble conglomerate and conglomeratic sandstone beds in the lower part of the Coalmont Formation that are locally exposed in the southernmost part of North Park (Hail, 1968). Pebble-sized clasts in deposits of the North Park Formation, exposed at Peterson Ridge along and near Colorado Highway 14, consist chiefly of Tertiary igneous rocks of mafic and intermediate composition, a subordinate amount of felsic composition, and about 1 percent igneous clasts of Proterozoic age. Pebble-sized clasts in deposits of the North Park Formation at Owl Ridge, exposed at the west end of Owl Ridge and farther east near County Road 21, consist chiefly of Tertiary igneous rocks of intermediate composition, subordinate amounts of felsic and mafic composition, and <5 percent igneous and metamorphic clasts of Proterozoic age. Cobbles composed of flow-banded rhyolite, eroded from lava flows erupted at Iron Mountain (Cole and others, 2008), are present at Owl Ridge as much as 35 km northwest of Iron Mountain near Cameron Pass (fig. 1). Clasts composed of the granodiorite and monzonite of the Mount Richthofen stock are not observed in the North Park Formation (E.E. Larson, Professor Emeritus, University of Colorado at Boulder, written commun., 2013), though the North Park Formation locally contains a very minor amount of thermally metamorphosed shale (hornfels) fragments that probably was derived from the Pierre Shale that was metamorphosed by the intrusion of the Mountain Richthofen stock.

Granodiorite and monzonite of the Mount Richthofen stock probably were intruded at 29.7±3 Ma (whole-rock K-Ar age; Marvin and others, 1974) and may not have been exposed by erosion until after the deposition of the North Park Formation. However, the presence of 29.6–28.5 Ma trachybasalts preserved in a paleovalley greater than 300 m deep, about 10 km northeast of Braddock Peak (Cole and others, 2008), suggests locally deep stream incision prior to 29.6 Ma. The relatively low content (<5 percent) of clasts of Proterozoic age in the North Park Formation, despite the relatively large amount of Proterozoic bedrock currently at or near the ground surface in the Never Summer Mountains (Cole and Braddock, 2009), suggests that much of this rock was not exposed by erosion until after the deposition of the North Park Formation. The minor amount of igneous and metamorphic clasts of Proterozoic age observed in the North Park Formation are commonly composed of durable rock types that are resistant to both physical and chemical weathering; many of these clasts may have been derived from the erosion of conglomerate and conglomeratic sandstone in the Coalmont Formation rather than from nearby exposed basement rocks.

Lithology and Particle Size of Rocks and Sediments of the North Park Formation

Widely spaced outcrops suggest that rocks and sediments of the North Park Formation consist chiefly of poorly consolidated sand, weakly cemented sandstone, and pebbly sandstone; subordinate amounts of pebble conglomerate; minor amounts of cobbly pebble gravel, siltstone, and sandy limestone; and rare beds of cobble conglomerate and altered tuff. Much of the pebble and larger clasts in the North Park Formation were derived from volcanic rocks in the Never Summer Mountains and Rabbit Ears Range (Montagne and Barnes, 1957; Hail, 1965; Montagne, 1991) and probably from the east flank of the Park Range at and near Rabbit Ears Peak. Much of the sand and finer grained particles in the North Park Formation probably were derived from the erosion of sandstone, shale, and sandy claystone of the Coalmont Formation. Likewise, much of the abundant sand-sized quartz and feldspar in sand, sandstone, and pebbly sandstone beds in the North Park Formation (Hail, 1965) probably were derived from the erosion of sandstone and conglomeratic sandstone of the Coalmont Formation. Ash in the North Park Formation may have erupted from nearby volcanic sources, such as those in Never Summer Mountains (Cole and others, 2008, and references cited within) and Rabbit Ears Range (Izett, 1966, 1968), or from distant sources in the Basin and Range province (Hansen, 1984; Luft, 1985; Buffler, 2003) hundreds of kilometers west of North Park.

Very Fine Grained Sandstone and Siltstone

Some of the fine sand, very fine sand, and silt in the very fine grained sandstone and siltstone of the North Park Formation may be derived from the erosion of eolian sand and loess in the Browns Park Formation that was transported across the Park Range by southwesterly winds. This deposition may have been contemporaneous with alluvial and eolian deposition of sandy and silty sediments in the Browns Park Formation along the west flank of the Park Range (Buffler, 2003) and, probably, farther west in northwestern Colorado. Much of the thick (≤610 m) sandstone unit of the Browns Park Formation, deposited along and near the west flank of the Park Range, is composed of eolian sand and loess preserved as thick deposits of medium-grained to very fine grained sandstone and very fine, sandy siltstone, respectively (Buffler, 2003). Likewise, some of the siltstone beds in the North Park Formation, exposed near the west end of Peterson Ridge and elsewhere within the North Park syncline, may be similar in origin to those of the Troublesome Formation in the Fraser basin and Middle Park, southeast and south of North Park, respectively (fig. 1). Limited particle-size and sorting data for siltstone of the Troublesome Formation in the Fraser basin suggests that this siltstone was formed from loess or alluvium derived from loess (Shroba and others, 2010). Although much of the clay in the North Park Formation may be eroded from shale and sandy claystone, which are abundant near the base of the Coalmont Formation (Dechesne and others, 2015), some of the clay may be smectite clay formed by the postdepositional alteration of rhyolitic volcanic ash (Zielinski, 1982) in the North Park Formation.

