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Geologic Map of the Denver West 30′ x 60′ Quadrangle, North-Central Colorado

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Pamphlet to accompany
Scientific Investigations Map 3000

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Contents

Table

Conversion Factors

To convert	Multiply by	To obtain
centimeters (cm)	0.39	inches (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Divisions of Quaternary and Neogene Time Used in This Report

Period or Subperiod	Epoch		Age
	Holocene		0–11.5 ka
Quaternary			
		late	11.5–132 ka
	Pleistocene	middle	132–788 ka
		early	788 ka–1.81 Ma
Neogene	Pliocene		1.81–5.32 Ma
	Miocene		5.32–23.8 Ma

From Hansen (1991) with these exceptions: 11.5 (Holocene–late Pleistocene boundary from U.S. Geological Survey Geologic Names Committee (2007); 132 ka (late-middle Pleistocene boundary) and 788 ka (middle-early Pleistocene boundary) from Richmond and Fullerton (1986a); 1.81 Ma (Pleistocene-Pliocene boundary) from Lourens and others (1996); 5.32 Ma (Pliocene-Miocene boundary) and 23.8 (Miocene-Oligocene boundary) from Berggren and others (1995). Ages expressed in ka for kilo-annum (thousand years) and Ma for mega-annum (million years).

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

[Surficial deposits in the Denver West quadrangle record alluvial, mass-movement, glacial, and eolian processes in the central part of the Front Range and the western margin of the Colorado Piedmont during the Quaternary and late Neogene. Many of the surficial deposits are poorly exposed. Deposits that are of limited extent (less than about 200 m wide) were not mapped, including (1) fill material in urban areas, (2) mine-and-mill waste and dredge tailings in mining areas, (3) thin mass-movement deposits above present treeline (such as block fields and block streams), and (4) thin sheetwash deposits that locally mantle gently sloping map units.

Descriptions of surficial units on this map are based chiefly on information in maps and reports by Birkeland and others (2003), Dethier and others (2003), Gable and Madole (1976), Lindsey and others (2005), Lindvall (1978, 1979, 1980), Machette (1977), Machette and others (1976), Madole (1986, 1991a), Madole and others (1998, 2005), Madole and Shroba (1979), Miller (1979), Moore and others (2001), Muhs and others (1996, 1999), Scott (1960, 1962, 1963a, 1972, 1975), Shroba (1977, 1980, 1982), Shroba and Birkeland (1983), Shroba and Carrara (1996), Trimble and Machette (1979), Van Horn (1972, 1976), and Wells (1967). Crosby (1978) mapped some of the landslide deposits (Qls) depicted in the Colorado Piedmont.

Most of the surficial units on this map are informal allostratigraphic units (discontinuity-bound sequences) of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983), whereas the other map units ("bedrock units") are informal or formal lithostratigraphic units. Subdivisions of map units use time terms "late" and "early" where applied to surficial units, but use position terms "upper" and "lower" where applied to lithostratigraphic units. Formal names for fluvial and pediment deposits east of the mountain front are those established by Scott (1960, 1963a) for the Colorado Piedmont. Informal names (such as young stream-terrace alluvium, Qg1, and lower pediment deposits, Qp1) are applied to deposits of similar origin near Fraser and in other valleys west of the mountain front.

The mapped distribution of surficial units on the Berthoud Pass, East Portal, Empire, Fraser, Grays Peak, Harris Park, Meridian Hill, Montezuma, Mount Evans, Nederland, and parts of the Bottle Pass, Central City, Eldorado Springs, Golden, and Louisville quadrangles is based primarily on interpretation of 1:40,000-scale, color-infrared aerial photographs taken in 1988, 1990, and 1992.

Age assignments for surficial deposits within the map area are based chiefly on the relative degree of modification of their original surface morphology, relative heights above present stream channels, and degree of soil development and clast weathering. Soil-horizon designations are based on those of the Soil Survey Staff (1999) and Birkeland (1999). Some of the surficial deposits contain secondary calcium carbonate of pedogenic (soil) origin. Stages of secondary calcium carbonate morphology (referred to as stages I through IV) in Bk and K soil horizons are from Gile and others (1966) and Machette (1985).

Grain or particle sizes of surficial deposits are field estimates. Size limits for sand (0.05–2 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) are those of the Soil Survey Staff (1951). In descriptions of surficial map units, the term "clasts" refers to granules and larger particles (>2 mm in diameter), whereas the term "matrix" refers to sand and finer particles (≤2 mm in diameter). In descriptions of clast composition of surficial map units, the terms "granite" and "granitic" refer chiefly to various igneous or meta-igneous rock types that are holocrystalline and felsic to intermediate in composition. The terms "gneiss" and "gneissic" refer chiefly to quartz-feldspar gneiss, biotite gneiss, hornblende gneiss, and amphibolite.

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

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

The term "mountain front" refers to the steep, eastward-sloping topography formed chiefly on the easternmost exposures of Precambrian rock. The term "hogback belt" refers to prominent ridges, parallel to and just east of the mountain front, that are composed of steeply tilted, resistant sedimentary strata (mostly rocks of the Dakota Group) that once covered the crystalline core of the Front Range (Hansen and Crosby, 1982).

In much of the report the terms "soil" and "soils" refer to pedogenic soils formed in surficial deposits (for example, Birkeland, 1999). However, in the section "Potential Geologic Hazards," these terms are used in the engineering sense (surficial deposits as well as the pedogenic soils formed in various surficial deposits).

Oxygen isotope ($\delta^{18}O$) records in marine cores provide an index of global climate [as expressed in global ice volume (for example, Shackleton and Opdyke, 1973, 1976)], and were used to estimate the ages of the some of the older alluvial deposits in the Colorado Piedmont. Oxygen isotope variation in marine cores may lag 500–3,000 years behind the corresponding changes in ice volume on the continents (Mix and Ruddiman, 1984)]

Artificial fill deposits

af **Artificial fill deposits (latest Holocene)**—Compacted fill material composed mainly of silt, sand, rock fragments, and, locally, trash. Mapped in an active landfill, about 8 km north of Golden on east side of U.S. Highway 93, and in inactive landfills north of Interstate 70, about 3 km southeast of Golden, and east of Marshall Lake, about 4 km southeast of Boulder. These landfills contain organic trash (such as plastic products and vegetation) and inorganic trash (such as metal and concrete). Lateral extent of active landfill north of Golden may change due to continued filling. Deposits of artificial fill (chiefly mine waste from the Henderson mine) are also mapped in the valleys of Woods Creek and West Fork Clear Creek, a few kilometers southwest of Berthoud Pass. Smaller deposits of artificial fill in areas where land surface was modified by earth-moving equipment are not mapped. Estimated thickness a few meters to more than 10 m

Alluvial deposits

Qa **Post-Piney Creek alluvium and Piney Creek Alluvium, undivided (Holocene)**—Mostly sand and gravel along major streams in piedmont that head in mountains, and mostly sand and locally sandy silt and silty clay along tributary streams that head in piedmont east of mountain front. Locally cobbly and slightly bouldery along major streams near mountain front and sandy and silty in mountain meadows. Post-Piney Creek alluvium commonly lies within stream channels cut in Piney Creek Alluvium and consists chiefly of silty to pebbly sand and pebble gravel that is subject to periodic stream flooding. Piney Creek Alluvium commonly consists of sandy silt, silty sand, lenses of silty clay, and detrital organic matter in upper part, and mostly sand and lenses of pebble gravel in lower part. Forms one or two terraces less than 5 m above present streams, and locally forms alluvial fans and sheetwash aprons along margins of major valleys. In valleys of major streams that head in glaciated drainages, Piney Creek Alluvium forms much of flood plain where it overlies Broadway Alluvium (Qb).

Grain size and content of organic matter in upper part of Piney Creek Alluvium suggests that it was eroded from soils formed in loess (Qlo) and other fine-grained deposits. Soils formed in upper part of post-Piney Creek alluvium have A/Cu profiles. Soils formed in upper part of Piney Creek Alluvium are better developed and have A/Bw/C profiles where formed in sand and A/Bw/Bk profiles with stage I carbonate morphology where formed in finer grained sediments. Some of the soil A horizons formed in Piney Creek Alluvium are over-thickened (cumulic) where A-horizon formation kept pace with sedimentation.

Radiocarbon (^{14}C) dating of organic material helps to constrain ages of post-Piney Creek alluvium and Piney Creek Alluvium. Wood from logs in post-Piney Creek alluvium near Fort Lupton, Colo., yielded radiocarbon ages of a few hundred years (Lindsey and others, 1998), and charcoal at an archeological site (stratigraphic position not specified) near Kassler, Colo., just south of map area, yielded an age of about 1,500 ^{14}C yr B.P. (carbon-14 years before present; Scott, 1962, 1963a). Radiocarbon ages of organic material in Piney Creek Alluvium near Colorado Springs range from about 1.1 to 2.2 ka (Madole and others, 2005). Gravelly alluvium overlying Broadway Alluvium near Longmont, Colo., was deposited between 1,900 and 3,900 ^{14}C years ago (Madole, 1976). Unit may locally contain pre-Piney Creek alluvium (Scott, 1960, 1962, 1963a). Low-lying deposits are prone to periodic stream flooding. Thickness about 1.5–6 m

Qva **Valley-floor alluvium (Holocene and late Pleistocene)**—Mostly poorly sorted coarse sand and pebbly to bouldery cobble gravel in stream channels, flood plains, and low terraces in mountain valleys. Flood-plain and terrace deposits of Holocene age are commonly about 1.3 m or less above present streams (Madole, 1996). Unit locally includes a minor amount of young stream-terrace alluvium (Qg1), colluvium (Qc) and other mass-movement deposits, fan deposits (Qf), and glacial deposits (Qtp and Qti) along valley margins and organic-rich sediments in bogs, marshes, and meadows. Locally may include minor lake sediments. Top of unit probably consists mostly of poorly sorted sand and gravel in nonglaciated valleys. Unit is commonly less than 5 m above the Fraser River and tributary streams near Fraser and Tabernash, Colo., and commonly less than 5 m above present streams elsewhere within map area. Low-lying deposits are prone to periodic flooding. Estimated thickness 5–10 m

Qb **Broadway Alluvium (late Pleistocene)**—Cobbly gravel along major streams in piedmont near hogback belt; mostly pebble gravel and pebbly sand interbedded with sandy silt along South Platte River; and sand to sandy silt along tributary streams. Uppermost 0.3–1 m of unit is commonly clayey silt to silty sand. Soils formed in upper part of unit have A/Bw/Cox profiles where formed in coarse sand and A/Bt/Bk profiles with stage I carbonate morphology where formed in finer grained sediments. Deposits of unit Qb underlie unit Qa in flood plains along major streams and terraces about 8–12 m above major present streams near hogback belt. Small deposits of unit Qb in flood plains of major streams are exposed in gravel pits. Broadway Alluvium was deposited during the Pinedale glaciation (Bryan and Ray, 1940; Hunt, 1954; Scott, 1960, 1975; Bradley, 1987; Madole, 1991a, 1995), about 30–12 ka (Nelson and others, 1979; Madole, 1986; Schildgen and others, 2002; Benson and others, 2004, 2005). Upper part of the Broadway probably was deposited after Pinedale glaciers reached their maximum extent about 21 ka (Madole, 1986), and ceased deposition by about 11–10 ka (Holliday, 1987). Broadway Alluvium, on east side of South Platte River in and near downtown Denver, overlies terrace deposits composed of Louviers Alluvium (Qlv). The presence of unit Qlv beneath unit Qb is indicated by a soil buried by unit Qb that (1) has a clayey, reddish-brown B (argillic?) horizon formed in overbank(?) sediments and (2) overlies a carbonate-enriched (Bk?) horizon formed in underlying cobbly gravel (Hunt, 1954, p. 101). The buried soil is similar to the surface soil formed in Louviers Alluvium. Unit may locally include small deposits of pre-Piney Creek alluvium (Scott, 1960, 1962, 1963a). Unit Qb is a source of coarse aggregate. Thickness commonly about 1–9 m; as much as 9 m in flood plain of South Platte River near downtown Denver; as much as 18 m in flood plain of Clear Creek east of Golden; possibly as much as 20 m beneath terrace on east side of South Platte River in and near downtown Denver

Qg1 **Young stream-terrace alluvium (late Pleistocene)**—Glacial outwash composed chiefly of cobbly pebble gravel that underlies one terrace (locally two) along streams in major mountain valleys near and below lower limit of glaciation and fluvial deposits of nonglacial origin along Pole Creek near Tabernash. Amount and size of small boulders (commonly 30–50 cm in diameter) and cobbles in deposits decrease downstream from ice-contact deposits. Pebbly sand or silty overbank sediments less than about 50 cm thick locally overlie the gravel. Fluvial deposits of nonglacial origin north of Pole Creek, about 1 km southwest of Tabernash, consist of slightly cobbly pebble gravel overlain by about 35 cm of slightly pebbly, sandy, clayey silt overbank sediment. Deposits of unit Qg1 in glaciated valleys are composed of gravelly glacial outwash deposited during the Pinedale glaciation, about 30–12 ka (Nelson and others, 1979; Madole, 1986; Benson and others, 2004, 2005). Cosmogenic dating (based on measurement of isotopes ^{10}Be and ^{26}Al) of Pinedale outwash, 4–14 m above stream level in Boulder Canyon east of Nederland, yielded exposure ages of 32–10 ka (Schildgen and others, 2002). Unit underlies terrace treads commonly about 6 and 12 m above the Fraser River between Winter Park and Fraser, about 5 m above the Fraser River near Tabernash, about 5–9 m above streams tributary to the Fraser River, and commonly less than 12 m above stream level elsewhere in map area. Unit locally may include a minor amount of valley-floor alluvium (Qva). Along Swan River, near southwest corner of map area, unit Qg1 includes extensive dredge tailings produced by placer mining during the late 1880s. Unit Qg1 is a source of coarse aggregate. Estimated thickness 3–20 m

Qlv **Louviers Alluvium (late and middle Pleistocene)**—Pebbly coarse sand, cobbly gravel, and lenticular masses of silt and clay along major streams in the piedmont; commonly sandy to clayey alluvium along tributary streams. Uppermost 0.3–1 m of unit is commonly clayey to pebbly silt. Some of silt and clay within upper part of unit may be of eolian origin (Reheis, 1980). Soils formed in upper part of unit have A/Bt/Bk profiles with stage II–III carbonate morphology. Deposits underlie terraces about 12–20 m above major present streams near hogback belt and about 21–24 m above South Platte River south of Denver. Farther downstream, unit Qlv underlies terrace deposits of unit Qb on east side of South Platte River in and near downtown Denver (Hunt, 1954, p. 101). Louviers Alluvium was deposited during the Bull Lake glaciation (Scott, 1972, 1975; Bradley, 1987; Madole, 1991a), about 170–120 ka (Schildgen and others, 2002; Sharp and others, 2003; Pierce, 2004). Unit Qlv is a source of coarse aggregate. Thickness commonly about 3–7.5 m; at least 4.5 m thick below unit Qb on east side of South Platte River in and near downtown Denver; about 6–14 m along Clear Creek between Golden and valley of South Platte River

Qg2 **Intermediate stream-terrace alluvium (late and middle Pleistocene)**—Glacial outwash composed chiefly of cobbly pebble gravel that underlies one terrace (locally two) along Fraser River below lower limit of glaciation and fluvial deposits of nonglacial origin along Crooked Creek near Tabernash. Deposits near lower limit of glaciation locally contain small boulders about 30–35 cm in diameter, and rarely as large as 70–120 cm in diameter. Large pebbles and cobbles commonly are subangular to subrounded granite and gneiss; some are rounded to well rounded. Pebbly sand or sandy silt overbank sediments about 1–3 m thick locally overlie the gravel. Fluvial deposits of nonglacial origin along Crooked Creek, about 3 km southwest of Tabernash, consist of slightly cobbly pebble gravel overlain by about 2.5–3 m of slightly pebbly and cobbly, sandy, clayey silt overbank sediments that contain lenses of cobbly pebble gravel. The soil formed in pebbly alluvium beneath the 24-m-high terrace west of Fraser has an argillic B (Bt) horizon 35 cm thick. The proximity of till of the Bull Lake glaciation (Qtb) to outwash terraces underlain by unit Qg2 suggests that unit Qg2 was deposited by glacial meltwater during the Bull Lake glaciation (about 170–120 ka; Sharp and others, 2003; Pierce, 2004). Recent cosmogenic dating (on ^{10}Be and ^{26}Al) of Bull Lake outwash, 16 m above stream level in Boulder Canyon east of Nederland, yielded an exposure age of 130 ka (Schildgen and others, 2002). Unit underlies terrace treads commonly about 24 m above the Fraser River near Winter Park and Fraser, about 12 and 18 m above the Fraser River east of Tabernash, and about 18–24 m above streams tributary to the Fraser River. About 15 km downstream of Tabernash at Granby, Colo., outwash of Bull Lake age underlies a terrace tread about 12 m above the Fraser River (Meierding, 1977). Unit Qg2 is a source of coarse aggregate. Estimated thickness 3–20 m

Qs **Slocum Alluvium (middle Pleistocene)**—Deposited in piedmont east of mountain front where it consists of silty sand and sandy to clayey silt in upper part and mostly pebbly to cobbly gravel interbedded with pebbly to clayey silt in lower part. Some of the silt and clay within upper part of unit may be of eolian origin (Reheis, 1980). Soils formed in upper part of unit have A/Bt/Bk/K/Bk profiles with stage II–III carbonate morphology. Amount of cobbles and boulders in lower part of unit decreases with increasing distance east of mountain front. Unit Qs consists of terrace, pediment, and valley-fill deposits locally at two levels, about 24–30 and 37–45 m above major streams near the hogback belt. The Slocum is considered to be about 240 ka (Madole, 1991a), based on a uranium-series age of 190±50 ka near Canon City, Colo. (Szabo, 1980). Based on tentative correlation with marine oxygen isotope stages and a nonlinear rate of stream incision in the Denver area since the deposition of the 640-ka Lava Creek B tephra, younger deposits of unit Qs may have accumulated between about 300 and 220 ka, and older deposits may have accumulated between about 390 and 320 ka (see discussion in section, "Post-Laramide Cenozoic History of the Front Range"). Thickness commonly about 3–6 m; locally as much as 12 m

Qg3 **Old stream-terrace alluvium (middle and early? Pleistocene)**—Glacial outwash and, locally, fluvial deposits of nonglacial origin, composed chiefly of cobbly pebble gravel, that underlie terrace remnants at five levels above the Fraser River, and at two levels above Ranch Creek near Fraser. Pebbly sand or clayey silt overbank sediments about 1–1.5 m thick locally overlie the gravel. Large pebbles and cobbles commonly are subangular to subrounded granite and gneiss. Deposits locally contain a few boulders commonly as large as 30–50 cm in diameter near ice-contact deposits. Deposits beneath one of the higher terrace treads may be equivalent in age to fluvial deposits beneath a 60-m-high terrace near Clark, Colo.; this terrace (about 125 km northwest of Fraser) has a water-laid deposit of 640-ka Lava Creek B tephra at the top of the fluvial deposits (Madole, 1991b, c). Unit underlies treads of terrace remnants about 30, 50–55, 67, 85–90, and 120 m above the Fraser River, and about 55 and 67 m above Ranch Creek near Fraser. The fluvial deposit about 120 m above the Fraser River is of nonglacial origin, and those about 67 m above the Fraser River and Ranch Creek may also be of nonglacial origin. Outwash deposits and probably deposits of nonglacial origin of unit Qg3 were deposited during multiple pre-Bull Lake glaciations. Estimated thickness 3–16 m