Relatively Fine Grained Sand and Sandstone

Particle-size data for one sample of relatively fine grained sand in the North Park Formation at Owl Ridge and three samples of relatively fine grained sandstone in the North Park Formation at Peterson Ridge indicate that these samples have mean particle sizes that range from 97 to 308 micrometers (µm), contain minor to moderate amounts of silt, and are poorly sorted to very poorly sorted (table 4). Mean particle size and sorting characteristics of the samples suggest that these sediments are not eolian sand or sandy loess, though they may have been eolian sediments that were subsequently eroded, mixed with detrital sediment, and redeposited as sheetwash alluvium or, possibly, as ephemeral pond or marsh deposits that contain eolian as well as detrital components.

Comparison of these samples to those analyzed in other studies lends insight to their genesis. Mean particle sizes of undivided eolian sand and alluvial sand in the white sandstone facies of Buffler (1967, 2003) are commonly about 90–350 µm, whereas his sandy (near-source?) loess in his brown sandstone facies of the Browns Park Formation along the west flank of the Park Range are commonly about 60 µm. Buffler's sandy loess is slightly coarser grained than unweathered loess of Quaternary age, which is composed chiefly of particles 10–50 µm in diameter (Pye, 1987, 1995, and references cited within). Sediments in the white and brown sandstone facies and the brown sandstone facies commonly are moderately sorted to well sorted (fig. 4) (Buffler, 1967). The mean particle sizes of the four samples of the North Park Formation are greater than those of sandy loess in the brown sandstone facies of Buffler, which is rich in very fine sand and coarse silt (Buffler, 1967). Samples of the North Park Formation are also more poorly sorted than both the white sandstone facies (eolian sand and alluvial sand) and the brown sandstone facies (sandy loess) in the Browns Park Formation (Buffler, 1967). Compared with eolian sediments of late Quaternary age near the South

Table 4. Particle-size analyses of slightly clayey, silty sand and slightly silty to very silty sandstones collected from the North Park Formation in the North Park syncline in North Park, Colorado.

[Samples were disaggregated using a porcelain mortar and pestle and were treated with hydrogen peroxide to remove organic matter. Sodium hexametaphosphate was then added as a dispersant to all samples. Following this procedure, the samples were shaken on a shaker table for about 4 hours to ensure deflocculation of the clay-size particles. Particle size was determined using a Malvern Mastersizer-S long-bed laser particle-size instrument. Samples analyzed in Denver, Colorado, by Eric Fisher, U.S. Geological Survey. Values are fraction of total volume (percent). All samples are noncalcareous. Datum: North America 1927. PS, poorly sorted; VPS, very poorly sorted; UTM, Universal Transverse Mercator]

Wentworth size class[1]	Size range in micrometers	Size range in phi units	Samples: DB–86 slightly clayey, silty sand[2,3]	OR–126–13 very silty sandstone[4]	MR–1R silty sandstone[5]	DB–83 slightly silty sandstone[6]
			Percent composition			
Very coarse sand	2,000–1,000	–1–0	0.1	1.8	6.7	0.0
Coarse sand	1,000–500	0–1	1.4	9.0	18.8	0.2
Medium sand	500–250	1–2	6.5	12.5	16.6	25.5
Fine sand	250–125	2–3	25.4	16.2	13.9	41.8
Very fine sand	125–62.5	3–4	28.7	19.4	15.0	16.9
Coarse silt	62.5–31	4–5	9.5	15.1	10.8	4.7
Medium silt	31–16	5–6	5.0	10.4	6.5	3.0
Fine silt	16–8	6–7	5.2	7.1	4.2	1.7
Very fine silt	8–4	7–8	5.6	4.3	2.9	1.9
"Coarse" clay	4–2	8–9	5.7	2.5	2.2	2.2
"Medium" clay	2–1	9–10	4.3	1.1	1.5	1.5
"Fine" clay	1–0.5	10–11	2.4	0.6	0.9	0.7
"Very fine" clay	<0.5	>11	0.2	0.0	0.0	0.0
Mean particle size, in micrometers			**97**	**147**	**281**	**308**
Mean particle size, in phi units[7]			**3.4**	**2.8**	**1.8**	**1.7**
Sorting[8]			**VPS**	**VPS**	**VPS**	**PS**
Location (UTM)			**0379300E 4502860N**	**0398460E 4492430N**	**0392250E 4497120N**	**0379310E 4502910N**

[1]Size ranges are those of the Wentworth scale (Folk, 1965). Terms in quotation marks are informal terminology.

[2]Lithologic designations are based on field descriptions.

[3]Sample collected from partial section DB–3 unit 3 (table 7).

[4]Sample collected from partial section OR–2 unit 5 (table 14).

[5]Sample collected from unit 1 near partial section MR–1 (table 12).

[6]Sample collected from partial section DB–3 unit 3 (table 7).

[7]Phi scale of Krumbein (1934).

[8]Sorting terminology is that of Folk and Ward (1957).

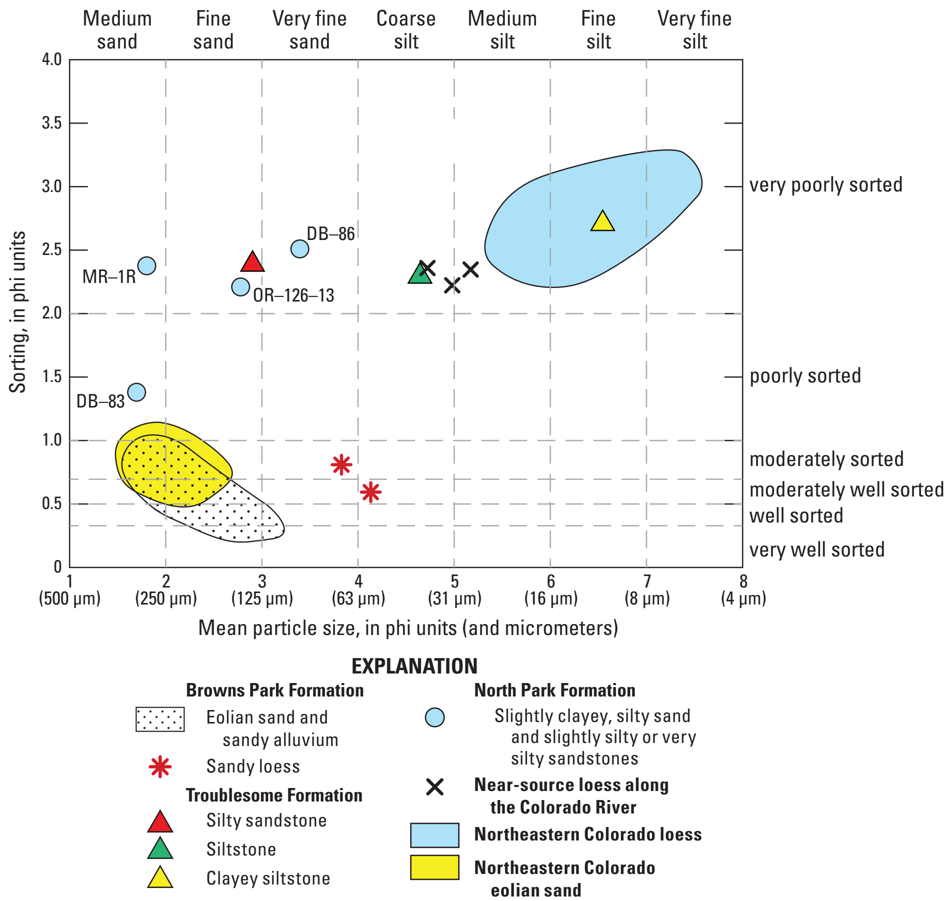


Figure 4. Plot of mean particle size and degree of sorting (standard deviation of the mean particle size) of slightly clayey, silty sand and slightly silty to very silty sandstones collected from the North Park Formation in the North Park syncline in North Park, Colorado. Categories of mean particle size, standard deviation, and sorting are those of Folk and Ward (1957). Data for eolian sand and loess of late Quaternary age in northeastern Colorado are from Muhs and others (1999, fig. 7). Data for eolian sand and sandy alluvium as well as for sandy loess in the Browns Park Formation west of the Park Range are from Buffler (1967). Data for silty sandstone, siltstone, and clayey siltstone in the Troublesome Formation in the Fraser basin are from Shroba and others (2010). Data for near-source loess of late Pleistocene age along the Colorado River near Rifle, Colo., are for deposits mapped by Shroba and Scott (1997). Sample numbers (for example, MR–1R) are the same as those used in table 4.

Platte River in northeastern Colorado and along the Colorado River in west-central Colorado, the mean particle sizes of the four samples of the North Park Formation are similar to those of eolian sand but are greater than those of loess (fig. 4). The mean particle size and sorting of samples DB–86 and OR–126–13 are similar to that of silty sandstone of the Troublesome Formation in the Fraser basin (Shroba and others, 2010). These three samples are similar in particle size but are more poorly sorted than those of the white sandstone facies of Buffler (1967, 2003).

North Park Formation at Peterson Ridge

In the western part of the North Park syncline at Peterson Ridge near and west of Colorado Highway 14, the North Park Formation is commonly composed of sand, sandstone, and pebbly sandstone; minor amounts of pebble conglomerate, cobbly pebble gravel, sandy siltstone, and sandy limestone; and rare beds of altered tuff (tables 5–10) (Hail, 1965). Shale beds reported by Hail (1965) were not observed in this study. Sand is loose to poorly consolidated, commonly very fine to fine grained, and, locally, slightly silty to silty. Sandstone commonly is very fine to fine grained, contains shards of altered volcanic ash, and locally is calcareous and slightly pebbly (Hail, 1965). Commonly, sandstone is weakly cemented, and sand-sized particles range in size from very fine to coarse grained (fig. 5). Pebbly sandstone commonly is poorly sorted, is fine to coarse grained, and contains scattered pebbles and lenses composed of volcanic rock and, locally, of quartz and feldspar. Pebble conglomerate commonly is poorly sorted and has a matrix composed of fine- to coarse-grained, calcareous, ashy sandstone (Hail, 1965). Beds and lenses of pebble conglomerate and cobbly pebble gravel are rich in volcanic clasts of intermediate and mafic composition (fig. 6). Sandy limestone locally contains abundant fragments composed of very fine grained volcanic glass, quartz, and feldspar (Hail, 1965).

Table 5. Partial section DB–1 of the lower part of the North Park Formation exposed on the south flank of Peterson Ridge near the west end of the ridge and the floodplain of the North Platte River, 4.7 kilometers northwest of Colorado Highway 14, in NW¼NE¼ sec. 14 and SW¼SE¼ sec. 11, T. 8 N., R. 81 W., Delaney Butte 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2011 by R.R. Shroba. Top of section at UTM 377630E and 4503445N; base of section at UTM 377530E and 4503150N. Datum: North American 1927. UTM, Universal Transverse Mercator]