Qv **Verdos Alluvium (middle Pleistocene)**—Unit was deposited in piedmont east of mountain front where it consists of pebbly, sandy to clayey silt in upper part and mostly cobbly gravel interbedded with pebbly sand and finer sediment in lower part. Some of the silt and clay within upper part of unit may be of eolian origin (Reheis, 1980). Soils formed in upper part of unit have A/Bt/Bk/K/Bk profiles with stage II–III and locally stage IV carbonate morphology. Amount of cobbles and boulders in lower part of unit decreases with increasing distance east of mountain front. Unit consists of younger (topographically lower) and older (higher) terrace, pediment, and valley-fill deposits locally at two levels, about 55–60 and 65–75 m above major streams near hogback belt. Beds and lenses of water-laid Lava Creek B tephra (about 640 ka; Lanphere and others, 2002) are present at several localities from Golden southward to southern boundary of map area. The tephra locally occurs at the base of older pediment deposits of unit Qv (Scott, 1963a), but is also present within or at top of older main-stream fluvial deposits of unit Qv (Hunt, 1954; Scott, 1972; Baker, 1973; Van Horn, 1976; Kirkham, 1977; Bradley, 1987). Water-laid Lava Creek B tephra is locally exposed beneath terraces about 61 m above Clear Creek at Golden (Baker, 1973; Van Horn, 1976) and about 65 m above Bear Creek near its confluence with the South Platte River in Denver (Hunt, 1954). Age and stratigraphic position of the Lava Creek B tephra indicate that older deposits of unit Qv are about 640 ka, possibly about 675–610 ka. Based on tentative correlation with marine oxygen isotope stages and a nonlinear rate of stream incision in the Denver area since the deposition of the 640-ka Lava Creek B tephra, younger deposits of unit Qv may have accumulated between about 475 and 410 ka (see discussion in section, "Post-Laramide Cenozoic History of the Front Range"). Unit Qv is a source of coarse aggregate. Thickness about 4.5–6 m; locally as much as 12 m

Qg4 **Oldest stream-terrace alluvium (middle or early Pleistocene)**—Chiefly slightly bouldery, cobbly pebble gravel that underlies terrace remnants about 145 m above the Fraser River southeast of Fraser. Gravel deposits locally contain (1) lenses of granule-rich, medium to very coarse sand, (2) a minor amount of boulders about 30–120 cm in diameter composed of granite, pegmatite, and sandstone probably from the Dakota Group (Kd), and (3) a few rounded rhyolite tuff (₽t) and red siltstone pebbles. Granitic clasts commonly weathered. Matrix is poorly sorted—mostly coarse to very coarse sand that contains abundant granules. Large pebbles and cobbles commonly are subangular to subrounded granite and gneiss as well as a minor amount of subangular pegmatite and sandstone probably from the Dakota Group. Cobbles are commonly as large as 25 cm in diameter. Unit probably is glacial outwash deposited during one or more pre-Bull Lake glaciations. Estimated thickness 2–18 m

QNr **Rocky Flats Alluvium (early Pleistocene and late Pliocene?)**—Mostly quartzite-rich cobble and pebble gravel that contains beds and lenses of pebbly sand, silty sand, and pebbly sandy clay at its type area on Rocky Flats about 9 km south of Boulder; mostly gravelly alluvium interbedded with pebbly silt and clay elsewhere in piedmont portion of map area. Some of the silty and clayey sediment mantling or within upper part of unit may be of eolian origin (Reheis, 1980; Shroba and Carrara, 1996). At Rocky Flats, upper part (typically ≤5 m) of unit forms an alluvial fan that locally buries a hogback composed of Fox Hills Sandstone (Kf), and lower part of unit (≤25 m) fills small basins and paleovalleys that are cut in Cretaceous sedimentary rocks. Paleovalleys radiate eastward away from apex of fan (Knepper, 2005; Lindsey and others, 2005). Elsewhere in map area, unit forms pediment and valley-fill deposits. At its type section (Scott, 1960), the soil formed in upper part of unit has an A/Bt/K profile with stage III–IV carbonate morphology. This soil directly overlies a buried soil that has a Btk/K/Btk profile with stage I and stage III carbonate morphology. Amount of cobbles and boulders in unit decreases with increasing distance east of mountain front. Unit consists of fan deposits and valley-fill deposits that mantle a dissected landscape at Rocky Flats (Knepper, 2005); elsewhere in map area consists of relatively thin pediment and valley-fill deposits. Soil properties and paleomagnetic data suggest that the Rocky Flats Alluvium is at least 1.6–1.4 Ma (Birkeland and others, 1996) and could be about 2 Ma (Birkeland and others, 2003). Cosmogenic dating (on ^{10}Be) indicates that upper part of the Rocky Flats Alluvium at Rocky Flats is about 1.5 Ma (Dethier and others, 2001); buried soils formed in upper part of unit suggest that the underlying valley-fill deposits in lower part of unit could be much older. Recent cosmogenic dating (on ^{10}Be and ^{26}Al) suggests that incision of eastern part of Rocky Flats surface began about 2–1 Ma (Riihimaki and others, 2006). A small area of Rocky Flats surface, which extends northeastward from the mouth of Coal Creek Canyon (red circle pattern), displays a braided pattern produced by subdued gravel bars and shallow channels. These features may have been produced by a major flash flood on Coal Creek that flowed across the Rocky Flats surface. Age of flash flood is inferred to predate the Verdos Alluvium (Qv), which is inset below Rocky Flats surface along Coal Creek. Top of Rocky Flats surface is about 140–230 m above most major streams near mountain front. Unit QNr is a source of coarse aggregate. Thickness at Rocky Flats commonly less than 6 m but locally greater than 40 m (Knepper, 2005); elsewhere in map area commonly about 3–6 m thick

QNpr **Pre-Rocky Flats alluvium or debris-flow deposits (early Pleistocene or late Pliocene)**—Three small deposits along eastern margin of mountain front a few kilometers north and south of mouth of Coal Creek Canyon consist chiefly of bouldery sand and gravel and clayey sand. Boulders are as large as 2 m in diameter. Unit includes alluvial-fan and channel-fill deposits. Top of unit is about 15–25 m above top of the Rocky Flats Alluvium and about 225–235 m above South Boulder Creek. Unit could be as old as Pliocene (Malde, 1955) and may be temporally equivalent, in part, to the Nussbaum Alluvium (about 3 Ma) along the South Platte River in northeastern Colorado (Scott, 1978, 1982). Thickness about 3–4.5 m

Alluvial and mass-movement deposits

Qac **Alluvium and colluvium, undivided (Holocene to middle? Pleistocene)**—Chiefly undifferentiated valley-floor alluvium (Qva), fan deposits (Qf), debris-flow deposits (Qdf), colluvium (Qc), and other mass-movement deposits along minor streams and on adjacent lower slopes. Low-lying areas of unit adjacent to stream channels may be subject to periodic stream flooding and debris-flow deposition. Estimated thickness 3–15 m

Qf **Fan deposits (Holocene and late Pleistocene)**—Mostly poorly sorted, slightly bouldery pebble and cobble gravel and locally pebbly and cobbly silty sand. Deposited chiefly by streams and debris flows in fan-shaped accumulations near base of moderate to steep slopes. Unit locally includes sheetwash deposits, colluvium (Qc), and probably hyperconcentrated-flow deposits. Near valley floors, areas underlain by map unit may be subject to stream flooding and debris-flow deposition. Estimated thickness 3–15 m

Qp1 **Lower pediment deposits (late Pleistocene)**—Crudely stratified, matrix-supported small boulders to granules in a sandy, clayey silt matrix that overlies northeast-sloping surface formed on Troublesome Formation (NꝐt) west of Crooked Creek southwest of Tabernash. Matrix makes up much of unit and is chiefly derived from siltstone of the Troublesome Formation. Unit probably deposited chiefly by debris flows and ephemeral streams under periglacial conditions during the Pinedale glaciation. Large pebbles and cobbles commonly are angular to subangular and consist of sandstone probably from the Dakota Group (Kd), gneiss, and pegmatite. Sandstone boulders are commonly as long as 50 cm. Lower limit of unit is about 5 m above Crooked Creek. Estimated thickness 2–5 m

Qp2 **Higher pediment deposits (late and middle Pleistocene)**—Crudely stratified, matrix-supported small boulders to granules in a sandy, clayey silt matrix that overlies a northeast-sloping surface formed on Troublesome Formation (NꝐt) west of Crooked Creek southwest of Tabernash. Matrix makes up much of unit and is chiefly derived from siltstone of the Troublesome Formation. Unit probably deposited chiefly by debris flows and ephemeral streams under periglacial conditions during the Bull Lake glaciation. Large pebbles and cobbles commonly are angular to subangular and consist of sandstone probably from the Dakota Group (Kd), gneiss, pegmatite, and, locally, a minor amount of volcanic porphyry. Boulders composed of sandstone and, locally, volcanic porphyry are commonly as long as 40 cm. Lower limit of unit is about 12 m above Crooked Creek. Eastern margin of unit locally includes cobbly fluvial gravel (Qg2). Estimated thickness 2–5 m

Qds **Debris-flow deposits and Slocum Alluvium, undivided (middle Pleistocene)**—Debris-flow deposits, probably hyperconcentrated-flow deposits, and minor stream alluvium at two or three levels near mouths of steep canyons along eastern margin of mountain front north of Eldorado Springs. Lower limits of these deposits are about 15–25 m above South Boulder Creek. Debris-flow deposits consist chiefly of nonsorted and nonstratified boulders to granules supported in sandy matrix. Clasts are angular to subangular and commonly are randomly oriented. Boulders greater than 1 m in length are more common in upper part of unit. Boulders composed of sandstone and conglomerate of the Fountain Formation (PIPf) on or near top of unit are as large as 3.1x7.0x8.1 m. Hyperconcentrated-flow deposits and stream alluvium are locally present in eastern (distal) part of unit. These deposits consist of poorly sorted and poorly stratified, gravelly sand and sandy gravel. Estimated thickness 3–8 m

QNdi **Diamicton (middle? Pleistocene to Pliocene?)**—Poorly exposed bouldery deposits that (1) overlie the Troublesome Formation (NꝐt) and, locally, rhyolite tuff (Ꝑt) on high ridges beyond outer limits of tills of the Pinedale and Bull Lake glaciations a few kilometers southeast, south, and southwest of Fraser and (2) mantle slopes above upper limit of glacial ice on northwest flank of Saxon Mountain about 4 km northeast of Georgetown.

Deposits near Fraser consist of (1) glacial outwash(?) deposited by the Fraser River, Elk Creek, and St Louis Creek, (2) till-like deposits probably deposited during one or more pre-Bull lake glaciations, and (3) mass-movement deposits having clayey-silt matrix on slopes steeper than about 6°. Glacial outwash(?) is poorly sorted, granite-rich, matrix-supported and clast-supported, slightly bouldery, cobbly pebble gravel. Deposits probably contain lenses of pebble gravel and sand. Matrix is mostly coarse to very coarse sand that contains abundant granules. Large pebbles and cobbles commonly are subangular to subrounded granite and gneiss. Boulders composed of granite, gneiss, pegmatite, and sandstone probably from the Dakota Group (Kd) are commonly as large as 40–90 cm in diameter. Dakota Group sandstone clasts are in deposits along Fraser River; nearest known outcrops of the Dakota Group are about 10 km to the west and southwest. Deposits along Fraser River also locally contain a few rounded, red siltstone pebbles. Till-like deposits are locally present at elevations of about 9,300–9,500 ft along Elk Creek and St Louis Creek. These deposits contain granite and gneiss boulders as long as 1–2 m. Deposits along Fraser River contain clasts derived from glacial outwash(?) and till-like deposits, and have a clayey-silt matrix derived chiefly from siltstone of the Troublesome Formation. Top of unit is about 35–170 m above Elk Creek, about 50–195 m above St Louis Creek, and about 140–270 m above the Fraser River. Small deposit about 270 m above the Fraser River, about 2 km northeast of Winter Park ski area, may be of Pliocene age. Unit locally may include debris-flow deposits. Estimated thickness of deposits near Fraser is as much as 15 m.

Deposit on northwest flank of Saxon Mountain near Georgetown is nonsorted and bouldery and has a sandy matrix (Widmann and Miersemann, 2001). Lower limit of this deposit is about 270 m above Clear Creek, and may be of Pliocene age. Estimated thickness of deposit near Georgetown probably greater than 5 m

Qdv **Debris-flow deposits and Verdos Alluvium, undivided (middle Pleistocene)**—Debris-flow deposits, probably hyperconcentrated-flow deposits, and minor stream alluvium on mesas at two levels near mouths of steep canyons along eastern margin of mountain front north of Eldorado Springs. Eastern lower limits of tops of upper and lower deposits are about 90 m and 35–45 m, respectively, above South Boulder Creek. Debris-flow deposits consist chiefly of nonsorted and nonstratified boulders to granules supported in a matrix of pebbly, slightly silty sand. Clasts are angular to subangular and commonly are randomly oriented. Boulders greater than 1 m in length are more common in upper part of unit. Boulders composed of sandstone and conglomerate of the Fountain Formation on or near top of unit are as large as 2.3x3.7x>3.7 m. Hyperconcentrated-flow deposits and stream alluvium are locally present in eastern (distal) part of unit. These deposits consist of poorly sorted and poorly stratified, gravelly sand and sandy gravel. Thickness about 3–5 m

QNdr **Debris-flow deposits and Rocky Flats Alluvium, undivided (early Pleistocene and late Pliocene?)**—Debris-flow deposits, probably hyperconcentrated-flow deposits, and minor stream alluvium on high mesas near mouths of steep canyons along eastern margin of mountain front north of Eldorado Springs. Tops of these mesas project to the top of the Rocky Flats Alluvium (QNr) at Rocky Flats, south of Eldorado Springs. Eastern lower limits of tops of these mesas are about 140–200 m above South Boulder Creek. Unit consists chiefly of nonsorted and nonstratified boulders to granules supported in a matrix of pebbly, slightly silty sand. Clasts are commonly randomly oriented and angular to subangular. Boulders greater than 1 m in length are more common in upper half of unit. Angular to subangular boulders composed of sandstone and conglomerate of the Fountain Formation on or near top of unit are as large as 2.8x3.2x5.8 m. Unit locally consists of three superimposed depositional units. Thickness 4.5–6 m

Ng **High-level gravel deposits (Miocene?)**—Scattered deposits of coarse boulder gravel mantle ridges and hills that range in elevation from about 2,715 m east of Nederland to about 2,300 m east of Conifer. From north to south, top of gravel is as much as 185 m above South Boulder Creek, 370 m above Clear Creek, 255 m above Bear Creek, and 70 m above Deer Creek. Unit consists of nonsorted, nonstratified to crudely stratified, matrix-supported and locally clast supported, bouldery gravel and slightly bouldery, coarse cobble gravel that locally contains lenses of boulder gravel, pebble gravel, and sand. Matrix material is slightly silty and clayey, coarse sand. Some deposits near Bear Creek have a clayey matrix (Sheridan and Marsh, 1976). Sediments in unit were deposited by stream flow and probably locally by debris flow. Clasts are angular to rounded and commonly subangular to subrounded. Biotite-rich clasts are partly or completely disintegrated. Boulders are commonly as large as 2 m in diameter; some are as large as 4.5 m in diameter (Sheridan and others, 1972). Clasts of Silver Plume Granite (YgSP) in deposits near Clear Creek indicate eastward transport of at least 10 km. Unit forms thick aggradational fills in the east-trending Tungsten, Clear Creek, Evergreen, and Wilds Peak paleovalleys. These paleovalleys are incised as much as about 240 m below an extensive erosion surface (Epis and others, 1980) that truncates South Park Formation (59.7 Ma; Bryant and others, 1981a) and is capped by the Wall Mountain Tuff of early Oligocene age (36.7 Ma; McIntosh and Chapin, 2004) south of map area (Scott and Taylor, 1986).

Unit may represent proximal facies of the Ogallala Formation of Miocene age (about 18–5 Ma; Swinehart and others, 1985) in the High Plains about 130 km east of mountain front. Unit is younger than bouldery deposits of Oligocene age (Scott and

Taylor, 1986) on Niwot Ridge and other nearby ridges, about 5–10 km north of map area (Madole, 1982; Gable and Madole, 1976). Maximum thickness 70 m near Boulder Creek, 110 m near Clear Creek, 25 m near Bear Creek, and 6 m near Deer Creek

Mass-movement deposits

Qc **Colluvium (Holocene to middle? Pleistocene)**—Nonsorted deposits that consist of clay, silt, sand, and angular to subrounded clasts that range in size from granules to large boulders. Composition of deposits reflects that of upslope bedrock or sediment from which colluvium was derived. Includes material transported by frost creep, solifluction, and other periglacial processes, sheetwash, landslide, debris flow, hyperconcentrated flow, and rock fall. Extensive periglacial deposits are locally present near or above present treeline (about 3,500 m). Estimated thickness 3–50 m

Qdf **Debris-flow deposits (Holocene to middle? Pleistocene)**—Lobate and fan-shaped masses of coarse debris deposited by sediment-charged flows. Deposits are chiefly very poorly sorted and very poorly stratified boulders to granules supported in a matrix of silty sand to slightly sandy clayey silt. Locally includes lenticular beds of poorly sorted, clast-supported, bouldery cobbly pebble gravel. Clasts are commonly randomly oriented and angular to subangular. Low-lying areas of unit adjacent to stream channels are prone to periodic stream flooding and debris-flow deposition. Unit probably includes minor stream-flow and hyperconcentrated-flow deposits. Mapped only in Eldorado Springs 7.5-minute quadrangle and at one locality in eastern part of Keystone 7.5-minute quadrangle. Estimated thickness 3–10 m

Qls **Landslide deposits (Holocene to middle? Pleistocene)**—Deposits of unsorted and unstratified debris, on slopes or at base of slopes, that are commonly characterized by hummocky topography. Many of the landslides and landslide deposits form on unstable slopes that are underlain by shale, siltstone, and claystone on east flank of hogback belt and on slopes of North Table Mountain and South Table Mountain near Golden. Younger deposits are commonly bounded upslope by crescent-shaped headwall scarps and downslope by lobate toes. Unit locally includes material displaced chiefly by rotational rock slides, rotational earth slides, debris slides, earth flows, and earth slide–earth flows as defined by Varnes and Cruden (1996). Some deposits probably are formed by translational slides and rock or earth creep. Sizes and lithologies of clasts and grain-size distributions of matrices of these deposits reflect those of the displaced bedrock units and surficial deposits. Landslide deposits are prone to continued movement or reactivation due to natural, as well as human-induced, processes. Deposits in mountainous terrain derived from Precambrian quartz-feldspar gneiss (Xf) and biotite gneiss (Xb) locally contain blocks of rock as long as several meters. Landslide deposits derived from Pierre Shale (Kp), Laramie Formation (Kl), and Denver Formation (₽Kd) are rich in clay. Some of this clay is expansive and locally may have high potential for shrinking and swelling (Shroba, 1982). Deposits on gentle slopes along and east of hogback belt locally include minor sheetwash and creep-deformed deposits. Deposits in mountains locally include minor rock-fall deposits. Estimated thickness 5–50 m

Qt **Talus deposits (Holocene to middle? Pleistocene)**—Angular pebbles to large boulders deposited chiefly by rock and snow avalanche, rockfall, rock slide, and debris flow at base of cliffs and steep slopes where debris forms aprons, cones, and fan-shaped deposits. Locally includes debris flow and rubbly scree deposits. In cirques, locally includes tills of the Satanta Peak and Triple Lakes advances of Benedict (1985), about 12–10 ka (Davis, 1988), and tills of Holocene age near cirque headwalls (Benson and others, 2007). Much of the talus in glaciated valleys and cirques postdates the retreat of Pinedale ice. Some of the talus derived from the Fountain Formation (PIPf) south of Boulder may be of middle Pleistocene age. Estimated thickness 3–15 m

Mass-movement and glacial deposits

Qrg **Rock-glacier deposits (Holocene and latest Pleistocene)**—Bouldery, lobate and tongue-shaped masses along valley walls and on valley floors that commonly have steep fronts and flanks. Deposits consist of a veneer of angular boulders that overlies a thick mass of rock rubble that contains finer interstitial rock fragments. Lower part of unit locally contains interstitial ice, ice lens, or an ice core. Lobate rock glaciers form along valley walls and contain interstitial ice. Tongue-shaped rock glaciers form on valley floors. East of the Continental Divide, tongue-shaped rock glaciers commonly have ice cores, and are covered by debris. Those on the west side contain interstitial ice, and are known as ice-cemented rock glaciers (Benedict, 1973; White, 1976). Ice-cored rock glaciers commonly have depressions adjacent to headwall cliffs (where glacial ice melted), longitudinal marginal-and-central meandering furrows, and collapse pits. Ice-cemented rock glaciers commonly lack these surface features (White, 1976). Rock fragments on and within rock-glacier deposits are derived from steep slopes chiefly by rockfall and locally by rock slide and avalanche. Unit Qrg locally includes protalus ramparts, minor talus deposits (Qt) displaced by post-depositional flowage, debris-flow deposits, colluvium (Qc), and other mass-movement deposits. Unit also includes till of the Satanta Peak and Triple Lakes advances of Benedict (1985), about 12–10 ka (Davis, 1988), as well as tills of Holocene age near cirque headwalls (Benson and others, 2007). Many of the rock-glacier deposits in Colorado are of latest Pleistocene or early Holocene age (Meierding and Birkeland, 1980). Rates of movement of active rock glaciers in the Front Range are approximately 1–10 cm/yr (White, 1971, 1976). Estimated thickness as much as 50 m

Qmg **Mass-movement and glacial deposits, undivided (Holocene and latest Pleistocene)**—Unit commonly includes talus (Qt), colluvium (Qc) and other mass-movement deposits, rock-glacier deposits (Qrg), and till of Pinedale age (Qtp) near heads of glaciated valleys. Unit locally includes tills of the Satanta Peak and Triple Lakes advances of Benedict (1985), about 12–10 ka (Davis, 1988), and tills of Holocene age near cirque headwalls (Benson and others, 2007). Unit also locally includes rotational rock-slide deposits (Qls) derived from bedrock that is extensively faulted and (or) highly altered. Estimated thickness 3–50 m; possibly as much as 100 m in large rotational rock-slide deposits

Glacial deposits

[Mostly nonsorted and nonstratified till deposited from ice. Deposits locally include a minor amount of stratified sand and pebble gravel (stratified drift) deposited by meltwater, mass-movement deposits, and small areas of bedrock outcrops on steep slopes. Most glacial deposits are derived chiefly from Precambrian granitic and gneissic rocks]

Qtp **Till of Pinedale age (late Pleistocene)**—Mostly nonsorted and nonstratified, subangular to subrounded boulders to granules in a silty sand matrix. Material less than 2 mm in diameter is estimated to be 20–40 percent of unit. This material consists chiefly of poorly sorted sand and ≤20 percent silt and ≤5 percent clay. Unit commonly forms large prominent, sharp-crested lateral and end moraines that are very bouldery and have distinct constructional morphology. Deposits in some areas have well-expressed knob-and-kettle topography. Surface soils have A/Cox profiles on moraines with narrow crests and A/Bw/Cox and A/Btj/Cox profiles on moraines with broad crests. Surface and near-surface O and E soil horizons are locally present. Cambic (Bw) and weak argillic (Btj) horizons are thin (10–40 cm) and commonly contain 1–5 percent more clay than the underlying till (<2 mm size fraction). Most of the biotite-rich granitic and gneissic clasts within the soil are unweathered, and disintegrated clasts are rare. Unit locally includes deposits of stratified drift, mass-movement and glacial deposits, undivided (Qmg), tills of the Satanta Peak and Triple Lakes advances of Benedict (1985), about 12–10 ka (Davis, 1988), till of Bull Lake age (Qtb), colluvium (Qc) and other mass-movement deposits, and valley-floor alluvium (Qva); locally may include till of pre-Bull Lake age. Radiocarbon (^{14}C) and cosmogenic-exposure ages indicate that till of unit Qtp is about 30–12 ka (Nelson and others, 1979; Madole, 1986; Schildgen and Dethier, 2000; Benson and others, 2004, 2005). Subsurface deposits and locally some surface deposits of unit Qtp may be older than 30 ka, because uranium-series ages of travertine in the northern Yellowstone area suggest an early advance of Pinedale ice about 47–34 ka (Sturchio and others, 1994). Estimated thickness 1.5–30 m

Qtb **Till of Bull Lake age (late and middle Pleistocene)**—Mostly nonsorted and nonstratified, subangular to subrounded boulders to granules in a silty sand matrix. Material <2 mm in diameter is estimated to be 20–40 percent of unit. Unit Qtb commonly forms prominent lateral moraines that have rounded crests beyond the outer limit of till of Pinedale age (Qtp). Surface boulders typically are less abundant on moraines of Bull Lake glaciation than on those of Pinedale glaciation. Till of Bull Lake age (Qtb) is more weathered than till of Pinedale age (Qtp). Surface soils have A/E/Bt/Cox profiles. Clay-enriched argillic (Bt) horizons are 35–75 cm thick and commonly contain 5–13 percent more clay than the underlying till (<2 mm size fraction). Many of the biotite-rich granitic and gneissic pebbles and cobbles within the soil are weathered and are partly to completely disintegrated. K-Ar and ^{230}Th/U analyses that constrain the ages of glaciofluvial deposits near the type area for the Bull Lake glaciation along north flank of Wind River Range, Wyo., and ages of glacial deposits near West Yellowstone indicate that the Bull Lake glaciation probably began prior to 167±6.4 ka (possibly 190 ka) and may have continued until about 122±10 ka (Sharp and others, 2003; Pierce, 2004). ^{10}Be and ^{26}Al analyses of surface boulders on moraines composed of till of Bull Lake age near Nederland yielded minimum age estimates of 101±21 and 122±26 ka (Schildgen and others, 2002). These age estimates are in accord with a uranium-trend age estimate of 130±40 ka for till of Bull Lake age (Shroba and others, 1983) near Allenspark, Colo. Unit locally includes deposits of stratified drift, such as those in the valley of Clear Creek at Dumont, till of Pinedale age (Qtp), colluvium (Qc), other mass-movement deposits, and thin deposits of loess or sheetwash deposits derived chiefly from loess; locally may include till of pre-Bull Lake age. Estimated thickness 1.5–15 m

Qti **Till of Pinedale age and till of Bull Lake age, undivided (late and middle Pleistocene)**—Unit consists of till chiefly of Pinedale age (Qtp) and a minor amount of till of Bull Lake age (Qtb) in areas where till of Bull Lake age is of limited extent and is difficult to distinguish from till of Pinedale age. In some areas, till of Bull Lake age may be mantled by till of Pinedale age and is not exposed. Locally includes stratified drift, mass-movement and glacial deposits, undivided (Qmg), colluvium (Qc), and other mass-movement deposits; locally may include a minor amount of till of pre-Bull Lake age that lacks depositional morphology. Estimated thickness 1.5–30 m

Eolian deposits

Qes **Eolian sand (Holocene and late Pleistocene)**—Slightly silty sand to silty and slightly clayey sand derived from deflation of sediment from flood plains of major streams east of mountain front by northwesterly paleowinds. Grain size decreases from northwest to southeast. Unit locally may include a minor amount of loess (Qlo). Deposits east of South Platte River probably contain less silt and clay than deposits of eolian sand elsewhere within map area. Soils formed in upper part of deposits of late Pleistocene age have A/Bt/Cox profiles where formed in slightly silty sand and A/Bt/Bk profiles with stage I or II carbonate morphology where formed in finer grained sediment. Unit forms sand sheets that mantle deposits as young as Broadway Alluvium (Qb) on east side of valley of South Platte River. Deposits locally reworked by sheetwash contain a minor amount of granules and a few pebbles.

Eolian sand in northeastern Colorado records at least three episodes of deposition between 27 and 11 ka, possibly between 11 and 4 ka, and within the past 1.5 ky (Muhs and others, 1996). Most deposits in map area probably formed between about 27 ka (Muhs and others, 1996) and 4.5 ka (Scott and Lindvall, 1970). Thickness commonly less than 3 m west of South Platte River, and commonly less than 6 m east of river

Qlo **Loess (late and middle? Pleistocene)**—Nonstratified, well-sorted, wind-deposited sandy silt and locally sandy, clayey silt derived by wind erosion from flood plains and possibly Cretaceous bedrock sources by westerly or northwesterly paleowinds. Soils formed in upper part of unit have A/Bt/Btk/Bk profiles with stage I–II carbonate morphology. Loess overlies deposits as young as Louviers Alluvium (Qlv) in map area, but locally overlies Broadway Alluvium (Qb) along South Platte River about 15 km northeast of map area (Lindvall, 1980). Thin (≈50 cm) layers of pebbly, clayey, sandy silt that locally mantle Slocum Alluvium (Qs) and older alluviums in the piedmont may consist in part of loess that contains clasts from the underlying gravelly alluvium. Deposits of unit Qlo locally reworked by unconfined overland flow contain a minor amount of coarse sand and granules, and locally a few pebbles. Unit Qlo locally contains deposits of silty eolian sand (Qes) near Louisville and Lafayette.

Loess in northeastern Colorado records two episodes of deposition at about 20–14 ka and 13–10 ka (Muhs and others, 1999). Holocene loess is locally extensive in eastern part of Colorado (Madole, 1995), but none has been recognized within or near map area. Some loess near southeast corner of map area (older loess of Scott, 1962, 1963a) may be as old as 170–120 ka and may be correlative with eolian silt and sand about 30 km northeast of map area that yielded thermoluminescence age estimates of about 150 ka (Forman and others, 1995). Pre-Bull Lake till near Allenspark, about 25 km north of Nederland, is locally mantled by about 15 cm of loess (Madole and Shroba, 1979). Some of the closed depressions on till of Pinedale age (Qtp, Qti) may contain thin (≤50 cm) deposits of loess or silty sheetwash deposits derived chiefly from loess. Dust deflated from flood plains in the Colorado Piedmont has influenced properties of soils downwind of flood plains (Reheis, 1980). Alpine soils in and near cirques on east side of the Continental Divide, just north of map area, contain eolian dust (Birkeland and others, 1987, 2003; Muhs and Benedict, 2006). Thickness about 1.5–3 m

LARAMIDE AND POST-LARAMIDE SEDIMENTARY AND VOLCANIC ROCKS OF FRASER BASIN

N₱t **Troublesome Formation (Miocene and Oligocene)**—Light-gray, light-brown, and light-grayish-orange tuffaceous siltstone and silty, fine-grained sandstone; local white, water-laid tuff; and light-tan and brown arkosic sandstone and conglomerate near base of unit. Tuffaceous beds are rich in swelling clay. ^{40}Ar/^{39}Ar ages for interbedded tuffs just west of quadrangle range from 11.0±05 Ma to 23.5±0.06 Ma (Izett and Obradovich, 2001). Thickness probably greater than 245 m (Taylor, 1975)

₱t **Rhyolite tuff (Oligocene)**—Rhyolitic crystal-lithic tuff and tuff breccia. Forms small outcrops beneath Troublesome Formation (N₱t) along south margin of Fraser basin (Bryant and others, 1981b). Contains conspicuous smoky quartz phenocrysts, sanidine, and biotite. K-Ar sanidine age on tuff breccia of 29.8±3 Ma (Taylor and others, 1968). Volcanic source may be either rhyolite porphyry at Red Mountain or volcanic center near Mount Richthofen (O’Neill, 1981), about 45 km north of northwest corner of map area

Middle Park Formation (Paleocene and Upper Cretaceous)

₱Kmu **Upper member (Paleocene and Upper Cretaceous?)**—Variegated gray, brown, maroon, and rusty-orange siltstone, mudstone, sandstone, and conglomerate; predominantly micaceous and arkosic (Taylor, 1975). Derived mostly from various Proterozoic intrusive rocks and feldspathic gneiss shed during Laramide uplift of the Front Range. Lower 150 m contains as much as 50 percent clasts of porphyritic andesite, trachyandesite, and other porphyries. Potentially unstable, even on gentle slopes. Maximum thickness greater than 600 m

Kmw **Windy Gap Volcanic Member (Upper Cretaceous)**—Medium- to dark-gray, greenish-gray, or purplish-gray volcanic breccia and conglomerate containing a trachyandesite flow near base at one locality. Beds include massive lahar breccias containing andesite and trachyandesite boulders as long as 1.2 m, bedded fluvial boulder and cobble conglomerates, and volcanic sandstone containing a substantial fraction of Proterozoic debris (Taylor, 1975) shed during Laramide uplift of the Front Range. Palynomorph data suggest age is Late Cretaceous (Izett, 1968). Thickness 0–215 m

TERTIARY AND CRETACEOUS INTRUSIVE ROCKS

[Petrographic nomenclature follows Streckeisen (1976); geochemical nomenclature (calcic, calc-alkalic, alkali-calcic, alkalic) follows De la Roche and others (1980)]

₱Ki **Intrusive rock, undifferentiated (Oligocene to Late Cretaceous)**—Dike rocks mapped only in northeastern part of Idaho Springs 7.5-minute quadrangle (Widmann and others, 2000); probably mostly older felsic to intermediate porphyries of alkali-calcic group (₽Kpc) or alkalic porphyries (₽Kpa)

₽rp **Rhyolite porphyry (Oligocene and Eocene)**—Mapped mostly in two areas: Red Mountain and northern Montezuma 7.5-minute quadrangle. The Red Mountain rocks contain quartz and sanidine in an aphanitic groundmass; rocks form dikes and a volcanic center on Red Mountain; rock altered and has locally associated molybdenite mineralization (Henderson ore body). All analyzed rocks on Red Mountain are alkali rhyolites (Ed Dewitt, written commun., 2007); fission-track and $^{40}Ar/^{39}Ar$ analyses on these rocks indicate age of 30–27 Ma (Geissman and others, 1992). Occurrences in Montezuma quadrangle are predominantly rhyolitic, and include aplitic-textured rhyolite porphyry, alkali-feldspar rhyolite porphyry, biotitic rhyolite porphyry, quartz latite porphyry, and rhyodacite porphyry; dated rhyolite porphyries yield fission-track ages of 39.4–37.4 Ma (Bookstrom and others, 1987), and are probably derived from same magma that produced the approximately coeval Montezuma stock

Rocks of Montezuma stock and vicinity (Eocene)

₽ma **Aplite**—Light-pinkish-gray to gray, fine-grained quartz-feldspar rock that forms two irregular bodies and numerous unmapped dikes that intrude granodiorite porphyry of Montezuma stock (₽mm). Chemical analysis indicates composition is alkali-calcic granite (Ed Dewitt, written commun., 2007). Undated, but considered about same age as monzogranite porphyry (≈37 Ma)

₽mm **Monzogranite porphyry**—Light-tan to gray, medium-grained, porphyritic, alkali-calcic monzogranite and granodiorite with euhedral to subhedral phenocrysts of orthoclase and quartz. Chemical composition indicates alkali-calcic granodiorite (Ed Dewitt, written commun., 2007). Orthoclase phenocrysts form as much as 20 percent of rock and are locally reported as long as 10 cm (Lovering, 1935). Quartz phenocrysts form as much as 10 percent of rock and are commonly partially resorbed. Matrix contains orthoclase, plagioclase, quartz, as much as 3 percent biotite, and trace amounts of hornblende, magnetite, and sphene. Locally includes light-pink aplite dikes (₽ma) not mapped separately. Includes several small intrusive bodies near Montezuma stock. Zircon fission-track ages between 39.8±4.2 and 34.8±3.7 Ma (Bookstrom and others, 1987); Cunningham and others (1994) reported a zircon fission-track age of 35.0±3.2 Ma; one K-Ar age is 37.0±1.4 Ma (Marvin and others, 1989)

₽pc **Younger felsic to intermediate porphyries of alkali-calcic group (Eocene)**—Occur principally in three areas: (1) in southwestern part of Georgetown 7.5-minute quadrangle near Leavenworth Creek, (2) near Empire, where the Mad Creek monzogranite to granodiorite stock intrudes the monzonitic Empire stock, and (3) in southwestern part of Keystone 7.5-minute quadrangle, where granodiorite to monzogranite intrude the Pierre Shale (Kp) as dikes, sills, and irregular-shaped bodies. Rhyolite porphyry near Leavenworth Creek is tan to pinkish gray and very fine grained, with phenocrysts of orthoclase, biotite, and quartz (Widmann and Miersemann, 2001); it has a zircon fission-track age of 36.6±4.2 Ma (Bookstrom and others, 1987). The Mad Creek stock consists of a very fine grained matrix containing phenocrysts mostly of altered plagioclase and subordinate sanidine, quartz, and biotite (Braddock, 1969); it has a fission-track age of 39.4±4.2 Ma (Bookstrom and others, 1987). Braddock (1969) reported monzogranite composition for the Mad Creek stock, but it also includes significant granodiorite (Ed Dewitt, written commun., 2007). The Keystone occurrences are gray, porphyritic quartz-plagioclase-orthoclase-biotite±hornblende granodiorite containing megacrysts of orthoclase as long as 4 cm and smaller plagioclase phenocrysts in a medium- to coarse-grained matrix (Widmann and others, 2003). Quartz phenocrysts are commonly partially resorbed and embayed. Rock weathers light tan in blocky outcrops. The Keystone rocks are almost identical mineralogically, texturally, and magnetically with rocks in the Mt. Guyot stock, about 5 km south of the Keystone quadrangle (Ed Dewitt, written commun., 2007). K-Ar biotite date on Mt. Guyot stock is 44.0±1.5 Ma (Bryant and others, 1981a)