Lithologic description	Approximate thickness (meters)
1. Pebble conglomerate; rich in volcanic clasts of intermediate and mafic composition; strikes S. 30° E. and dips 16° NE.; overlying deposits of the North Park Formation are not exposed	1.0
2. Sand, fine-grained; mostly concealed by sandy slope deposits	0.5
3. Concealed by sandy slope deposits	8.5
4. Pebble conglomerate; rich in volcanic clasts of intermediate and mafic composition	1.0
5. Sandstone, weakly cemented, fine-grained	1.0
6. Concealed by sandy slope deposits	4.0
7. Sandstone, weakly cemented, fine-grained; strikes S. 50° E. and dips 11° NE	1.0
8. Concealed by sandy slope deposits	2.0
9. Sandstone, weakly cemented, fine-grained; mostly concealed by sandy slope deposits; contains thin lenses of pebble conglomerate that are rich in volcanic clasts of intermediate and mafic composition	7.0
10. Sandstone; weakly cemented by calcium carbonate; well stratified; mostly very fine to fine-grained; forms layers commonly 20–90 centimeters thick; common small root casts; no scour-and-fill structures or lenses of granules or coarser grained sediment were observed; underlying deposits of the North Park Formation are not exposed	7.5
Total measured North Park Formation	**33.5**

Figure 5. Gently dipping beds composed of weakly cemented, mostly very fine to fine-grained sandstone of unit 10 exposed at partial section DB–1 (fig. 2, table 5). Trekking pole is 1.1 meter long and is roughly perpendicular to bedding. Photograph by R.R. Shroba, U.S. Geological Survey, July 25, 2011.

Table 6. Partial section DB–2 of the lower part of the North Park Formation exposed on the south flank of Peterson Ridge near the west end of the ridge and the floodplain of the North Platte River, 4.5 kilometers northwest of Colorado Highway 14, in NE¼NE¼ sec. 14, T. 8 N., R. 81 W., Delaney Butte 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2011 by R.R. Shroba. Base of section at UTM 377750E and 4503080N. Datum: North American 1927. UTM, Universal Transverse Mercator. Base of partial section DB–2 is 220 meters (m) east and 70 m south of the base of partial section DB–1. Color designations are based on informal field terminology as well as values for air-dried samples determined with the aid of Munsell soil color charts (Munsell Color, 1973)]

Lithologic description	Approximate thickness (meters)
1. Sandstone and thin lenses of pebble conglomerate; sandstone is composed chiefly of very fine to medium sand and minor amounts of coarse and very coarse sand, granules, and small pebbles; light tan (7.5YR 8/4); conglomerate is composed of thin lenses (2–35 centimeters) that are rich in volcanic clasts of intermediate and mafic composition that fill shallow channels inset into the sandstone; overlying and underlying deposits of the North Park Formation are not exposed	15.0
Total measured North Park Formation	**15.0**

Table 7. Partial section DB–3 of the North Park Formation exposed at Peterson Ridge, 3 kilometers northwest of Colorado Highway 14, in NE¼NE¼ sec. 13, T. 8 N., R. 81 W., Delaney Butte 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2012 by R.R. Shroba. Top of section at UTM 379170E and 4502620N; base of section at UTM 379290E and 4503020N. Datum: North American 1927. UTM, Universal Transverse Mercator. Color designations are based on informal field terminology as well as values for air-dried samples determined with the aid of Munsell soil color charts (Munsell Color, 1973)]

Lithologic description	Approximate thickness (meters)
1. Cobbly pebble gravel; rich in volcanic clasts of intermediate and mafic composition; gravel overlies sandy sediment	5
2. Mostly sand or very weakly cemented sandstone; mostly concealed by thin mantle of colluvium	21
3. Mostly sand and sandstone, minor sandy siltstone, and scattered, thin (10–70 centimeters [cm]) carbonate-cemented lenses composed of fine-grained to very coarse grained sandstone and, possibly, sandy limestone; sand is commonly slightly silty to silty and very fine to fine grained; sandstone is fine to very coarse grained; deposits commonly white and light tan (7.5YR 8/2 and 7.5YR 8/4); sandstone and siltstone are weakly to moderately cemented; one lens of altered volcanic ash(?), 40 cm thick, is exposed about 14 meters (m) below the top of unit 3; thin, fine-grained sandstone, exposed about 20 m below the top of unit 3, strikes N. 75° E. and dips 15° SE.; sediments are poorly exposed; carbonate in carbonate-cemented sediments appears to be non-pedogenic in origin; layers or lenses of gravel or conglomerate were not observed; underlying deposits of the North Park Formation are not exposed	49
Total measured North Park Formation	**75**

Table 8. Partial section DB–4 near the base of the North Park Formation exposed at Peterson Ridge, 0.2 kilometers (km) east of County Road 9 and 2.2 km west of Colorado Highway 14, in NW¼ sec. 17, T. 8 N., R. 80 W., Delaney Butte 7.5′ quadrangle.

[Measured with hand level in 2012 and 2014 by R.R. Shroba. Top of section at UTM 381150E and 4502910N; base of section at UTM 381075E and 4503010N. Datum: North American 1927. UTM, Universal Transverse Mercator]