₽Kix **Intrusive breccia (Eocene to Late Cretaceous?)**—Occurs as a pipe-shaped body in Central City mining district, as a fault-bounded body in southern Nederland 7.5-minute quadrangle, and as a small body associated with intrusion of the Eocene Mad Creek stock near Empire. Central City breccia pipe consists of altered fragments of biotite gneiss, pegmatite, and quartzofeldspathic gneiss in a matrix of monzogranite (Sims, 1964, 1988; Sims and Gable, 1967); undated, but probably Paleocene based on age of intrusive activity in area. Nederland occurrence consists of altered fragments of Proterozoic rock in a matrix of altered porphyry (Gable, 1969) probably associated with the 61 Ma Bryan Mountain (Eldora) stock. Breccia near Empire is composed of angular fragments of Silver Plume Granite, monzonite of the Empire stock (Braddock, 1969), and the Eocene granodiorite Mad Creek stock (Bookstrom and others, 1987)

PeKdg **Diorite, gabbro, and lamprophyre (Tertiary and Cretaceous?)**—In Nederland and Tungsten 7.5-minute quadrangles, consists of dikes and small stocks of biotite-hornblende-pyroxene diorite, diorite porphyry, fine-grained andesite porphyry, diabase, gabbro, lamprophyre, and pyroxenite (Gable, 1969, 1972). Pyroxenite, in particular, is commonly associated with biotite-hornblende-pyroxene diorite in the Caribou stock. In the Loveland Pass and Byers Peak 7.5-minute quadrangles, consists of north-striking, fine-grained pyroxene diorite dikes containing phenocrysts of augite and plagioclase (Eppinger and others, 1984). Undated, but in Nederland quadrangle intrudes, and probably closely postdates, rocks of the Caribou stock, part of the older felsic to intermediate porphyries of the alkali-calcic group (PeKpc)

PeKpc **Older felsic to intermediate porphyries of alkali-calcic group (Paleocene to Late Cretaceous?)**—Large stocks, adjacent smaller bodies, and dikes in Nederland area and in southern Empire and northern Georgetown 7.5-minute quadrangles. Includes the Caribou, Bryan Mountain (also called Eldora), and Apex stocks. Includes monzogranite, monzogranite porphyry, biotite-hornblende±pyroxene monzogranite (Gable, 1969), and granodiorite (Ed Dewitt, written commun., 2007). K-Ar age of Caribou stock is 68.2±4.1 Ma on hornblende and 65.5±2.4 Ma on biotite (Marvin and others 1989). K-Ar age on Bryan Mountain stock is 60.6±1.8 Ma on biotite (McDowell, 1971; Marvin and others, 1974)

PeKpa **Porphyries of the alkalic group (Paleocene and Late Cretaceous?)**—Numerous small bodies and northeast-trending dikes primarily in southern parts of Central City and Empire 7.5-minute quadrangles and northern part of Idaho Springs 7.5-minute quadrangle. Includes trachyte porphyry, quartz trachyte porphyry, quartz latite porphyry, quartz syenite porphyry, syenogranite porphyry, and dark- to light-gray monzonite porphyry. In Central City and Idaho Springs area, includes leucocratic trachyte and quartz trachyte porphyries, typically with a purplish tinge and locally containing garnet; commonly called bostonite porphyry and quartz bostonite porphyry, respectively (for example, Harrison and Wells, 1959; Sims and others, 1963; Moench and Drake, 1966). K-Ar whole-rock ages of 65.2±1.4 Ma and 61.6±1.3 Ma are from a bostonite dike in Central City quadrangle (Rice and others, 1982). K-Ar whole-rock ages from syenite and quartz syenite from Central City, Black Hawk, and Idaho Springs quadrangles range from 61.6±1.3 Ma to 60.0 Ma (Simmons and Hedge, 1978; Rice and others, 1982). Rocks of the Empire stock are strongly silica undersaturated; include alkali gabbro, syenodiorite, essexite (feldspathoid-bearing monzodiorite or monzogabbro), syenite, and quartz syenite (Ed Dewitt, written commun., 2007); commonly contain abundant hornblende or pyroxene, and locally contain the feldsphathoids nepheline and (or) sodalite (Braddock, 1969). Rb-Sr whole-rock age of monzonitic Empire stock is 65.0 Ma (no uncertainty given; Simmons and Hedge, 1978); fission-track ages on sphene are 67.8±4.5 Ma (Marvin and others, 1974) and 66.0±6.2 Ma (Cunningham and others, 1994). The Lincoln Mountain stock ranges from quartz syenite to monzogranite. Economic mineralization in Idaho Springs–Central City mineral district is synchronous with or slightly younger than alkalic intrusive activity in area

Pebi **Potassic basalt (shoshonite) intrusive of Ralston Buttes (Paleocene)**—Very dark gray porphyritic rock containing stubby phenocrysts of glassy plagioclase and green augite generally as long as about 5 mm, in a very fine grained groundmass. At one locality, a single plagioclase crystal 3 cm long and an augite crystal 2 cm long were reported (Van Horn, 1976). Contains a few small xenoliths of metamorphic rock and sandstone. Rock weathers light brown and crops out in rounded knobs. Forms a large dike (Ralston dike), about 2,300 m long and 600 m wide, and several irregular plugs, all intruding Pierre Shale (Kp), about 5 km north of Golden. Unit is probably the source for potassic basalt lava flows (₽db) on North and South Table Mountains. Two K-Ar whole-rock ages are 63.5±2.5 Ma (Marvin and others, 1974) and 61.9±2.5 Ma (Hobblitt and Larson, 1975); a Rb-Sr whole-rock age is 64.0 Ma (no uncertainty given; Simmons and Hedge, 1978). Paleomagnetic directions from the Ralston intrusive body are rotated, indicating that unit was emplaced before major movement on the Golden fault (Hoblitt and Larson, 1975)

LARAMIDE SEDIMENTARY AND VOLCANIC ROCKS OF THE DENVER BASIN

[Sedimentary rocks contain Proterozoic, upper Paleozoic, Mesozoic, and (or) volcanic debris shed from uplifting Front Range during Laramide orogeny, which began about 70 Ma and lasted for about 20 m.y.]

₽g **Green Mountain Conglomerate (Paleocene)**—Well-rounded to subrounded cobble and boulder conglomerate containing minor layers and lenses of sandstone, siltstone, and claystone. Grain size increases upward. Andesite clasts form minor component of lower part and decrease in amount upward. Other clasts include gneiss, pegmatite, quartzite, and sandstone. Contains Paleocene pollen and plant remains in lower 135 m. A rhyolite tuff in upper part of unit has $^{40}Ar/^{39}Ar$ age on sanidine of 63.94±0.28 Ma (Obradovich, 2002). Top of unit eroded; total exposed thickness 200 m (mostly considerably thinner)

₽Kd **Denver Formation (Paleocene and Upper Cretaceous)**—Yellowish-brown to grayish-brown fluvial claystone, siltstone, friable sandstone, and conglomerate. Sandstone and finer grained rocks are tuffaceous and commonly weather to montmorillonitic clay with high swelling potential. Clasts composed of about 95 percent andesite and 5 percent granitic and metamorphic rocks. Locally contains fossil leaves, silicified wood, and dinosaur and mammal bones. Unit susceptible to landsliding on steeper slopes. On South Table Mountain near Golden, Cretaceous-Tertiary (K-T) boundary layer (65.4 Ma; Obradovich, 1993) is 71 m below base of lowest basalt flow (see ₽db description). Conformably overlies Arapahoe Formation. Total thickness in Morrison 7.5-minute quadrangle 290 m (Scott, 1972)

₽db **Potassic basalt (shoshonite) lava flows (Paleocene)**—Dark-gray, porphyritic flow rock containing small pheonocrysts of augite, plagioclase, magnetite, and olivine in a fine-grained matrix. Called mafic latite by Van Horn (1976), although only upper flows are latitic; basal flow is a trachytitic basalt. Formerly mapped as three flows on North Table Mountain and two flows on South Table Mountain (Van Horn, 1976); four total flows now recognized (Drewes, 2004). Clinkery bases and vesicular tops are visible, except on upper flow where top is eroded. Locally forms prominent cliffs. Cavities at some localities contain a variety of zeolite minerals (Ellemeier, 1947). Flows most likely erupted from Ralston Buttes area, about 5 km north of Golden. Interlayered with and considered here as members of Denver Formation. $^{40}Ar/^{39}Ar$ age of upper flow is 63.9±1.2 Ma (Obradovich, 2002). Flows are as thick as 30 m where they filled channels

Ka **Arapahoe Formation (Upper Cretaceous)**—Coarse- and fine-grained sandstone, siltstone, claystone, and thin pebble beds in upper part; white, yellowish-gray, and yellowish-orange, coarse-grained sandstone and poorly sorted pebble-and-cobble conglomerate in lower part. Clasts include sandstone (as long as 0.5 m), shale (some more than 1 m long), igneous and metamorphic rocks, and minor chert and petrified wood; most clasts less than 3 cm long. Proportion of sedimentary clasts to Precambrian crystalline clasts about 60:40 near base of unit, but decreases stratigraphically upward (Scott, 1972), reflecting progressive stripping of Phanerozoic cover from Precambrian basement. Contains ironstone and dinosaur bones in localized concentrations. Unconformably overlies Laramie Formation (Kl). High potential for landslides in clayey beds of unit (Shroba and Carrara, 1996). Total thickness in Morrison 7.5-minute quadrangle 120 m (Scott, 1972)

₽Kda **Denver Formation (Paleocene and Upper Cretaceous) and Arapahoe Formation (Upper Cretaceous), undivided**

PRE-LARAMIDE SEDIMENTARY ROCKS OF THE DENVER BASIN, BLUE RIVER VALLEY, AND FRASER BASIN

Kl **Laramie Formation (Upper Cretaceous)**—Upper 130–200 m is light-gray micaceous siltstone, light-olive silty claystone, grayish-brown lignitic claystone, minor white, friable, resistant sandstone, and, near top of unit, thin layers of sedimentary-clast conglomerate; lower 60 m of upper part contains subbituminous coal beds as thick as 2.5 m, mined extensively in Marshall district. Commonly stained yellowish orange and contains orange, sandy ironstone concretions. Lower 35 m of Laramie Formation consists of sandstone and sandy shale, with minor claystone and coal. Gray and white claystone beds are mined locally for ceramic clay and for brick making. Contains abundant fossil leaves and wood fragments. Deposited in near-shore swamps and meandering stream channels. High potential for landslides in claystones of unit (Shroba and Carrara, 1996). Mapped only in the Denver Basin. Conformable with underlying Fox Hills Sandstone (Kf). Thickness in Morrison 7.5-minute quadrangle 165 m (Scott, 1972); in Marshall area (in Louisville 7.5-minute quadrangle), thickness as much as about 240 m (Spencer, 1961)

Kf **Fox Hills Sandstone (Upper Cretaceous)**—Upper 32 m is olive-gray to dark-yellowish-brown, silty shale and interbedded friable, micaceous sandstone locally containing flattened limestone concretions. Lower 23 m is yellowish-orange, massive to thin-bedded, locally cross bedded, fine-grained, resistant sandstone and interbedded dark-olive-gray shale and claystone. Reddish-brown, calcareous concretions near top of lower sequence. Fossil pelecypods support interpretation of near-shore marine deposition during regression of Cretaceous inland sea. Mapped only in the Denver Basin. Conformably overlies Pierre Shale (Kp). Total thickness in Morrison 7.5-minute quadrangle 55 m (Scott, 1972); due to intertonguing relationships with underlying Pierre Shale, thickness in Louisville 7.5-minute quadrangle highly variable, ranging from 20 to 65 m (Spencer, 1961)

Klf **Laramie Formation (Upper Cretaceous) and Fox Hills Sandstone (Upper Cretaceous), undivided**

Kp **Pierre Shale (Upper Cretaceous)**—Predominantly olive-gray marine shale with subordinate fine-grained, brown sandstone beds. Locally contains ironstone and limestone concretions. Lower shale member, below Hygiene Sandstone Member (Kph), is olive-gray, clayey shale with common, thin, bentonitic layers. Shale and bentonite beds susceptible to swelling. Beds above Hygiene Sandstone Member similar to lower shale member. Conformable above Niobrara Formation (Kn). Total thickness in Indian Hills 7.5-minute quadrangle about 1,750 m (Bryant and others, 1973) and in Morrison quadrangle about 1,885 m (Scott, 1972); near Louisville, thickness in one oil well test hole is 2,395 m (Malde, 1955). Thickness in two oil well test holes in Fort Logan 7.5-minute quadrangle is 2,115 and 2,205 m (Lindvall, 1978).

In Blue River valley in southwest corner of quadrangle, Pierre Shale may have been as thick as about 2,600 m (Izett and others, 1971), although at least the upper 1,000 m has been removed by erosion. Thickness greater than 1,400 m in and adjacent to Fraser basin (Taylor, 1975)

Kpf **Hornfels**—Dense, black hornfels and metasandstone in window of Williams Range thrust near Keystone; Pierre Shale metamorphosed by nearby Eocene Montezuma stock. Bedding is preserved at most locations

Kph **Hygiene Sandstone Member**—Yellowish-gray or olive-brown, friable, massive sandstone that grades upward into fine-grained, thinly bedded sandstone. Crops out in Denver Basin about 500 m above base of Pierre Shale. Unit about 30 m thick in Louisville 7.5-minute quadrangle; about 18 m thick in Keystone 7.5-minute quadrangle where it is exposed (but not shown separately on map) in a resistant cliff along western border of map (Widmann and others, 2003)

Kn **Niobrara Formation (Upper Cretaceous)**—Upper part is Smoky Hill Shale Member, which is a pale- to yellowish-brown, soft, thin-bedded calcareous shale with interbedded thin limestone layers; weathers pale gray to white and platy; contains many bentonite beds; thickness 125 m. Underlying Fort Hays Limestone Member is a gray, dense limestone in beds as thick as 2 m; contains abundant large inoceramid bivalve (oyster) fossils in Denver Basin, which are less abundant in Blue River valley; thickness about 10 m in Denver Basin. The Fort Hays is slightly less thick and less distinct from the Smoky Hill in Blue River valley, where combined thickness of Niobrara is about 135 m (Kellogg and others, 2002). In Fraser basin, combined thickness about 125 m, but thinned considerably by folding (Taylor, 1975)

Kb **Benton Group (Upper and Lower Cretaceous)**—Consists of three formations in Denver Basin: in descending order, Carlile Shale (Upper Cretaceous), Greenhorn Limestone (Upper Cretaceous), and Graneros Shale (Upper and Lower Cretaceous). Carlile Shale consists of upper grayish-brown, hard calcarenite containing abundant shell fragments (Juana Lopez Member), middle gray silty sandstone (Blue Hill Shale Member), and lower yellowish-gray, soft calcareous shale (Fairport Chalky Shale Member). The Carlile conformably overlies the Greenhorn Limestone, which consists of an upper gray, dense limestone and hard calcareous shale (Bridge Creek Limestone Member), middle gray, shaly calcareous sandstone (Hartland Shale Member), and lower grayish-brown, thin beds of hard calcareous sandstone and shale with a marker bentonite bed as base (Lincoln Limestone Member). Graneros Shale consists of dark-gray, hard, clayey shale and siltstone. In Blue River valley, the Juana Lopez Member of the Carlile forms a prominent marker above about 3 m of brown, soft sandstone sequence [Codell Sandstone Member of Carlile Shale of Berman and others (1980)] that, in turn, unconformably overlies sequence of hard black shale of the Graneros; lower 25 m of this sequence is a wavy black shale that contains abundant fish scales, equivalent to the Lower Cretaceous Mowry Shale. Benton Group is about 136 m thick in the Eldorado Springs 7.5-minute quadrangle (Wells, 1967) and thickens to the south, where it is about 182 m thick just south of Chatfield Lake (Scott, 1963b). In Blue River valley, the Benton is only about 80–100 m thick (Kellogg and others, 2002; Widmann and others, 2003). In Fraser basin, thickness is about 140 m, but thinned considerably by folding (Taylor, 1975)

Kd **Dakota Group (Lower Cretaceous)**—Consists of South Platte Formation and underlying Lytle Formation. South Platte Formation contains two or three yellowish-gray, well-sorted, cross-stratified, porous, fine- to medium-grained quartz sandstone sequences separated by dark-gray, silty, hard, locally carbonaceous shale, interbedded with thin quartz sandstone beds and gray to white refractory clay or porcellanite layers [see Bryant and others (1973) for more detailed description of members of South Platte Formation]. The South Platte is about 67 m thick. Lytle Formation consists of yellowish-gray, medium- to fine-grained sandstone and conglomerate; locally contains reddish iron stain. Well-rounded clasts in conglomerate composed of quartz, quartzite, chert, and some petrified wood; conglomerate generally near base of unit. The Lytle is about 24 m thick. In Fraser basin, combined thickness about 75 m (Taylor, 1975)

Jm **Morrison Formation (Upper Jurassic)**—Red siltstone and thin, brown sandstone beds in upper part; green siltstone and claystone, with some interbedded sandstone and limestone beds, in middle part; lower part contains several brown lenticular sandstone beds and red jasper. Dinosaur bones locally contained in middle green siltstone beds and in lower sandstone. Thickness in Morrison 7.5-minute quadrangle about 91 m (Scott, 1972) and 105 m in Eldorado Springs 7.5-minute quadrangle (Wells, 1967). Not exposed in Blue River valley in map area, but thickness just west of map area near Dillon, Colo., about 70 m (Wahlstrom and Hornbeck, 1962). In Fraser basin, thickness about 45–75 m, but thickened or thinned considerably by folding (Taylor, 1975)

Jmr **Morrison Formation (Upper Jurassic) and Ralston Creek Formation (Upper and Middle Jurassic), undivided**—Morrison Formation described in previous paragraph. Ralston Creek Formation is purplish-gray sandstone and siltstone, underlain by grayish-yellow silty sandstone containing clayey limestone and shale beds with red jasper. Thin layers of purple and white sandstone near base. Contains gypsiferous shale and white gypsum as thick as 8 m south of Turkey Creek (Bryant and others, 1973). Crops out only in Denver Basin. Thickness of Ralston Creek about 27 m in Morrison 7.5-minute quadrangle (Scott, 1972), but thins to the north, where it is about 10 m thick in Eldorado

Springs quadrangle (Wells, 1967). Not mapped separately. Not recognized in either Blue River valley or Fraser basin