Lithologic description	Approximate thickness (meters)
1. Sandstone; composed of mostly very fine to medium sand plus a minor amount of granule- and small-pebble-sized volcanic clasts; overlying sediments of the North Park Formation are not exposed	0.3
2. Covered by loose, sandy sediment and pebbly sediment	3.0
3. Small-pebble conglomerate and pebbly sandstone; mostly matrix supported, well stratified; conglomerate lenses are rich in intermediate and mafic volcanic clasts; strikes S. 85° E. and dips 27° SW.	2.5
4. Mostly covered, loose, sandy sediment that locally contains thin (5–30 centimeters [cm]) lenses of small-pebble conglomerate rich in intermediate and mafic volcanic clasts and mostly very fine to medium-grained sandstone that contains a minor amount of granule- and small-pebble-sized volcanic clasts; sandstone lens near base of unit strikes S. 80° E. and dips 29° SW.	15.1
5. Sandstone, mostly very fine to fine-grained; cemented by calcium carbonate; contains one or more thin (10 cm) conglomerate lenses rich in white tuff pebbles; strikes S. 85° E. and dips 32° SW.	2.1
6. Covered by loose, sandy sediment and angular rock fragments	1.9
7. Sandstone, very fine to fine-grained; cemented by calcium carbonate	0.4
8. Sandstone, very fine to fine-grained; cemented by calcium carbonate; fills channel with 30 cm of relief at base; contains a few lenses of pebble conglomerate, as much as 30 cm thick, composed of white and pink tuff or intermediate and mafic volcanic clasts; root casts, as much as 1 cm in diameter, are locally abundant; locally low-amplitude wavy bedding likely due to soft-sediment deformation	0.7
9. Sandstone, very fine to fine-grained; slightly silty; locally very fine to coarse-grained and slightly pebbly; weakly consolidated	1.0
10. Conglomeratic sandstone, coarse-grained sandstone, and lenses of small-pebble conglomerate; well stratified; beds commonly 1–15 cm thick; conglomeratic sandstone is rich in intermediate and mafic volcanic pebbles; beds strike S. 85° E. and dip 28° SW.; underlying sediments and base of the North Park Formation are not exposed; highest exposed sediments of the Coalmont Formation are about 80 meters (m) east and 30 m north of base of section	3.0
Total measured North Park Formation	**30.0**

Table 9. Partial section DB–5 of the basal part of the North Park Formation exposed along the south flank of Peterson Ridge, 0.3 kilometers (km) east of Colorado Highway 14 and 1.3 km north of the Peterson Ranch, in NW¼SW¼ sec. 20, T. 8 N., R. 80 W., Delaney Butte 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2012 by R.R. Shroba. Top of section at UTM 382220E and 4500640N; base of section at UTM 382060E and 4500610N. Datum: North American 1927. UTM, Universal Transverse Mercator]

	Lithologic description	Approximate thickness (meters)
1.	Small-pebble conglomerate; pebbles are ≤1 centimeter (cm) in diameter; rich in volcanic clasts of intermediate and mafic composition; overlying deposits of the North Park Formation are not exposed	0.3
2.	Concealed by sandy slope deposits	4.0
3.	Sandstone and lenses of small-pebble conglomerate; sandstone is well stratified and is well cemented by calcium carbonate; very fine to coarse-grained; contains about 10 percent dark (mafic?) volcanic granules; lenses of small-pebble conglomerate (≤1.9 meters thick) are well cemented by calcium carbonate and commonly are rich in volcanic clasts of intermediate and mafic composition that are ≤5 cm in diameter; locally, some of the lenses contain abundant tuff pebbles, about 1 cm in diameter, that contain abundant biotite; beds in unit 3 strike S. 60° E. and dip 28° NE.	3.6
4.	Concealed by sandy slope deposits	3.0
5.	Sand, poorly consolidated, calcareous, very fine to fine-grained; contains few percent volcanic granules and pebbles; mostly concealed by sandy slope deposits	0.8
6.	Siltstone, blocky	0.3
7.	Concealed by sandy slope deposits	3.0
8.	Sandstone, very fine to medium-grained; mostly concealed by sandy slope deposits	0.5
9.	Concealed by sandy slope deposits	7.0
10.	Sandstone, very fine to coarse-grained, calcareous; locally contains abundant root casts; sandstone strikes S. 65° E. and dips 23° NE.; overlies deposits of the Coalmont Formation	1.2
Total measured North Park Formation		**23.7**

Figure 6. Northeast-dipping lens composed of small-pebble conglomerate of unit 3 exposed at partial section DB–5 (fig. 2, table 9). Lens is rich in volcanic clasts of intermediate and mafic composition. Hammer is 28 centimeters long, and handle is roughly perpendicular to bedding. Photograph by R.R. Shroba, U.S. Geological Survey, August 29, 2012.

Table 10. Partial section W–1 of the basal part of the North Park Formation exposed along the south flank of Peterson Ridge, 2.0 kilometers east of Colorado Highway 14, in NE¼NE¼ sec. 28, T. 8 N., R. 80 W., Walden 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2011 by R.R. Shroba. Top of section at UTM 384240E and 4499740N; base of section at UTM 384210E and 4499660N. Datum: North American 1927. UTM, Universal Transverse Mercator]

Lithologic description	Approximate thickness (meters)
1. Pebble conglomerate and sand; conglomerate is rich in volcanic clasts of intermediate and mafic composition and fills channels as much as 1.2 meters (m) thick and about 5.5 m wide that are inset into sand; conglomerate strikes S. 63° E. and dips 15° NE.; overlying deposits of the North Park Formation are not exposed	1.2
2. Concealed by sandy slope deposits	8.0
3. Sand, sandstone, and pebble conglomerate; sand is loose, fine grained, and contains lenses of sandstone and pebble conglomerate 20–25 centimeters thick; conglomerate is composed of volcanic clasts, commonly of intermediate and mafic composition; one lens is composed of white tuff pebbles that contain abundant biotite; one of the conglomerate lenses strikes S. 70° E. and dips 30° NE.; mostly concealed by sandy slope deposits	6.6
4. Sandstone, very fine to medium-grained, calcareous; sandstone strikes S. 73° E. and dips 30° NE.; overlies light-colored silty deposits of the White River Formation	2.3
Total measured North Park Formation	**18.1**

North Park Formation at Owl Ridge

At the west end of Owl Ridge near the Illinois River, the North Park Formation consists mostly of thin (10–40 cm) lenses of pebble conglomerate rich in volcanic clasts of intermediate composition that form thin (20–30 cm) lenses that fill shallow channels that are inset into weakly cemented, slightly pebbly, slightly silty, very fine to very coarse grained (mostly very fine to medium-grained) sandstone that is locally weakly cemented by calcium carbonate (table 11, fig. 7). In nearby outcrops, beds of silty, very fine to fine-grained sand, locally greater than 10 m thick (table 12), and thin (50–55 cm) lenses of poorly sorted, clast-supported, cobbly pebble conglomerate cemented by non-pedogenic calcium carbonate are exposed.

Deposits of the North Park Formation and a thin (≤10 m), rhyolitic, pumice-rich, 28.1-Ma ash-flow tuff near the base of the formation are locally exposed at Owl Ridge about 1 km east of County Road 21 (fig. 2). Exposed deposits of the North Park Formation below the ash-flow tuff consist chiefly of poorly consolidated sand and weakly to moderately cemented sandstone and pebbly sandstone, lenses of pebble conglomerate, and, locally, minor amounts of limestone (figs. 8 and 9, table 13) and siltstone. The limestone lacks pedogenic features and may have been deposited in a small ephemeral waterbody, such as a pond. Similarly, the Troublesome Formation exposed near Kremmling, Colo., contains a few beds of freshwater limestone that likely formed in small ephemeral ponds (Izett, 1968). Locally, conglomerate and gravel make up about 25 percent of the exposed deposits (table 14). The North Park Formation above the ash-flow tuff locally contains channel-fill sequences, some as much as about 8 m in total thickness (table 15). These deposits consist chiefly of slightly cobbly pebble conglomerate (fig. 10) that is overlain by finer grained deposits. A few of the conglomerate beds contain scattered (<1 percent) volcanic boulders commonly about 30–75 cm long; the largest is about 2.7 m long. These boulders likely were transported by a large-discharge flash flood that issued from relatively steep volcanic terrain probably in either the north part of the Never Summer Mountains or in the central part of the Rabbit Ears Range near Arapahoe Ridge (fig. 1). Some of the nearby channel-fill deposits are composed of beds of cobble conglomerate (table 16, fig. 11). Some of the channel-fill deposits fine upward and are overlain by deposits of pebble conglomerate and sandy pebble conglomerate. These fining-upward channel-fill deposits probably represent fluvial transport and deposition under conditions of diminishing discharge and lower stream power. Locally, channel-fill deposits are stacked one upon the other, separated by abrupt planar erosional contacts. Deposits at the eroded top of the North Park Formation, east of County Road 21, are composed of poorly sorted, cobbly pebble gravel rich in volcanic clasts that contains less than 1 percent boulders; the largest is a volcanic boulder 80 cm in diameter (table 17).

The higher proportion of gravel and conglomerate exposed in the North Park Formation at Owl Ridge than at Peterson Ridge may be due to the shorter distance of fluvial transport to the Owl Ridge area from volcanic source areas in the Never Summer Mountains and the Rabbit Ears Range.

Table 11. Partial section W–2 of the North Park Formation exposed in a road cut at the west end of Owl Ridge near the floodplain of the Illinois River, 1.7 kilometers (km) east of Colorado Highway 125 and 0.9 km north of the office of the Arapahoe National Wildlife Refuge, in NW¼NE¼ sec. 32, T. 8 N., R. 79 W., Walden 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2012 by R.R. Shroba. Base of section at UTM 392220E and 4497830N. Datum: North American 1927. UTM, Universal Transverse Mercator. Color designations are based on informal field terminology as well as values for air-dried samples determined with the aid of Munsell soil color charts (Munsell Color, 1973)]

Lithologic description	Approximate thickness (meters)
1. Lenses of pebble conglomerate and sandstone; conglomerate is composed of thin lenses (10–40 centimeters) that are rich in angular and subangular volcanic clasts of intermediate composition that fill shallow channels inset into sandstone; few lenses of pebble conglomerate are rich in white tuff fragments; locally, conglomerate is slightly cobbly; sandstone is composed chiefly of slightly silty, very fine to medium sand and minor amounts of coarse and very coarse sand, granules, and small pebbles; light tan (7.5YR 8/4); locally cemented by calcium carbonate; two exposed beds strike S. 80° E. and S. 70° E. and dip 24° and 28° SW., respectively; underlying deposits of the North Park Formation are not exposed	5.0
Total measured North Park Formation	**5.0**

Figure 7. Southwest-dipping lenses composed of small-pebble conglomerate (gray) and mostly very fine to medium-grained sandstone (tan) of unit 1 exposed at partial section W–2 (fig. 2, table 11). Conglomerate is rich in volcanic clasts of intermediate composition. Trekking pole is 1.1 meter long and is roughly perpendicular to bedding. Photograph by R.R. Shroba, U.S. Geological Survey, August 27, 2012.

Table 12. Partial section MR–1 of the North Park Formation exposed in small gully at the west end of Owl Ridge near the floodplain of the Illinois River, 1.7 kilometers (km) east of Colorado Highway 125 and 0.4 km northeast of the office of the Arapahoe National Wildlife Refuge, in NE¼SE¼ sec. 32, T. 8 N., R. 79 W., Mac Farlane Reservoir 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2010 by R.R. Shroba. Base of section at UTM 392270E and 4497120N. Datum: North American 1927. UTM, Universal Transverse Mercator. Color designations are based on informal field terminology as well as values for air-dried samples determined with the aid of Munsell soil color charts (Munsell Color, 1973)]

Lithologic description	Approximate thickness (meters)
1. Sand; poorly consolidated, non-calcareous, slightly clayey, silty, very fine to fine sand; light tan (7.5YR 8/4); reddish-brown, non-pedogenic(?) clay films coat blocky aggregates in lower part of unit 1; mostly concealed by sandy slope deposits; underlying deposits of the North Park Formation are not exposed	10.0
Total measured North Park Formation	**10.0**