₸Pl **Lykins Formation (Triassic? and Permian)**—Upper part is Strain Shale Member, which consists of about 90 m of maroon, stratified, micaceous, fine-grained, silty sandstone and siltstone with some green siltstone layers. About 2 m of light-brown, fine-grained sandstone locally occurs at top of map unit. Middle part is Forelle Limestone Member, which consists of 5 m of pink, wavy-laminated, sandy, marine, algal limestone. Lower part is Bergen Shale Member and underlying Harriman Shale Member, which together are about 40 m thick and consist of maroon and green siltstone separated by a thin (1 m thick), laminated, red-weathering, gray and yellow crystalline limestone (Falcon Limestone Member). Mapped only in Denver Basin

Pl **Lyons Sandstone (Lower Permian)**—In Morrison 7.5-minute quadrangle, composed of yellowish-gray conglomerate with Proterozoic detritus as large as 5 cm. Grades downward into pale-tan and yellowish-orange (iron stained from weathering), fine-grained, calcite-cemented, cross-stratified eolian sandstone that also contains conglomerate near base (Scott, 1972). Thickness about 58 m. Conglomerate beds, not reported in Indian Hills 7.5-minute quadrangle (Bryant and others, 1973), disappear to the north where formation thickens; in Eldorado Springs 7.5-minute quadrangle, formation is almost entirely pink to pinkish-gray, cross-laminated, silica-cemented, fine- to coarse-grained eolian sandstone as thick as 76 m (Wells, 1967). Mapped only in Denver Basin

PPf **Fountain Formation (Lower Permian and Pennsylvanian)**—Maroon and red, arkosic, thick-bedded, coarse-grained to pebbly, cross-bedded fluvial sandstone and conglomerate containing thin layers of dark-maroon, hard (siliceous), micaceous siltstone and silty, fine-grained sandstone. Coarser beds commonly fill shallow channels. Sandstone locally bleached light tan to white. Clasts are well rounded to subrounded, as long as 25 cm, and composed mostly of Proterozoic rocks. Scott (1972) reported rare lower Paleozoic clasts in lower part of formation in Morrison 7.5-minute quadrangle. Thickness in Indian Hills quadrangle about 600 m; in Eldorado Springs quadrangle a measured section is 305 m thick (Wells, 1967). Mapped only in Denver Basin

CAMBRIAN AND PROTEROZOIC INTRUSIVE ROCKS

[**Note on unit-symbol nomenclature**. Proterozoic intrusive rocks in the Denver West quadrangle were emplaced during two principal time periods, recognized and formalized by Tweto (1987) as the Paleoproterozoic Routt Plutonic Suite (roughly 1,700±25 Ma) and the Mesoproterozoic Berthoud Plutonic Suite (roughly 1,400±25 Ma). Formerly, some rocks of similar composition, texture, and age in separate plutons in the Front Range have been given the same rock name. For example, Silver Plume Granite has been applied to rocks of similar age and composition within several different batholitis (for example, Braddock and Cole, 1979). However, because these batholiths represent distinctly different intrusive events, we employ a unit-symbol nomenclature that differentiates the rocks of these plutons, as follows:

Age: X=Paleoproterozoic (2,500–1,600 Ma), Y=Mesoproterozoic (1,600–900 Ma).

Composition: g=granite, gd=granodiorite, d=diorite, qd=quartz diorite, and gb=gabbro; in addition, where appropriate, textural and (or) mineralogic variants that are mapped separately within an intrusive complex are symbolized with an additional lower-case letter (for example, p=porphyritic phase, h=hornblende bearing, and x=intrusion breccia).

Pluton: P=Pikes Peak batholith, SP=Silver Plume batholith, R=Rosalie Peak pluton, M=Mount Evans batholith, T=Twin Spruce monzogranite of Boulder Creek batholith, and B=granodiorite of Boulder Creek batholith.

Thus, the symbol for granodiorite of the Boulder Creek batholith is XgdB; the symbol for the fine-grained porphyritic phase of the Pikes Peak Granite is YgPp.

Classification of intrusive rocks follows that of Streckeisen (1976), in which “granite” includes syenogranite and monzogranite]

€Zk **Kimberlite (Cambrian or Late Proterozoic)**—Black to dark-green rock consisting of olivine, ilmenite, garnet, diopside, and biotite in a groundmass of fine-grained olivine, diopside, magnetite, ilmenite (with leucoxene rims), and pyrite (Kellogg, 1973). Olivine is rounded, variably serpentenized, and as long as 1 cm; the larger ilmenite grains are unaltered and as long as 1 cm. The garnets commonly have dark kelyphite rims.

Rock crops out in a roughly circular diatreme about 30 m across on northern flank of Green Mountain near Boulder. On the basis of paleomagnetic data, Kellogg (1973) suggested the kimberlite is Proterozoic, which is supported by a recent Sm-Nd isochron date of 572±49 Ma (Lester and others, 2001), although the uncertainty permits an earliest Cambrian age

YgP **Pikes Peak Granite (Middle Proterozoic)**—Pinkish-orange to light-gray, medium- to coarse-grained biotite- and biotite-hornblende granite with feldspar crystals as long as 2.5 cm. Forms large, slabby outcrops and weathers to orange-brown grussy soil (contains abundant feldspar and mica fragments). U-Pb zircon age about 1,080 Ma (Unruh and others, 1995; Smith and others, 1999)

YgPp **Fine-grained porphyritic phase**—Pink, fine- to medium-grained, massive porphyritic biotite granite with phenocrysts of spheroidal gray quartz, subhedral microcline, and oligoclase

Ygi **Gabbro dike ("Iron dike") (Middle Proterozoic)**—Dark-brown, medium- to fine-grained, iron-rich ferrogabbro dike with chilled margins; contains augite and labradorite, and lesser amounts of opaque minerals, biotite, secondary chlorite, and nontronite probably after olivine (Wells, 1967). Forms 10-m-wide, north-northwest-trending dike near Magnolia, which marks southern end of a narrow dike swarm that has been traced north to the Wyoming border (Braddock and Cole, 1990). Weathers to dark-brownish-orange, fractured outcrops. Described in detail by Wahlstrom (1956), who considered it as Cretaceous or Tertiary in age. Rb-Sr whole-rock age of 1,316±50 Ma (Braddock and Peterman, 1989)

Ypd **Pyroxene diorite dike (Middle? Proterozoic)**—In Loveland Pass and Byers Peak 7.5-minute quadrangles, consists of north-striking, dark-gray, fine-grained, unmetamorphosed pyroxene diorite dikes containing phenocrysts of augite and plagioclase (Eppinger and others, 1984). Undated, but are older than mineralization associated with rhyolite porphyry (₽rp) and younger than Silver Plume Granite (YgSP); assigned Tertiary age by Lovering (1935), but due to similarity to Middle Proterozoic dikes in northern Front Range (for example, Kellogg, 1973), we interpret age as Middle Proterozoic

YXp **Pegmatite and aplite (Middle and Early Proterozoic)**—Pegmatite is coarse-grained to very coarse grained, white to light-pink, inequigranular quartz-feldspar-mica rock that forms irregular-shaped, commonly zoned dikes and intrusive bodies cutting Silver Plume Granite (YgSP) and all older rocks; few pegmatites cut Pikes Peak Granite (YgP and YgPp). Microcline may be longer than 1 m in some pegmatites; mica is mostly biotite, but locally includes or is entirely muscovite. Accessory minerals include tourmaline, garnet, and opaque minerals. Unit consists predominantly of pegmatite, which commonly grades into and is intimately mixed with aplite, which also forms separate dikes and bodies. Aplite is similar in composition to pegmatite but is a pinkish-tan, fine- to medium-grained, leucocratic, equigranular rock. Pegmatite and aplite may be late-stage intrusions associated with rocks of either the Routt Plutonic Suite (about 1,700 Ma) or the Berthoud Plutonic Suite (about 1,400 Ma) of Tweto (1987). Muscovite±tourmaline-bearing varieties probably related to intrusions of the Berthoud Plutonic Suite

YXgd **Granodiorite and monzogranite of unknown age (Middle or Early Proterozoic)**—Gray, medium- to coarse-grained, equigranular to porphyritic, massive to weakly foliated quartz-plagioclase-microcline-biotite±hornblende tonalite, granodiorite, and monzogranite. May include a younger, medium-grained monzogranite phase and an older, medium- to coarse-grained granodiorite phase. Most rocks of unit similar to Boulder Creek Granodiorite (XgdB), but here mapped separately due to uncertainty in age and whether derived from same magma and intrusive event as Boulder Creek Granodiorite (Tweto, 1987). Dated Middle Proterozoic rocks similar to Early Proterozoic Boulder Creek Granodiorite, such as granodiorite of the Mount Evans batholith (YgdM) and granodiorite and monzogranite unit (Ygd), attest to the difficulty in assigning a Middle or Early Proterozoic age to some granodiorites and monzogranites

YgSP **Silver Plume Granite (Middle Proterozoic)**—Gray to pinkish-gray, medium- to coarse-grained, equigranular, seriate, or porphyritic, massive to flow-foliated, biotite-muscovite peraluminous syenogranite and monzogranite. Porphyritic varieties contain tabular microcline phenocrysts. Locally includes muscovite-bearing pegmatite, alaskite, and aplite. Muscovite in equivalent rocks north of quadrangle is almost entirely subsolidus, indicating that it formed during retrograde crystallization (J.C. Cole, written commun., 2005). Rb-Sr whole-rock age is 1,409±40 Ma (Hedge, 1969); preliminary U-Pb zircon ages are 1,424±6 Ma (W.R. Premo, unpub. data, 2005) and 1,422 Ma (no error given; Graubard and Mattison, 1990)

Yg **Peraluminous monzogranite (Middle Proterozoic)**—Rocks are very similar to those of Silver Plume Granite (YgSP). Mapped by many people as Silver Plume Granite; however, uncertainty as to whether they formed from same magma or intrusive episode (Tweto, 1987) is reason unit is mapped separately. Undated

Ygd **Granodiorite and monzogranite (Middle Proterozoic)**—Gray to light-pinkish-gray, medium- to coarse-grained, equigranular to porphyritic biotite-plagioclase-microcline-quartz granitoid rocks. Unit consists of two distinct phases: medium-grained rock of approximate monzogranite composition intrudes coarse-grained rock of approximate granodiorite composition. Forms an irregular-shaped pluton near Empire and a larger pluton along Continental Divide near north margin of quadrangle. Formerly considered part of the Routt Plutonic Suite, but preliminary U-Pb zircon ages between 1,435 and 1,425 Ma on two granodiorite samples and one monzogranite sample demonstrate these plutons are part of the Berthoud Plutonic Suite (W.R. Premo, unpub. data, 2006)

Ygb **Younger gabbro (Middle Proterozoic)**—Dark-gray, dark-greenish-gray, and black, medium- to coarse-grained, massive, generally equigranular intrusive rocks ranging from melagabbro to quartz diorite; most samples are either gabbro or pyroxene diorite (Taylor and Sims, 1962). Contains calcic plagioclase, orthopyroxene, clinopyroxene, magnetite, ilmenite, and secondary hornblende and biotite. Forms large body (Elk Creek pluton of Taylor and Sims, 1962) and several nearby smaller bodies in northern Central City 7.5-minute quadrangle (Sims and Gable, 1967). Prelininary U-Pb zircon age is 1,436±6 Ma (W.R. Premo, unpub. data, 2007)

Yd **Younger diorite and hornblendite (Middle Proterozoic?)**—Dark-gray to mottled dark-gray and white, medium- to coarse-grained plagioclase-hornblende diorite with minor quartz and biotite; includes local hornblendite. Forms three small equant plutons in northern part of Georgetown 7.5-minute quadrangle (Widmann and Miersemann, 2001). Undated, but Middle Proterozoic age suspected by Widmann and Miersemann (2001) because Spurr and others (1908) suggested unit derived by differentiation from magma that generated granodiorite of Mount Evans

YgR **Granite of Rosalie Peak (Middle Proterozoic)**—Gray to light-pinkish-gray, coarse-grained, equigranular to porphyritic biotite syenogranite and monzogranite (Bryant and Hedge, 1978). Locally contains Carlsbad-twinned microcline phenocrysts as long as 4 cm and has weak foliation defined by aligned biotite. Two small plutons intrude the Mount Evans batholith near Rosalie Peak. May be relatively felsic phase of granodiorite of Mount Evans batholith (unit YgdM). U-Pb zircon date is 1,448±9 Ma (Aleinikoff and others, 1993a). Includes the granite of Sheep Mountain in southeastern Keystone quadrangle (Widmann and others, 2003), which Lovering (1935) included with the granite of Rosalie Peak

YgdM **Granodiorite of Mount Evans batholith (Middle Proterozoic)**—Gray, massive to strongly foliated, coarse-grained, mostly porphyritic biotite-hornblende granodiorite, which ranges in composition from monzogranite to tonalite (Aleinikoff and others, 1993a). Locally contains as much as 5 percent of an aplite-pegmatite phase consisting of dikes and irregular-shaped bodies of massive to weakly foliated aplite and magnetite-bearing pegmatite. Formerly believed to be part of the Early Proterozoic Routt Plutonic Suite of Tweto (1987), due to petrographic and textural similarities to rocks of that suite and limited Rb-Sr data (for example, Bryant and Hedge, 1978). However, U-Pb zircon date is 1,442±2 Ma (Aleinikoff and others, 1993a), confirming emplacement with Middle Proterozoic Berthoud Plutonic Suite of Tweto (1987)

YXgT **Twin Spruce Monzogranite (Middle? and Early Proterozoic)**—Gray, fine- to medium-grained, equigranular, massive to weakly foliated biotite-muscovite monzogranite and rare granodiorite. Twin Spruce Monzogranite intrudes rocks of Boulder Creek Granodiorite (XgdB) in a complex pattern. Weathers tan in rounded outcrops. Preliminary U-Pb zircon data suggest age about 1,704±6 Ma (W.R. Premo and K.S. Kellogg, unpub. data, 2007), supporting the observation (Gable, 1980) that the unit is younger than Boulder Creek Granodiorite. Two samples of rock petrographically similar to Twin Spruce Monzogranite from within the Boulder Creek batholith have U-Pb zircon dates of 1,443±19 Ma and 1,412±25 Ma (W.R. Premo, unpub. data, 2005), indicating a local resurgence within the batholith of magmatism of the Berthoud Plutonic Suite. Twin Spruce Monzogranite also referred to as Twin Spruce Quartz Monzonite (for example, Gable, 1980); the lithic term "monzogranite" follows Streckeisen (1976)

Xgr **Monzogranite of Elephant Butte (Early Proterozoic)**—Fine- to medium-grained, massive to moderately foliated biotite monzogranite and minor granodiorite. Forms stock-size outcrop on and near Elephant Butte at intersection of Squaw Pass, Evergreen, Meridian Hill, and Conifer 7.5-minute quadrangles, and elongate body in Indian Hills 7.5-minute quadrangle (Bryant and others, 1973). Moderately foliated biotite monzogranite from southeast corner of Squaw Pass 7.5-minute quadrangle has a U-Pb zircon date of 1,684±9 Ma; sample from Indian Hills quadrangle has a U-Pb date of 1,678±6 Ma (W.R. Premo, unpub. data., 2006)

Xgh **Mafic granodiorite, quartz diorite, hornblende diorite, and hornblendite (Early Proterozoic)**—Quartz diorite is gray, black, or mottled black-and-white, medium- to coarse-grained rock consisting mostly of plagioclase, hornblende, biotite, ±microcline, and quartz. Hornblendite is a black to dark-green rock composed principally of hornblende with minor plagioclase and quartz. Unit includes mafic phases of granodioritic rocks. Includes a quartz diorite pluton near St Marys Lake in Empire quadrangle that has a gradational contact with surrounding granodiorite (YXgd) and may be older than the granodiorite (Braddock, 1969). Includes hornblendite near Nederland (Gable, 2000). Two small bodies of mafic quartz diorite or hornblendite are mapped in southeast corner of Empire quadrangle (Braddock, 1969). Preliminary U-Pb zircon date from a biotite-hornblende diorite from Clear Creek is 1,702±8 Ma and a quartz diorite from Turkey Creek drainage (Indian Hills quadrangle) is 1,708±4 Ma (W.R. Premo, unpub. data, 2005), which indicates a 1,706±8 Ma quartz diorite intrusive event (Premo and others, 2007; W.R. Premo, unpub. data, 2007)

Xgb **Gabbro (Early Proterozoic)**—Gray, dark-gray, and dark-greenish-gray, medium- to coarse-grained, massive, generally equigranular intrusive rocks ranging from melagabbro to pyroxene diorite. Composed mostly of calcic plagioclase (bytonite), clinopyroxene, bronzite, magnetite, ilmenite, and variable amounts of secondary amphibole and mica (Taylor and Sims, 1962). Hornblende surrounds most pyroxene grains. Forms a large, irregular-shaped body, the Upson Creek pluton of Taylor and Sims (1962), in southwest corner of Bottle Pass 7.5-minute quadrangle (Taylor, 1975). Intrudes granodiorite (YXgd) that is probably similar in age to Boulder Creek Granodiorite (XgdB). Preliminary U-Pb zircon date is 1,706±9 Ma (W.R. Premo, unpub. data, 2007)

XgdB **Boulder Creek Granodiorite (Early Proterozoic)**—Gray, coarse-grained, equigranular to porphyritic, massive to weakly foliated biotite±hornblende±muscovite monzogranite, granodiorite, and tonalite. Forms large intrusive body (Boulder Creek batholith) west of Boulder (Gable, 1980). Typically weathers into grayish-tan rounded outcrops. Mean U-Pb zircon date from numerous analyses is 1,716±3 Ma (W.R. Premo and K.S. Kellogg, unpub. data, 2007), which supports earlier U-Pb zircon dates of 1,725 Ma (Stern and others, 1971) and 1,721±15 Ma (Premo and Fanning, 2000)

Xgg **Granitic gneiss (Early Proterozoic)**—Light- to medium-gray, fine- to medium-grained, weakly to strongly foliated monzogranite, granodiorite, and trondhjemite. Composed mostly of quartz, plagioclase, and microcline, with lesser amounts of biotite, ±hornblende, and ±muscovite. Locally contains metasedimentary and amphibolitic inclusions indicating igneous origin, although protolith of some granitic gneiss is uncertain (Braddock, 1969). Age inferred by Sheridan and others (1972) to be same as Boulder Creek Granodiorite (XgdB) and may, in part, be equivalent to foliated facies of Boulder Creek Granodiorite. However, most mapped granitic gneiss probably older than Boulder

Creek Granodiorite. Two preliminary U-Pb zircon ages from foliated granodiorite on Mount Morrison in the Morrison 7.5-minute quadrangle are 1,772±10 Ma and 1,771±11 Ma, and a foliated monzogranite from near Deer Creek in the southern Harris Park 7.5-minute quadrangle is 1,766±9 Ma (W.R. Premo, unpub. data, 2007)

PROTEROZOIC CATACLASTIC AND DUCTILEY DEFORMED ROCKS

YXcr **Cataclastically and ductilely sheared rocks of the Idaho Springs–Ralston shear zone (Middle and Early Proterozoic)**—Gray, pinkish-gray, and pink, moderately to strongly foliated, fine- to medium-grained, quartz-feldspar cataclastic gneiss. Contains small white to pink feldspar porphyroclasts as long as 2.5 mm, quartz, and lesser amounts of biotite, muscovite, and, locally, microantiperthite (Sheridan and others, 1967). In some places, cataclastic gneiss is interlayered with biotite gneiss and schist, which are included with map unit. Includes small (generally <10 m wide), discrete zones of mylonite and ultramylonite. Mapped along southern part of Idaho Springs–Ralston shear zone, in northern part of Ralston Buttes 7.5-minute quadrangle, where rocks are sheared, granulated, and recrystallized and parent rock cannot be identified (Sheridan and others, 1967). Includes rocks mapped as augen gneiss, containing small, lensoid, feldspar porphyroclasts, in southern part of Eldorado Springs 7.5-minute quadrangle (Wells, 1967). Monazite dating shows that age of shearing occurred in two discrete stages: early, wide, high-temperature strain and amphibolite-grade metamorphism about 1.71–1.63 Ma, producing closely spaced, upright compositional layering, and localized mylonitic and ultramylonitic deformation about 1.45-1.38 Ma (Shaw and others, 2001)

EARLY PROTEROZOIC METASEDIMENTARY AND META-IGNEOUS ROCKS

[**Note on migmatite**—Migmatite is mostly biotite gneiss (Xb) containing numerous layers of light-gray to white granitic rock (leucosomes), which are typically 0.1–10 cm thick, although locally may be much thicker. Some other units, such as quartz-feldspar gneiss (Xf), may locally be migmatitic. In most cases, leucosomes form <50 percent of rock, have sharp contacts with the host rock, and are composed of equigranular, massive to weakly foliated, microcline-plagioclase-quartz-biotite rock ("granite"); leucosomes may also contain minor or accessory muscovite, opaque minerals, sphene, apatite, garnet, and zircon. Layers show much pinch and swell and in some places are strongly folded. Formation of leucosome may be due to either injection from distant source, or in-situ partial melting (anatexis) (Olsen, 1982; Johannes and Gupta, 1982); in the latter case, host rock adjacent to the leucosomes commonly has dark, biotite-rich selvages (melanosomes). Distribution of mapped migmatite is highly subjective, as criteria for defining mapped migmatite varies from place to place. For example, many felsic rocks in Squaw Pass (Sheridan and Marsh, 1976), Central City (Sims, 1964; Sims and Gable, 1967), Black Hawk (Taylor, 1975), Nederland (Gable, 1969), and Tungsten (Gable, 1972) 7.5-minute quadrangles are migmatitic; in these quadrangles only the rocks that are host to leucosomes were mapped. Most areas underlain by biotite gneiss are variably migmatitic, but for the reasons cited above, migmatitic areas are not indicated on map. Two preliminary U-Pb zircon dates from melt phase in migmatitic gneiss from Clear Creek are 1,698±3 Ma and 1,693±35 Ma; one date from melt phase from just south of quadrangle (near Pine) is 1,692±6 Ma (W.R. Premo, unpub. data, 2005). These data suggest peak metamorphism and partial melting in region at 1,693±5 Ma]

Xq **Quartzite (Early Proterozoic?)**—White, gray, and purplish-gray, medium- to coarse-grained quartzite and quartz-rich gneiss and schist. Locally conglomeratic with clasts of coarser grained, lighter colored quartzite that are commonly tectonically stretched. Generally contains as much as a few percent muscovite and traces of garnet, magnetite-ilmenite, and epidote. Unit includes muscovite-quartz gneiss and schist layers and some calc-silicate gneiss lenses. Forms a large, synformal body ("Coal Creek quartzite") in southern part of Eldorado Springs 7.5-minute quadrangle (Wells, 1967) and northern part of Ralston Buttes quadrangle (Sheridan and others, 1967); most contacts with Twin Spruce Monzogranite (YXgT) are sheared, and relative age of quartzite and intrusive rocks is uncertain. Gable (1980) and Wells and others (1964) described intrusive contacts between rocks of the Boulder Creek batholith and quartzite. However, preliminary detrital zircon evidence suggests quartzite is younger than the batholith (J.N.

Aleinikoff, unpub. data, 2007), a suggestion supported by structural and stratigraphic evidence (McCoy and others, 2005). If this interpretation is correct, the depositional age of quartzite is less than 1,704±6 Ma

Xqs **Muscovite-quartz schist (Early Proterozoic?)**—Mostly gray, well-foliated, fine- to medium-grained schist composed of quartz, muscovite, biotite, and local occurrences of andalusite, cordierite, garnet, plagioclase, and staurolite (Wells, 1967). At most places, rock is conspicuously lineated and foliation planes are crinkled. Interlayered with quartzite in Eldorado Springs 7.5-minute quadrangle (Wells, 1967) and Ralston Buttes quadrangle (Sheridan and others, 1967)

Xbp **Porphyroblastic quartz-biotite-muscovite schist of White Ranch (Early Proterozoic)**—Silvery gray schist layers composed mostly of fine- to medium-grained, foliated, locally porphyroblastic schist composed principally of quartz, biotite, and muscovite, with small amounts of sillimanite and staurolite (Wells, 1967). Porphyroblasts include andalusite, cordierite, and garnet; some andalusite crystals in central Ralston Buttes 7.5-minute quadrangle are as long as 30 cm (Sheridan and others, 1967). Where rock is relatively unstrained, original sedimentary structures (graded bedding and cross bedding) are visible. Locally contains lenses of meta-conglomerate and calc-silicate rock (Sheridan and others, 1967). U-Pb zircon ages from clasts in metaconglomerate are ≈1,750 Ma, which is maximum depositional age of sediments in basin that includes rocks of this unit

Xlg **Mixed layered gneiss (Early Proterozoic)**—Interlayered gneiss of varied types, including, but not limited to, quartz-feldspar gneiss (Xf), biotite gneiss (Xb), and hornblende-plagioclase gneiss and amphibolite (Xh). Migmatitic in places. Mapped where individual units too small to map

Xb **Biotite gneiss (Early Proterozoic)**—Gray, medium-grained, equigranular, well-foliated gneiss typically containing approximately 25–50 percent quartz, 20–30 percent plagioclase (approximately An_{30}), 0–30 percent microcline, 10–15 percent biotite, 0–15 percent muscovite, 0–10 percent sillimanite, 0–5 percent hornblende, 1–2 percent opaque minerals, and a trace zircon. Most outcrops contain 5–20 percent granitic layers (leucosomes). Sillimanite, where abundant, occurs in fibrous, elongate, light-colored aggregates or clots as wide as about 1 cm. Migmatitic biotite gneiss in Clear Creek gave preliminary U-Pb zircon date on nonmelt phase of 1,773±18 Ma; near Pine, just south of map area, similar rock gave U-Pb zircon date of 1,780±9 Ma (W.R. Premo, unpub. data, 2005)

Xbhc **Biotite gneiss, hornblende gneiss, and calc-silicate gneiss (Early Proterozoic)**—Gray to dark-gray, foliated, interlayered biotite gneiss (Xb), hornblende-plagioclase gneiss and amphibolite (Xh), and calc-silicate gneiss (Xc). Mapped where individual units too small to show separately

Xbg **Biotite gneiss and schist with garnet (Early Proterozoic)**—Gray, fine- to medium-grained, well-foliated gneiss composed chiefly of quartz, plagioclase, and biotite; garnet crystals in some layers as large as 1 cm in diameter. Locally schistose and contains muscovite. Mapped in western Morrison 7.5-minute quadrangle (Scott, 1972) and northern Indian Hills quadrangle (Bryant and others, 1973)

Xc **Calc-silicate gneiss (Early Proterozoic)**—Dark-gray, light-green, yellowish-green, white, pink, or black, fine- to coarse-grained, compositionally layered rock commonly associated with hornblende-plagioclase gneiss and amphibolite (Xh). Wide variation in colors due to relative amounts of constituent minerals, which include plagioclase, hornblende, clinopyroxene, epidote, quartz, microcline, garnet, scapolite, vesuvianite, calcite, dolomite, cummingtonite, tremolite, sphene, and magnetite-ilmenite (Sheridan and Marsh, 1976). May include layers of impure marble. Commonly occurs in lenses and pods. Derived from metamorphosed carbonate-rich sedimentary rocks. Mapped mostly in Ralston Buttes, Evergreen, and Byers Peak 7.5-minute quadrangles (Sheridan and others, 1967, 1972; Eppinger and others, 1984)

Xbc **Cordierite-biotite gneiss (Early Proterozoic)**—Light- to dark-gray, fine- to medium-grained, cordierite-bearing biotite gneiss. Composed principally of quartz, plagioclase, biotite (phlogopitic in lighter varieties), as much as 20 percent cordierite, and variable amounts of sillimanite. Cordierite inconspicuous in outcrop, so distinguished from biotite gneiss (Xb) mostly by thin-section study. Typically has conspicuous, alternating, light- and dark-colored layers 2 mm to 2.5 cm thick. Mapped in Nederland and Tungsten 7.5-minute quadrangles (Gable, 1969, 1972) and along a west-northwest trend through the Morrison, Evergreen, and Squaw Pass quadrangles (Sheridan and others, 1972; Sheridan and Marsh, 1976). Due to difficulty in identifying cordierite, this unit is probably much more common in map area, particularly where biotite gneiss (Xb) is mapped

Xsr **Rutile-sillimanite-quartz gneiss (Early Proterozoic)**—Mostly white to light-gray, fine- to medium-grained, rutile-bearing, biotite-quartz-plagioclase-sillimanite gneiss and sillimanite-quartz gneiss in thin (<15 cm to as much as 150 m thick) but regionally extensive layers and lenses. Rutile forms a few tenths of a percent to as much as 5 percent of gneiss. Variants contain gahnite (zinc spinel), in which the rock commonly appears bleached, and topaz, which locally forms as much as 67 percent of rock (Sheridan and others, 1967). Mapped mostly in Squaw Pass 7.5-minute quadrangle (Sheridan and Marsh, 1976); one small occurrence mapped in northern Indian Hills quadrangle (Bryant and others, 1973)

Xhq **Amphibolite, marble, and quartzite (Early Proterozoic)**—Interlayered amphibolite, quartzite, coarse-grained, locally siliceous, white to light-gray marble, quartz-rich calc-silicate gneiss and schist, and quartz-sillimanite-muscovite-biotite gneiss and schist. Marble and quartzite layers locally as thick as 10 m. Mapped only in Indian Hills 7.5-minute quadrangle (Bryant and others, 1973)

Xaq **Amphibolite and quartzite (Early Proterozoic)**—Gray to dark-gray, interlayered amphibolite, hornblende gneiss, biotite-hornblende-plagioclase gneiss, and subordinate calc-silicate gneiss and quartzite. Mapped only in Indian Hills 7.5-minute quadrangle (Bryant and others, 1973), where it forms a structurally overlying carapace to two antiformal bodies of quartz-feldspar gneiss (Xf). One U-Pb zircon age on a quartz-rich layer in a hornblende-gneiss sequence from near Phillipsburg is 1,773±4 Ma (W.R. Premo, unpub. data, 2006), which is minimum age of deposition of the quartz-rich sand protolith

Xf **Quartz-feldspar gneiss (Early Proterozoic)**—Gray, dark-gray, white, pinkish-gray, and tan, moderately foliated to well-foliated, layered, fine- to coarse-grained (mostly medium grained) quartz-plagioclase-microcline-biotite gneiss. Proportion of minerals varies widely. Layers typically 10 cm to several tens of meters thick and commonly wavy. Locally contains layers of foliated monzogranite and granodiorite. May contain minor, thin layers of hornblende gneiss and amphibolite. Commonly migmatitic. U-Pb date on weakly foliated rock of monzogranitic composition in northwestern part of Indian Hills 7.5-minute quadrangle is 1,776±4 Ma. Weathers tan to pinkish tan in rounded outcrops. Crops out widely throughout map area

Xfh **Quartz-feldspar gneiss and hornblende gneiss (Early Proterozoic)**—Interlayered dark-gray and light-gray, well-foliated quartz-feldspar gneiss (Xf) and hornblende-plagioclase gneiss and amphibolite (Xh), including amphibolite, in approximately equal amounts. Some areas in Squaw Pass 7.5-minute quadrangle are equivalent to the mixed layered gneiss unit (Xlg) of Evergreen quadrangle

Xh **Hornblende-plagioclase gneiss and amphibolite (Early Proterozoic)**—Dark-gray to black, weakly to strongly foliated, layered, mostly medium grained, hornblende-plagioclase gneiss and amphibolite containing variable amounts of biotite, quartz, and augite. Commonly has black-and-white mottled texture due to weathered plagioclase (white) and hornblende (black). Amphibolite contains greater than 50 percent amphibole. Hornblende-plagioclase gneiss contains interlayered amphibolite, particularly in Nederland 7.5-minute quadrangle, and minor calc-silicate gneiss (Xc) and cordierite-biotite gneiss (Xbc) (Gable, 1969). Commonly intimately interlayered with more felsic gneissic rocks, so many occurrences are included with other units (particularly Xlg, Xbhc, Xaq, Xf, Xfh, Xh, and Xhc)

Xhc **Hornblende gneiss and calc-silicate gneiss (Early Proterozoic)**—Interlayered hornblende-plagioclase gneiss and amphibolite (Xh), with lesser amounts of interlayered, commonly lensoidal or pod-shaped bodies of calc-silicate gneiss (Xc). Mapped widely in Ralston Buttes, Squaw Pass, and Evergreen 7.5-minute quadrangles (Sheridan and others, 1972; Sheridan and Marsh, 1976; Sheridan and others, 1967) and in northwest corner of quadrangle (Eppinger and others, 1984)

Xgc **Mixed calc-silicate and biotite gneiss (Early Proterozoic)**—Biotite schist and gneiss, calcareous quartzite, calc-silicate quartzite, biotite marble, and some pegmatites as much as 5 m thick that are concordant with layering. Mapped along north border of quadrangle near Tabernash, Colo., and joins units in Strawberry Lake quadrangle to north (Schroeder, 1995)

Geologic History of the Denver West Quadrangle

The Denver West quadrangle spans the entire axis of the Front Range, one of numerous uplifts in the Rocky Mountain region in which Precambrian rocks are exposed. The history of the basement rocks in the Denver West quadrangle extends as far back as 1,790 Ma. Along the east side of the range, a sequence of sedimentary rocks as old as Pennsylvanian, but dominated by Cretaceous-age rocks, overlies these ancient basement rocks and was upturned and locally faulted during Laramide (Late Cretaceous to early Tertiary) uplift of the range. The increasingly coarser grained sediments up section in rocks of latest Cretaceous to early Tertiary age record in remarkable detail this Laramide period of mountain building. On the west side of the range, a major Laramide fault (Williams Range thrust) places Precambrian rocks over Cretaceous marine sedimentary rocks. The geologic history of the quadrangle, therefore, can be divided into four major periods: (1) Precambrian history, (2) Pennsylvanian to pre-Laramide, Late Cretaceous history, (3) Late Cretaceous to early Tertiary Laramide mountain building, and (4) post-Laramide history. Much of the geologic history herein is summarized from Kellogg and others (2004).

Precambrian History

Marine sediments, as well as mafic and felsic volcanic rocks, that were generally metamorphosed to amphibolite grade and intruded by calc-alkaline granitic rocks form the core of the Front Range and are part of an Early Proterozoic terrane called the Colorado province (Bickford and others, 1986). These rocks are interpreted to have formed over a long orogenic episode, beginning at about 1,790 Ma and lasting about 130 m.y., that may have accompanied Early Proterozoic accretion of island arcs and back-arc basins to the southern margin of an Archean continent (Reed and others, 1987; Aleinikoff and others, 1993b).

Proterozoic rocks of the Front Range include complexly folded and interlayered quartz-feldspar gneiss, amphibolite, biotite schist, and partial-melt migmatite. The biotite-rich rocks locally contain layers and lenses of marble, quartzite, and conglomerate, indicating sedimentary protoliths. Amphibolite (part of units Xh and Xhc) and quartz-feldspar gneiss (Xf) are generally abundant in separate areas from the metasedimentary rocks and probably represent original volcanic complexes, although locally both the metasedimentary and metavolcanic packages are complexly interlayered on a regional scale. The rocks are commonly metamorphosed to high-temperature, low-pressure, upper amphibolite assemblages; the metasedimentary rocks are mostly partially melted (migmatitic) and chiefly contain potassium-feldspar, biotite, sillimanite, ±garnet, and ±cordierite.

Details of the history of the Proterozoic rocks in Colorado are only locally well known (see, for example, Bickford and others, 1986, 1989; Braddock and Cole, 1979; Aleinikoff and others, 1993b; Premo and Fanning, 2000; Premo and others, 2007). Early metavolcanic and metasedimentary rocks were deposited in the northern Front Range region about 1,780–1,770 Ma (Premo and others, 2007). A younger sedimentary basin, now occupied by porphyoblastic quartz-biotite-muscovite schist of White Ranch (Xbp) and possibly rocks of some adjacent units (for example, Xc, Xbhc, Xh, and Xf), formed after ≈1,750 Ma.. Reliable facing directions have been found in unit Xbp and in the large syncline in quartzite (Xq, "Coal Creek quartzite") in the Eldorado Springs and Ralston Buttes 7.5-minute quadrangles (Wells, 1967; Sheridan and others, 1967; McCoy and others, 2005; K.S. Kellogg and Bruce Bryant, unpub. data, 2004). If the interpretation of McCoy and others (2005) is correct, and Coal Creek quartzite was deposited on rocks of the Boulder Creek batholith, then a possible third depositional basin, younger than ≈1,704 Ma, exists in the Denver West quadrangle.

At most places in the quadrangle, the Early Proterozoic metasedimentary and metavolcanic rocks have been strongly deformed in a ductile fashion, recrystallized, and partially melted. Peak metamorphism, presumably during crustal accretion to the Archean Wyoming province to the north near the Wyoming border, is thought to have occurred ≈1,750 Ma (Reed and others, 1993), although new single-crystal, U-Pb zircon results from several localities in and near the Denver West quadrangle indicate that a period of partial melting (anatexis) and formation of migmatites occurred about 1,697 Ma (W.R. Premo, unpub. data, 2005). Coeval with or closely following the ≈1,750 Ma metamorphic and deformational event, extensive batholiths and smaller bodies of mostly granodiorite and monzogranite, referred to as the Routt Plutonic Suite (Tweto, 1987), intruded the older layered rocks of the

Front Range. The Boulder Creek Granodiorite (XgdB), dated at 1,716±3 Ma (W.R. Premo and K.S. Kellogg, unpub. data, 2007), was emplaced synchronous with late folding (Gable, 2000) in these high-grade terranes. Numerous bodies of plutonic rock have been correlated with this batholith, but many of these rocks vary widely in age, with dates as old as ≈1,770 Ma and as young as ≈1,430 Ma (W.R. Premo and K.S. Kellogg, unpub. data, 2006).

The Early Proterozoic basement of the Front Range was extensively modified by widespread intrusions, regional heating, and local deformation during a regional orogenic event about 1,400 Ma. Large and small plutons of this age, called the Berthoud Plutonic Suite (Tweto, 1987), are characterized by mostly nonfoliated, commonly porphyritic biotite monzogranite and syenogranite.