Table 13. Partial section OR–1 of the basal part of the North Park Formation exposed along the south flank of Peterson Ridge about 10 meters below the base of a 28.1-Ma ash-flow tuff, 1.0 kilometer (km) east of County Road 21 and 0.3 km south of the tower at Owl Ridge, in NW¼NE¼ sec. 13, T. 7 N., R. 79 W., Owl Ridge 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2012 by R.R. Shroba. Top of section at UTM 398140E and 4492290N; base of section at UTM 398180E and 4492210N. Datum: North American 1927. UTM, Universal Transverse Mercator. Color designations are based on informal field terminology. Ma, mega-annum (million years ago)]

Lithologic description	Approximate thickness (meters)
1. Pebbly sand; overlying deposits of the North Park Formation are not exposed	1.0
2. Pebble gravel; rich in clasts of intermediate composition; clasts are angular and subangular	1.0
3. Ash-flow tuff; disintegrated and altered; light red; consists of small fragment of ash-flow tuff in a matrix of slightly clayey sand	7.0
4. Sand, very fine to medium-grained; silty; poorly consolidated; mostly concealed by sandy slope deposits	2.5
5. Limestone; pond(?) deposit; well cemented; forms prominent ledge	0.6
6. Sandstone, mostly very fine to fine-grained; well cemented by calcium carbonate; light gray; contains lenses and channel-fill deposits (about 15–120 centimeters [cm] thick) that are composed mostly of poorly sorted, matrix-supported, locally slightly cobbly, angular to subangular, volcanic-pebble conglomerate that is rich in clasts of intermediate composition as well as a subordinate amount of dark, fine-grained, mafic, volcanic clasts, and about 1 percent composed of quartz plus pegmatite; steep-sided, 120-cm-thick channel-fill deposit near base of unit (see fig. 8) appears to trend N. 15° W.; thin (0.5–6 cm) sandstone beds near base of unit strike S. 55° E. and dip 20° NE.; underlying beds and base of the North Park Formation are not exposed; highest exposed sediments of the Coalmont Formation are about 20 meters (m) east and 5 m south of base of section	7.5
Total measured North Park Formation	**19.6**

Figure 8, left. View toward the northwest of pebble conglomerate in a steep-sided channel that is inset into mostly very fine to fine-grained sandstone of unit 6 exposed at partial section OR–1 (fig. 2, table 13). Conglomerate consists chiefly of volcanic clasts of intermediate and mafic composition. Hammer is 28 centimeters (cm) long and is oriented vertically on the outcrop; notebook is 20 cm long. Fracture zone in left part of image strikes N. 30° W. and dips 73° SE. Photograph by R.R. Shroba, U.S. Geological Survey, August 26, 2014.

Figure 9, above. Ledge-forming limestone bed of unit 5 exposed at partial section OR–1 (fig. 2, table 13). Base of bed not in image. Hammer is 28 centimeters long; hammerhead is at top of bed, and handle is roughly perpendicular to bedding. The joints in the bed are probably chiefly due to near-surface, physical weathering processes. Photograph by R.R. Shroba, U.S. Geological Survey, August 10, 2012.

Table 14. Partial section OR–2 of the North Park Formation exposed along the crest of a southwest-northeast trending ridge, 1.3 kilometers (km) east of County Road 21 and 0.3 km southeast of the tower at Owl Ridge, in SE¼NE¼ sec. 13, T. 7 N., R. 79 W., Owl Ridge 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2012 by R.R. Shroba. Top of section at UTM 398500E and 4492470N; base of section at UTM 398410E and 4492280N. Datum: North American 1927. UTM, Universal Transverse Mercator. Color designations are based on informal field terminology as well as values for air-dried samples determined with the aid of Munsell soil color charts (Munsell Color, 1973). At UTM 398457E and 4492270N (50 meters [m] east, 10 m south, and about 20 m below the base of this partial section), sandy deposits of the North Park Formation exposed in a small gully strike N. 70° W. and dip 29° NE.]

Lithologic description	Approximate thickness (meters)
1. Sand; mostly concealed by sandy slope deposits	4.8
2. Cobbly pebble gravel; rich in volcanic clasts of intermediate composition	1.2
3. Sand; mostly concealed by sandy slope deposits	4.3
4. Cobbly pebble gravel; rich in volcanic clasts of intermediate composition	0.8
5. Sandstone, weakly cemented, non-calcareous, white (10YR 8/2); composed of slightly silty, mostly very fine to fine sand that contains one or more pebbles; probably water-lain; possibly sheetwash alluvium	3.5
6. Slightly cobbly pebble conglomerate; rich in volcanic clasts of intermediate composition; well cemented; contains and one or more lenses of pebbly sandstone rich in subangular volcanic pebbles of intermediate composition; conglomerate strikes S. 32° E. and dips 19° NE.	1.9
7. Sand; mostly concealed by sandy slope deposits	1.0
8. Cobbly pebble gravel; rich in volcanic clasts of intermediate composition	1.6
9. Sandstone; weakly cemented, non-calcareous; light tan (7.5YR 8/4); very slightly pebbly and slightly silty; composed mostly of very fine to fine sand; contains minor amounts of medium to very coarse sand and granules; granules are composed chiefly of volcanics of intermediate composition; probably water-lain; possibly sheetwash alluvium	7.9
10. Cobbly pebble gravel; rich in volcanic clasts of intermediate composition	0.5
11. Sand; poorly consolidated, non-calcareous, slightly silty, very fine to coarse sand and few pebbles; very light brown (10YR 7/3); mostly concealed by sandy slope deposits	3.6
12. Cobbly pebble gravel; rich in volcanic clasts of intermediate composition	1.6
13. Sand; mostly concealed by sandy slope deposits	5.3
14. Sand; contains a thin lens of pebbly sandstone at top of unit; mostly concealed by sandy slope deposits	1.5
15. Cobbly pebble gravel, slightly bouldery; rich in volcanic clasts of intermediate composition	1.0
16. Sand; mostly concealed by sandy slope deposits	1.5
17. Cobbly pebble gravel; poorly sorted and clast-supported; rich in volcanic clasts of intermediate composition	1.2
18. Sandstone; weakly cemented, non-calcareous; composed of very fine to coarse sand and minor amount of granules	1.0
19. Cobbly pebble gravel; rich in volcanic clasts of intermediate composition; underlying deposits of the North Park Formation are not exposed	1.1
Total measured North Park Formation	**45.3**