The Silver Plume Granite (YgSP), a peraluminous biotite-muscovite monzogranite, forms a batholith that extends from the town of Silver Plume to west of the Continental Divide. The Silver Plume Granite has a U-Pb zircon date of 1,424±6 Ma (W.R. Premo, unpub. data, 2006) and was derived by limited partial melting of lower crustal material and emplaced possibly as shallow as 8 or 9 km (Anderson and Thomas, 1985). This batholith and similar intrusions contain many inclusions of country rock and have complex contacts composed of numerous dikes and irregular bodies intruded into the country rock.

The Mount Evans batholith of metaluminous granodiorite and monzogranite (YgdM) superficially resembles the Boulder Creek batholith but has a U-Pb zircon date of 1,442 Ma (Aleinikoff and others, 1993a). Similarly, granitic rocks near Empire and along the Continental Divide in the northern part of the quadrangle, formerly interpreted as part of the Routt Plutonic Suite based on their similarity to the Boulder Creek Granodiorite, have new U-Pb zircon dates between 1,435 and 1,425 Ma (W.R. Premo and K.S. Kellogg, unpub. data, 2006).

The Middle Proterozoic (≈1,400 Ma) magmatism reset the rubidium-strontium and potassium-argon isotopic systems (Peterman and others, 1968; Shaw and others, 1999). $^{40}Ar/^{39}Ar$ dates on muscovite and biotite are all 1,400–1,340 Ma, reflecting cooling through closure temperature after 1,400 Ma. $^{40}Ar/^{39}Ar$ dates on hornblende range from 1,600 to 1,390 Ma and represent variable retention of radiogenic argon (Shaw and others, 1999).

North-northwest-trending, ≈1,415 Ma diabase dikes [not mapped; more extensive north of the quadrangle (Peterman and others, 1968)] and undated lamprophyre dikes (not mapped, but well exposed in Clear Creek Canyon) are among some of the late Precambrian intrusives. A north-northwest-striking gabbro dike (“Iron dike,” Ygb), dated at 1,316±50 Ma (Braddock and Peterman, 1989), can be traced north to the Wyoming border from the northern part of the Denver West quadrangle just west of Boulder. Emplacement of the anorogenic, peralkalic Pikes Peak batholith at ≈1,080 Ma (Unruh and others, 1995) in the southern Front Range marks the final major Proterozoic rock-forming event.

The Proterozoic rocks of the Front Range are transected by a number of northeast- to east-trending, discontinuous, en echelon shear zones consisting of steeply dipping fabric exposed in mylonitic and nonmylonitic rocks. Three of these major shear zones, the Idaho Springs–Ralston shear zone (Sheridan and others, 1967; Wells, 1967), the Saint Louis Lake shear zone in the Byers Peak quadrangle (Shaw and others, 2002), and the Montezuma shear zone in the Montezuma quadrangle, transect the rocks of the Denver West quadrangle.

Recent study of the Idaho Springs–Ralston shear zone and another major shear zone (Homestake shear zone) west of the quadrangle shows that a zone of steeply dipping, highly strained but nonmylonitic rock formed about 1,720 Ma. Mylonites and ultramylonites formed locally along the same shear zones during or slightly after the ≈1,400 Ma plutonic event (Shaw and others, 2001, 2002; McCoy and others, 2005). Youngest shear-sense indicators in mylonites within the shear zones suggest southeast-up reverse movement (Braddock and Cole, 1979; Selverstone and others, 2000). The shear zones are interpreted by Shaw and others (2001) to have initially developed as a system of diffuse, high-strain zones related to continental assembly of terranes to form the Early Proterozoic crust of the region. Braddock and Cole (1979) conversely suggested that shearing was localized by gravitational buoyancy of major ≈1,400 Ma granitic plutons.

Northeast of the Mount Evans batholith, the Idaho Springs–Ralston shear zone marks a discontinuity in the trends of the major folds in the metamorphic rocks, although there is no major lithologic contrast across the zone. North of the zone, folds trend north-northeast, whereas south of the zone they generally trend northwest.

A third period of plutonism at ≈1,080 Ma (Unruh and others, 1995) is marked by emplacement of the anorogenic Pikes Peak Granite batholith, the northern lobe of which occupies the southern part of the quadrangle.

Paleozoic and Pre-Laramide Mesozoic History

During the early Paleozoic, thin continental-shelf sequences of quartz-rich sands and carbonates were deposited in shallow seas over the region. In the late Paleozoic, however, northwest- and north-northwest-trending mountain ranges and basins formed during the Ancestral Rocky Mountain orogeny. Erosion during uplift of the Ancestral Front Range removed the lower Paleozoic sedimentary cover and no sedimentary strata older than Pennsylvanian are preserved in the quadrangle. About 500 m of mostly red and pink, arkosic sandstone and conglomerate of the Fountain Formation (Pℙf), exposed along the east flank of the Front Range, were deposited adjacent to the east flank of the Ancestral Front Range.

Permian eolian deposits of the Lyons Formation (Pl) and Permian and Triassic fluvial and near-shore deposits of the Lykins Formation (ŦPl) overlie the thick clastic sequences of the Fountain Formation. By the Middle Jurassic, the Ancestral Front Range had been eroded to low relief and was mostly covered by fluvial and lacustrine deposits of the Morrison Formation (Jm) and, on the east side of the range, the Ralston Creek Formation. Near the end of the Early Cretaceous, major subsidence coeval with a rise in sea level caused transgression of the western interior seaway over the entire Front Range, which commenced with deposition of shoreline deposits of the Dakota Group (Kd), followed by deposition of more than 2 km of marine shale and minor amounts of sandstone and limestone [Benton Group (Kb), Niobrara Formation (Kn), and Pierre Shale (Kp)].

The Laramide Orogeny

The Laramide orogeny was a 20-m.y. period of crustal contraction, uplift, faulting, and igneous activity that initiated the building of the present Rocky Mountains. Its early stirrings were marked by renewed uplift of the Front Range region in the Late Cretaceous. The western interior seaway began to withdraw from the quadrangle area after 69 Ma, the age of the youngest ammonite zone in the Pierre Shale (Scott and Cobban, 1965; Cobban, 1993). This age is based on $^{40}Ar/^{39}Ar$ dating of tuffs outside the quadrangle but in the same ammonite zone (Obradovich, 1993). The Upper Cretaceous–lower Tertiary rocks overlying the Pierre Shale record the uplift history, starting with the regressive shoreline deposits of the Fox Hills Sandstone, followed by coastal-plain deposits that formed the sandstones and coal beds of the Laramie Formation (the namesake for the Laramide orogeny), in turn overlain by the fluvial conglomerates, sandstones, and claystones of the Arapahoe Formation and Denver Formation (Raynolds, 1997, 2002). Uplift in this area was geologically rapid; only a few million years separate the ages of the Upper Cretaceous marine deposits of the Pierre Shale and the earliest conglomerates of the terrestrial Upper Cretaceous Arapahoe Formation (Ka), which contains clasts derived from Proterozoic basement rocks. During this short period, the newly formed Rocky Mountains rose from the sea, and more than 2 km of upper Paleozoic and Mesozoic sedimentary rocks were eroded from the core of the range.

Debris of roughly andesitic composition derived from volcanoes somewhere west of the present mountain front forms a major part of the uppermost-Cretaceous–lowest Paleocene Denver Formation (₱Kd). Mostly alkali-calcic and alkalic dikes and stocks intruded the central Front Range region beginning about 68 Ma and continuing until about 27 Ma. The only Upper Cretaceous or lower Tertiary extrusive equivalent of the intrusions in this region are the lahars and minor andesitic flows in the Windy Gap Volcanic Member of the Middle Park Formation, which crops out in the northwestern part of the quadrangle (Izett, 1968; Taylor, 1975).

In the Golden area, the upper part of the Denver Formation contains ≈65 Ma potassic basalt (shoshonite) flows (₱db) that almost certainly erupted from a source a few kilometers to the north (Ralston Buttes intrusive). On South Table Mountain, the K-T (Cretaceous-Tertiary) boundary layer (65.4 Ma; Obradovich, 1993) is 71 m below the lowest of these basalts. Paleomagnetic directions from the Ralston Buttes intrusive (₱bi) are rotated, indicating that the body was emplaced before major movement on the Golden fault (Hoblitt and Larson, 1975) and, by inference, before uplift of the Front Range. Near the summit of Green Mountain, about 240 m stratigraphically above beds that are laterally equivalent to the basalts, the Green Mountain Conglomerate (₱g), which overlies the Denver Formation, contains a 64 Ma tuff (Obradovich, 2002). The similarity of all these ages within a relatively thick sedimentary sequence attests to rapid sedimentation, which, in turn, was due to the rapid erosion of the uplifting Front Range, during the close of the Cretaceous and the opening of the Tertiary.

The northeast-trending Boulder-Weld fault zone (Davis and Weimer, 1976) in the northeastern part of the quadrangle has been interpreted as a series of predominantly high-angle normal and reverse faults (“horst-and-graben” structures) that offset coal beds in the upper Laramie Formation (Kl) (Spencer, 1961; Lawrie, 1966). These faults are remarkably on strike with the Proterozoic Idaho Springs–Ralston shear zone, and have been interpreted as the result of renewed right-lateral strike-slip movement along this trend (Spencer, 1961), although intervening east-dipping beds of Dakota Group have not been offset or deformed relative to beds north and south of the trend. More recently, these faults have been interpreted as resulting from southeast-directed, low-angle decollement faulting on weak beds in the Pierre Shale, producing a series of southeast-directed reverse faults at the surface (Kittleson, 1989). Many of the faults of the Boulder-Weld fault zone have northwest-side-down offset, which could be explained in the decollement model as back thrusts. If the Boulder-Weld fault zone is due to decollement faulting, alignment with the Idaho Springs–Ralston shear zone is probably fortuitous.

At the margin of the Laramide Middle Park basin in the Bottle Pass 7.5-minute quadrangle west of Fraser, Paleocene and Upper Cretaceous(?) Middle Park Formation unconformably overlies rocks as old as Proterozoic biotite gneiss and as young as the Late Cretaceous Pierre Shale. At the base of the Windy Gap Volcanic Member of the Middle Park Formation (Kmw), which palynomorph data suggest is Late Cretaceous in age (Izett, 1968), these relationships indicate that deformation and erosion started at this locality before the end of the Cretaceous. Trachyandesite lahars, conglomerates, and minor lava flows are interbedded with well-bedded fluvial conglomerate and sandstone containing debris from both Cretaceous volcanic rocks and Precambrian rocks. Volcanic detritus decreases up section from the Windy Gap Volcanic Member, and 150 m above its top, clasts in the upper member of the Middle Park Formation (₱Kmu) are mainly derived from Precambrian basement rocks.

The principal Laramide structure on the east side of the Front Range is the Golden fault. Seismic sections and a few well data indicate that the Golden fault dips about 50°–70º to the west and has as much as 3 km of eastward thrust displacement (Weimer and Ray, 1997). On the west side of the

Front Range, the Williams Range thrust defines the western structural boundary of the Front Range, and, in contrast to the Golden fault, is a low-angle thrust with a minimum lateral displacement of 9 km, a distance known due to a thrust window related to uplift by the 38 Ma Montezuma stock (Ulrich, 1963; Kellogg and others, 2004). Movement on the Williams Range thrust is thought to be as young as late Paleocene and early Eocene, by analogy with the timing of movement on the probable southern extension of the Williams Range thrust, the Elkhorn thrust in South Park (Bryant and others, 1981a). The connection between the Williams Range and Elkhorn thrusts is obscured by intrusive rocks and surficial deposits.

In the Bottle Pass quadrangle west of Fraser (Taylor, 1975), Proterozoic rocks are faulted against rocks of the Paleocene and Upper Cretaceous Middle Park Formation along a high-angle reverse fault. Exploratory drilling on the crest of an anticline in the Middle Park Formation west of that fault revealed that Cretaceous rocks as old as the Dakota Group were thrust at least 2 km over the Middle Park Formation. The age of this thrusting is not closely constrained but is probably Paleocene or early Eocene. These reverse faults are overlain by the Oligocene and Miocene Troublesome Formation, which covers most of the Fraser basin.

In the western part of the quadrangle, the northeast-trending zone of closely spaced faults is called the Loveland Pass–Berthoud fault zone (Bryant and others, 1981b); pervasive fracturing of rocks in this zone is widespread. Fracturing may have been caused during Laramide movement along the low-angle Williams Range thrust, in which brittle hanging-wall Proterozoic rocks accommodated a bend in the thrust surface, from steep at depth to gentle near the surface (Kellogg, 2001; Kellogg and others, 2004).

The Colorado Mineral Belt

The Colorado mineral belt is a northeast-trending irregular zone of Late Cretaceous and Tertiary (68–27 Ma) mostly alkali-calcic and alkalic stocks and dikes, some of which are associated with several world-class ore deposits. The mineral belt crosses a large part of the area of Precambrian outcrop in the Denver West quadrangle. It extends northeastward across the mountainous part of Colorado from the western San Juan Mountains in southwestern Colorado to the east flank of the Front Range north of Boulder. The mineral belt contains most of the major metallic-mining districts in Colorado and seems to be related to a zone of crustal weakness marked by the northeast-trending ductile shear zones in the Precambrian rocks (Tweto and Sims, 1963). The belt of intrusives has been interpreted as the expression of a large subjacent batholith or series of batholiths, a suggestion that is consistent with the fact that the mineral belt is nearly coincident with a major gravity low, one of the lowest Bouguer gravity minimums in the United States (Tweto, 1975).

The abundant Laramide and post-Laramide stocks and dikes of the Colorado mineral belt have a wide range of composition and a long and complicated history of emplacement. The earliest intrusions in the Front Range region are chiefly monzonites and granodiorites, followed by more alkalic magmas, all emplaced during the interval from 68 to about 54 Ma (Rice and others, 1982). Ore deposits at Central City and Idaho Springs may have developed from a short-lived (≈1 m.y.), complex hydrothermal system that developed about 62 Ma (Nelson and others, 2003) at the end of the period of alkalic intrusive activity. The deposits consist of a zoned hydrothermal system having a core of gold-bearing pyrite-quartz veins, an intermediate zone of pyrite veins carrying copper, lead, and zinc sulfide minerals, and a peripheral zone of galena-sphalerite-quartz-carbonate veins (Sims and others, 1963; Moench and Drake, 1966; Sims, 1988; Rice and others, 1982).

Farther to the southwest, large granitic plutons emplaced at about 40±5 Ma (late Eocene) include the Montezuma stock in the Denver West quadrangle. Hydrothermal systems that formed the base- and precious-metal deposits at the Georgetown, Silver Plume, Montezuma, and (just west of the quadrangle) Breckenridge districts are associated with these younger granitic intrusives. The ≈37 Ma Silver Plume–Georgetown district, west of the Central City district, has silver-lead-zinc-bearing quartz-carbonate veins and some gold-silver veins trending east to northeast and controlled by several sets of steeply dipping fractures (Bookstrom, 1988; Bookstrom and others, 1987).

Some of the largest ore bodies in the mineral belt are associated with the youngest intrusives (30–26 Ma) in the Front Range region, many of which are high-silica alkali granite or rhyolite porphyries (rhyolite-A suite) (Geissman and others, 1992; White and others, 1981). One of these ore bodies is the world-class molybdenum deposit at the Henderson mine on Red Mountain (Wallace and others, 1978).

Post-Laramide Cenozoic History of the Front Range

Paleogene

By the close of the Laramide orogeny, during the early Eocene (about 50 Ma), erosional debris derived from the Laramide Front Range uplift formed a sedimentary apron, now largely eroded, that lapped onto the flanks of the range. Much of the topographic relief now visible along the eastern margin of the Front Range is due to post-Eocene erosion (Leonard and Langford, 1994), which removed most (as much as about 400 m) of the sedimentary apron (Kelley and Chapin, 1995). By the end of the Eocene (about 34 Ma), a widespread erosion surface cut on Precambrian rock had formed across the Front Range (Epis and Chapin, 1975), due in part to the relatively stable base level, unusually warm equable climate, and deep weathering during the Eocene (Chapin and Kelly, 1997). The erosion surface was a mature landscape of low relief, locally bordered by subdued ridges and summits, some as much as a few hundred meters high (Epis and others, 1980). The relict surface is visible from Denver and consists of accordant ridges and low-relief terrain at elevations of about 2,200–2,750 m (Scott and Taylor, 1986). High peaks, similar in form to those along the present-day Continental Divide, rose west of the erosion surface.

Extensive gently sloping alpine regions are locally present in the map area above modern timberline at elevations of about 3,550–3,800 m along and near the Continental Divide and about 3,770–3,850 m near Mount Evans. These areas are composed chiefly of scattered granitic bedrock tors surrounded by thin (probably about 1–2 m) regolith that consists of rock debris produced and transported by periglacial processes and, locally, residuum formed by in-place disintegration of granitic bedrock. Geologists have debated the origin of alpine regions for nearly 90 years (Bradley, 1987); they may be the alpine equivalent of the montane erosion surface (Epis and others, 1980) east of Mount Evans at elevations of about 2,200–2,750 m (Scott and Taylor, 1986).

The Fraser basin began to form at the end of the Oligocene, at about the same time that the graben beneath the Blue River valley formed, beginning about 29 Ma in response to tectonic activity along the Rio Grande rift (Tweto, 1978). Basal deposits of the sedimentary fill (Troublesome Formation) in both areas are of late Oligocene age (Izett, 1974; Kron, 1988; Naeser and others, 2002).

Neogene

Renewed uplift of the western part of the Front Range and probable eastward tilting of the range during the Miocene (Raynolds, 1997; Steven and others, 1997; Naeser and others, 2002) were accompanied by active faulting in the western part of the range (Geissman and others, 1992). Uplift of the range and the west side of the Denver Basin promoted erosion, which removed large volumes of the upper Paleozoic and Mesozoic sedimentary rocks. Erosional detritus was deposited in the Ogallala Group on the eastern plains. During the Miocene, ancestral Clear Creek cut a paleovalley 1.5 km or more wide and about 240 m deep (Epis and others, 1980). High-level gravel deposits (Ng) preserved on some of the ridges in the Front Range east of the Continental Divide are probably coarse-grained proximal equivalents of the Ogallala Group that filled or partly filled Miocene paleovalleys (Scott and Taylor, 1986; Steven and others, 1997). These east-trending, gravel-capped ridges, once valley bottoms, are resistant to erosion and, therefore, now form an inverted topography. Some of the gravel deposits have sinuous patterns and are not aligned with bedrock structure, suggesting deposition by low-gradient streams. Other deposits, such as those near Tungsten Mountain southeast of Nederland, contain boulders 1–2 m long in a granule-rich, poorly sorted matrix and may have been deposited by debris flows.