Table 15. Partial section OR–3 of the North Park Formation exposed on the south and east sides of a small hill, 1.2 kilometers (km) east of County Road 21 and 0.2 km southeast of the tower at Owl Ridge, in SE¼NE¼ sec. 13, T. 7 N., R. 79 W., Owl Ridge 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2011 by R.R. Shroba. Base of section at UTM 398310E and 4492390N. Datum: North American 1927. UTM, Universal Transverse Mercator. Base of partial section OR–3 is 110 meters (m) west and 100 m north of the base of partial section OR–2]

Lithologic description	Approximate thickness (meters)
1. Slightly cobbly pebble conglomerate; well stratified; planar bedded; probably large channel-fill deposit; contains lenses (35–75 centimeters [cm] thick) composed of clast-supported and matrix-supported, coarse-pebble and small-cobble gravel that are rich in volcanic clasts of intermediate composition; contains minor lenses of pebbly sandstone and a few thin (5 cm) lenses of silty fine sand; a few thin sandy lenses (20–40 cm) contain thin layers that are rich in white tuff fragments ≤1 cm in diameter; local shallow scour-and-fill structures; few (<1 percent) angular to subangular boulders; largest boulder is about 2.7 meters long; these boulders probably were transported by a flash flood; beds strike S. 45° E. and dip 26° NE.; overlying and underlying deposits of the North Park Formation are not exposed	8.0
Total measured North Park Formation	**8.0**

Figure 10. Northeast-dipping, upward-fining deposits of unit 1 exposed at partial section OR–3 (fig. 2, table 15). From bottom to top, deposits are composed of slightly cobbly pebble conglomerate rich in volcanic clasts of intermediate composition (greater than 35 centimeters [cm] thick; base is not exposed), overlain by mostly coarse sand and granule-rich small-pebble conglomerate (7 cm thick), overlain by well-stratified mostly medium to coarse sand (14 cm thick) that contains a thin (1–2 cm) lens rich in white tuff fragments. Hammerhead is 17 cm long, and handle is roughly parallel to bedding. Photograph by R.R. Shroba, U.S. Geological Survey, August 7, 2011.

Table 16. Partial section OR–4 of the North Park Formation exposed in a gully, 1.4 kilometers (km) east of County Road 21 and 0.4 km southeast of the tower at Owl Ridge, in SE¼NE¼ sec. 13, T. 7 N., R. 79 W., Owl Ridge 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2011 by R.R. Shroba. Base of section at UTM 398520E and 4492400N. Datum: North American 1927. UTM, Universal Transverse Mercator. Base of partial section OR–4 is 40 meters east of unit 8 in partial section OR–2]

Lithologic description	Approximate thickness (meters)
1. Cobbly pebble conglomerate; rich in volcanic clasts of intermediate composition; poorly exposed; overlying deposits of the North Park Formation are not exposed	1.2
2. Large-cobble conglomerate, slightly bouldery, clast-supported; rich in volcanic clasts of intermediate composition; contains volcanic clasts that are as large as 15×30×40 centimeters; fills channel tens of meters wide	2.5
3. Sand, mostly fine- to medium-grained; mostly concealed by sandy slope deposits	2.0
4. Cobble conglomerate, slightly bouldery, clast-supported; rich in volcanic clasts of intermediate composition; underlying deposits of the North Park Formation are not exposed	2.0
Total measured North Park Formation	**7.7**

Figure 11. Slightly bouldery, clast-supported, large-cobble conglomerate of unit 2 exposed at partial section OR–4 (fig. 2, table 16) in the left foreground and mostly pebble conglomerate exposed in right background. Conglomerate is rich in volcanic clasts of intermediate composition. Hammer is 28 centimeters long. Photograph by R.R. Shroba, U.S. Geological Survey, August 8, 2011.

Table 17. Partial section OR–5 of the North Park Formation exposed on the south side of a northwest-southeast trending ridge, 0.8 kilometers (km) east of County Road 21 and 0.2 km northwest of the tower at Owl Ridge, in NW¼NE¼ sec. 13, T. 7 N., R. 79 W., Owl Ridge 7.5′ quadrangle, Jackson County, Colorado.

[Measured with hand level in 2011 by R.R. Shroba. Base of section at UTM 398020E and 4492665N. Datum: North American 1927. UTM, Universal Transverse Mercator]

Lithologic description	Approximate thickness (meters)
1. Cobbly pebble gravel; poorly sorted; contains less than one percent boulders; largest boulder is an intermediate volcanics that measures 35×80×120 centimeters; clasts are chiefly angular and subangular; minor amount of subrounded clasts; rich in volcanic clasts of intermediate composition; contains minor amounts of clasts composed of ash-flow tuff and flow-banded rhyolite	6.5
2. Sand; unconsolidated; mostly concealed by sandy slope deposits	2.0
3. Cobbly pebble gravel; rich in volcanic clasts; clasts composed of ash-flow tuff and flow-banded rhyolite were not observed; underlying deposits of the North Park Formation are not exposed	3.0
Total measured North Park Formation	**11.5**

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