Following the deposition of the Ogallala Group during the Miocene (about 18–5 Ma; Swinehart and others, 1985), the Pliocene Epoch appears to have been chiefly a time of widespread erosion in upland areas, major canyon cutting in Precambrian crystalline rock along the east flank of the Front Range, and incision by major streams of Tertiary and underlying Upper Cretaceous sedimentary rocks in the adjacent piedmont (Steven and others, 1997). The South Platte River and its major tributaries eroded the Ogallala Group and a substantial amount of the underlying sedimentary rocks from the eastern part of the map area, but extensive deposits of the Ogallala Group are present north and east of Denver (Leonard, 2002), outside the map area. During Pliocene time, Clear Creek Canyon was incised about 405–435 m below the level of the montane erosion surface (Epis and others, 1980).

Accelerated stream erosion, canyon cutting, and steepened stream profiles were probably fostered by greater stream power, due in part to wetter climate as well as tectonic and isostatic uplift during the Pliocene. Marine isotopic records since about 15 Ma (middle Miocene) show a long-term trend toward global cooling, except for a warming trend during the early part of the Pliocene (about 5–3 Ma; Zachos and others, 2001, and references cited therein). The Pliocene Epoch in the western United States was characterized by climatic conditions significantly wetter (more effective precipitation) and stormier than those of today, particularly about 4.5–3.5 Ma (Forester, 1991) and 3.2–2.8 Ma (Smith and others, 1993). Globally averaged temperatures during the early part of the epoch (5–3 Ma) were substantially higher than they are today (Fedorov and others, 2006). At 3 Ma there was a major change in ocean circulation (Federov and others, 2006) accompanied by renewed global cooling (Zachos and others, 2001, and references cited therein), significant increases in the magnitude of temperature ranges during cold (glacial)/warm (interglacial) climatic cycles (Morrison, 1991), and the development of major northern hemisphere ice sheets after 2.5 Ma (Shackleton and others, 1984; Prell, 1984; Thompson, 1991; Ravelo and others, 2006).

Some of the sediments produced by erosion and stream incision during the Pliocene are preserved in the Nussbaum Alluvium (about 3 Ma) along the South Platte River in northeastern Colorado (Scott, 1978, 1982). Post-Ogallala tectonic and erosion-induced isostatic uplift are inferred from post-depositional increases in tilt of the Ogallala Group in southern Wyoming (McMillan and others, 2002) as well as from warping of the base of the Ogallala in the Colorado Piedmont (Leonard, 2002).

Erosion rates in Front Range canyons and on upland surfaces are linked to, and were enhanced by, erosional processes that were intensified by global cooling during the past 3 m.y. Measurements of cosmogenic isotopes ^{10}Be and ^{26}Al suggest maximum rates of surface lowering of 5–9 m/m.y. for granite tors in alpine upland areas in the Front Range (Small and others, 1997; Anderson and others, 2006). These long-term rates are compatible with short-term rates of surface lowering of 10 mm/k.y. (10 m/m.y.) in other alpine areas, such as the crest of Niwot Ridge and in the Green Lakes valley west of the town of Ward (Caine, 1974, 1984), about 5 km north of the map area. Small, unglaciated, upland drainage basins that formed on Precambrian granite and gneiss in montane areas of the northern part of the Front Range and adjacent Laramie and Medicine Bow Mountains to the north have long-term erosion rates of 18–30 m/m.y. (Dethier and others, 2002); those near Boulder Canyon have rates of about 22 m/m.y. (Dethier and Lazarus, 2006). Soil-profile development at stable sites on the upland surface in and near the northern part of the map area suggests erosion rates much less than 0.01 m/k.y. (10 m/m.y.) and perhaps no more than 0.001 m/k.y. (1 m/m.y.) (Birkeland and others, 2003). Long-term erosion rates in Front Range canyons are considerably greater than those determined in nearby alpine upland areas (Small and Anderson, 1998; Anderson and others, 2006), but are lower than the late Pleistocene rate of roughly 0.15 m/k.y. (150 m/m.y.) at a major knickpoint in Boulder Canyon (Schildgen and others, 2002).

Quaternary

Quaternary deposits and landforms within the map area reflect the influence of earth-surface processes in concert with global climate-driven glacial-interglacial cycles during the past 1.8 m.y. Global climatic cooling of the later part of the Pliocene continued into the Pleistocene and intensified after 900 ka (Clark and Pollard, 1998). The stratigraphic record suggests that there were at least 12 glaciations in the mountains of the western United States during the Quaternary (Richmond and Fullerton, 1986b, Chart 1). Pleistocene glacial deposits in Colorado and elsewhere in the Rocky Mountains are commonly correlated with Pinedale, Bull Lake, and pre-Bull Lake glaciations (Meierding and Birkeland, 1980; Pierce, 2004). Blackwelder (1915) named the Pinedale (last major) and Bull Lake (penultimate) glaciations for younger and older sets of moraines on the eastern and western flanks of the Wind River Range, Wyo. Glacial deposits that predated the Bull Lake glaciation typically lack morainal form and commonly are locally preserved just beyond the lower limits of Pinedale and Bull Lake ice. These deposits have been identified in a few areas near the map area (Meierding and Birkeland, 1980). Sharp-crested moraines produced by post-Pinedale glacial advances of Holocene age and latest Pleistocene age are locally present within cirques in the map area (Davis, 1988).

There are no known glacial deposits of pre-Bull Lake age exposed within the map area. The absence of these deposits is probably due chiefly to erosion and subsequent burial by deposits of younger and more extensive glacial advances (Meierding and Birkeland, 1980). Glacial deposits of early Pleistocene age are especially likely to be buried by younger glacial deposits because cold (glacial)/warm (interglacial) climatic cycles prior to 900 ka [marine oxygen isotope stage (MIS) 22] were of lower amplitude (lower global ice volume) and of much shorter duration (about 40 percent as long) than those after 900 ka (Clark and Pollard, 1998). Also, marine oxygen isotope records show only two glacial episodes (MIS 12 and 16; about 475–424 ka and 675–621 ka, respectively; Lisiecki and Raymo, 2005) as severe (in terms of temperature and global ice volume) as those during the Bull Lake and Pinedale glaciations. This suggests that all pre-Bull Lake glaciations prior to MIS 16 were likely to be less extensive than the Bull Lake and Pinedale glaciations.

The oldest glacial deposits exposed in the map area are till and, locally, stratified drift, which form subdued moraines of the Bull Lake glaciation. Bull Lake deposits in their type area in Wyoming are about 170–120 ka (Sharp and others, 2003; Pierce, 2004). These deposits accumulated during one or more major cold climatic episodes during MIS 6 (190–130 ka, Lisiecki and Raymo, 2005) and probably during the early part of MIS 5 (130–70 ka, Lisiecki and Raymo, 2005; Pierce, 2004). Mapped deposits of the Bull Lake glaciation may locally include small, unrecognized deposits of pre-Bull Lake glaciations.

Till and minor amounts of stratified drift of the Pinedale glaciation form well-preserved moraines that are widespread in the upper part of glaciated valleys of the Front Range at the lower limit of glaciation. Pinedale glacial deposits in Colorado are about 30–12 ka (Nelson and others, 1979; Madole, 1986; Schildgen and Dethier, 2000; Benson and others, 2004, 2005). They accumulated during a major cold climatic episode of MIS 2 (35–14 ka; Lisiecki and Raymo, 2005). Till and other ice-contact deposits of the Pinedale glaciation may locally include or overlie glacial deposits of early Wisconsin age (MIS 4, 70–55 ka; Lisiecki and Raymo, 2005), which are identified in a few areas of the western United States (Pierce, 2004). For example, till near Mary Jane Creek, about 9 km southeast of Fraser, is older than 30,480 and 30,050 ^{14}C yr B.P. (Nelson and others, 1979) and may be early Wisconsin in age (Richmond, 1986; Richmond and Fullerton, 1986b); or it may have been deposited during an early advance of Pinedale ice (Sturchio and others, 1994). This till is overlain by three thin (30–50 cm) till units or debris-flow deposits that accumulated during the Pinedale glaciation and by interstratified silty lake sediments, all of which are older than 13,740 ^{14}C yr B.P. (Short and Elias, 1987).

Glaciers in the map area during the Bull Lake and Pinedale glaciations were as much as 7–19 km in length, and typically descended to elevations of about 2,500–2,850 m. In the valley of Clear Creek, however, glaciers were much larger because of the large area of ice accumulation in the upper part of the valley. The lowermost ice-contact deposits of the Bull Lake glaciation in the Clear Creek drainage are about 39 km down-valley of the Continental Divide at an elevation of about 2,400 m. In the Boulder Creek drainage just west of Nederland, glaciers during the Bull Lake glaciation reached about 2,500 m and were about 300 m thick (Porter and others, 1983). In comparison, glaciers during the Bull Lake and Pinedale glaciations throughout the Front Range typically attained lengths of 10–20 km, terminated at elevations between 2,500 and 2,700 m, and were 180–350 m thick (Benson and others, 2004).

The youngest glacial deposits in the map area are tills of Holocene age (Benedict, 1985) and latest Pleistocene age (about 12–10 ka; Davis, 1988). These tills lie above present treeline within roughly 1 km of cirque head walls, typically above an elevation of about 3,350 m. They were deposited during minor glacial advances after the Pinedale glaciation, chiefly during MIS 1 (14–0 ka; Lisiecki and Raymo, 2005).

Snow lines during the Pleistocene in the western United States were roughly 1,000 m lower than present (Porter and others, 1983). Fossil beetles near Denver (1,731 m), dated at 14,500 ^{14}C yr B.P., suggest that during full- or late-glacial climatic conditions, mean July temperatures were 10°–11°C colder than present, and mean January temperatures were 26°–30°C colder than present (Elias, 1996). Relict permafrost features in Wyoming suggest that temperatures could have been 10°–13°C colder than they are at present (Mears, 1981). More effective precipitation and vigorous freeze-thaw action likely accompanied expanded periglacial environments during glacial episodes, and would have promoted slope instability and intensified mass-movement processes in the Front Range and adjacent Colorado Piedmont. Much of the coarse debris, which forms features such as block fields and block streams on interfluves above and beyond the limit of glacial ice in the Front Range, and some of the large landslide deposits along the hogback belt probably formed chiefly under periglacial conditions. Some of the landslide deposits in glaciated valleys formed after glaciers retreated and glacial ice no longer provided lateral support to weakly consolidated material on steep, unstable slopes. Increased infiltration of precipitation may have locally promoted deep-seated rock creep on steep slopes in periglacial environments.

Streams draining from glaciers within the map area produced broad, gravelly glacial outwash deposits in mountain valleys, particularly during times of significantly greater sediment yield during deglaciation (Church and Ryder, 1972). Some of the glacial outwash likely is slightly younger than corresponding tills, because fluvial deposition lagged (perhaps by a few to several thousand years) the onset of the climatic change that affected glaciation, such as the transition from glacial to interglacial climates (Church and Ryder, 1972; Hancock and Anderson, 2002). Large glacial outwash deposits within the map area locally extend about 16 km or more downstream of former glacier fronts, such as those in the valley of Clear Creek. Maximum grain size and the surface slope of glacial outwash deposits decrease significantly within a distance of about 10 km downstream of former glacier fronts (Church and Ryder, 1972; Ritter, 1987).

Glacial outwash deposits and till of the Pinedale glaciation in the Front Range are correlated with the Broadway Alluvium in the Colorado Piedmont east of the mountain front; deposits of the Bull Lake glaciation are correlated with the Louviers Alluvium (Scott, 1975; Madole, 1991a). These correlations (table 1) are based chiefly on the (1) morphology of surface soils formed in these deposits (Birkeland and others, 2003) and (2) height of glacial outwash and piedmont alluvial deposits above present streams. Recent cosmogenic dating supports these correlations (Schildgen and Dethier, 2000). ^{10}Be and ^{26}Al ages of Pinedale (32–10 ka) and Bull Lake (130 ka) glacial outwash deposits in Boulder Canyon east of Nederland (Schildgen and others, 2002) and their heights above stream level support the concept that Pinedale outwash (8–12 m above present stream level) is equivalent in age to Broadway Alluvium (8–12 m), and Bull Lake outwash (15–20 m) is equivalent in age to Louviers Alluvium (12–24 m). Deposition of alluvium of Holocene age in present flood plains and as terrace deposits less than 5 m above present streams in the Colorado Piedmont are difficult to correlate with climatic episodes, but some may reflect past climatic conditions that were colder than at present, and possibly more moist (or due to more effective precipitation) than at present. These latter climatic episodes promoted glacial and (or) periglacial activity in the Front Range during the Holocene (Scott, 1975).

The depositional chronology, as well as the climatic (glacial or interglacial) and fluvial conditions that prevailed during the deposition of most of the pre-Louviers (pre-Bull Lake) alluvial deposits in the Colorado Piedmont near Denver, can only be inferred. The following interpretations and age estimates are based on tentative correlation with marine oxygen isotope stages and a nonlinear rate of stream incision in the Denver area since the deposition of the 640 ka Lava Creek B tephra. Stream incision is likely to be nonlinear, because numerical modeling suggests that the formation of strath terraces (and probably pediments) can span tens of thousands of years of stream stability between shorter episodes of stream incision (Hancock and Anderson, 2002), and heights of terrace deposits of known or inferred ages suggest increased rate of stream incision after about 400 ka (Dethier, 2001; Hancock and Anderson, 2002). Pre-Louviers alluvial deposits were transported and deposited by streams that headed in glaciated as well as nonglaciated drainage basins in the Front Range. Many of these deposits probably accumulated chiefly during glacial episodes, particularly during maximum glaciation or deglacial phases of glacial episodes, when climatic (glacial and periglacial) and fluvial conditions, as well as abundant sediment supply, promoted increased stream discharge and sediment load (Church and Ryder, 1972; Sinnock, 1981; Ritter, 1987; Madole, 1991c). However, events unrelated to glaciation, such as stream capture and minor periods of cutting and filling unrelated to major climatic events (such as lateral migration of the South Platte River and its influence on tributary streams), likely accounted for deposition of some of these deposits (Ritter, 1987; Reheis and others, 1991).

Comparison of the isotopic ages for deposits of the Pinedale glaciation (30–12 ka) and Bull Lake glaciation (170–120 ka) with cold and warm climatic episodes of the marine oxygen isotope record (for example, Shackleton and Opdyke, 1973, 1976; Lisiecki and Raymo, 2005) suggest that outwash deposits of the Pinedale and Bull Lake glaciations and the temporally correlative fluvial deposits in the Colorado Piedmont (Broadway Alluvium and Louviers Alluvium, respectively) were deposited chiefly during major cold climatic episodes, and in part during succeeding warm climatic episodes. These relations suggest that pre-Louviers alluvial deposits in the Colorado Piedmont may have accumulated under somewhat similar climatic conditions.

Table 1. Estimated age ranges and correlation of alluvial deposits younger than the Rocky Flats Alluvium in the Colorado Piedmont near Golden and Morrison, Colorado.

Deposit	Height (m)[a]	Age or age estimate (ka)	Correlative glaciation in Rocky Mountains	Marine oxygen isotope stage and age (ka)[b]
Post-Piney Creek alluvium and Piney Creek Alluvium.	<5	0–4[c]	Minor post-Pinedale ice advances.	1 (0–14)
Broadway Alluvium	12	12–30[d]	Pinedale	2 (14–35) 3 (35–55)
No known deposits	--	--	Early Wisconsin.	4 (55–70)
Louviers Alluvium	20	120–170[d]	Bull Lake	5 (70–130) 6 (130–190)
Slocum Alluvium younger deposits.	30	220–300[e]	--	7 (190–243) 8 (243–300)
Slocum Alluvium older deposits.	45	320–390[e]	--	9 (300–337) 10 (337–390) 11 (390–424)
Verdos Alluvium younger deposits.	60	410–475[e, f]	--	12 (424–475)
No known deposits	--	--	--	13 (475–533) 14 (533–570) 15 (570–621)
Verdos Alluvium older deposits.	75	610–675[g]	Sacagawea Ridge.	16 (621–675)

[a]Approximate height of deposit above present stream level near the east side of the hogback belt.

[b]Ages for marine oxygen isotope stages are those of Lisiecki and Raymo (2005, fig. 4 and table 3), and are based on benthic $\delta^{18}O$ records from 57 globally distributed sites. Even-numbered stages represent cold (glacial) climatic episodes; odd-numbered stages represent warm (interglacial) climatic episodes (for example, Shackleton and Opdyke, 1973, 1976).

[c]Age of alluvial deposits based on limited radiocarbon analyses (Scott, 1962, 1963a; Madole, 1976; Lindsey and others, 1998; Madole and others, 2005).

[d]Age of till and outwash of the Pinedale glaciation is based on radiocarbon and cosmogenic isotopic ages (Nelson and others, 1979; Madole, 1986; Schildgen and Dethier, 2000; Schildgen and others, 2002; Benson and others, 2004, 2005). Age of till and outwash of the Bull Lake glaciation is based on cosmogenic ages (Schildgen and Dethier, 2000; Schildgen and others, 2002; Sharp and others, 2003; Pierce, 2004).

[e]Age estimate for alluvial deposits based on tentative correlation with marine oxygen isotope stages and a nonlinear rate of stream incision in the Denver area since the deposition of 640 ka Lava Creek B tephra.

[f]Younger deposits of Verdos Alluvium may locally include alluvium deposited during marine oxygen isotope stage 14 (about 533–570 ka).

[g]Age estimate for alluvial deposits based on stratigraphic position of 640 ka Lava Creek B tephra and tentative correlation with marine oxygen isotope stages.

Younger (topographically lower) and older (higher) deposits of Slocum Alluvium are locally present within the map area. Near the hogback belt, these deposits are as much as about 30 and 45 m, respectively, above present streams. Tentative correlation with marine oxygen isotope stages and a nonlinear rate of stream incision in the Denver area since the deposition of the 640 ka Lava Creek B tephra suggest that the younger deposits may have accumulated between about 300 and 220 ka and older deposits between about 390 and 320 ka (table 1).

Younger (topographically lower) and older (higher) deposits of Verdos Alluvium are also locally present within the eastern part of the map area. Near the hogback belt, these deposits are as much as about 60 and 75 m, respectively, above present streams. The age of older deposits of Verdos Alluvium is fairly well constrained, because these deposits locally overlie, contain, or are overlain by water-laid deposits of Lava Creek B tephra (Machette, 1975; Machette and others, 1976; Van Horn, 1976), which was deposited when glaciers were retreating, during the transition from glacial to interglacial climatic conditions (Dethier, 2001; D.S. Fullerton, oral commun., 2006). The age of the tephra (640 ka) indicates that older deposits of Verdos Alluvium were deposited near the end of a major cold climatic episode during MIS 16 (675–621 ka; Lisiecki and Raymo, 2005), and possibly in part during the early part of MIS 15. These deposits are similar in age to till and outwash of the Sacagawea Ridge glaciation near the type area for this glaciation on the eastern flank of the Wind River Range, Wyo., where water-laid Lava Creek B tephra is present in the top of the outwash (Jaworowski, 1992; Chadwick and others, 1997). The stratigraphic position of the water-laid tephra with respect to older pediment and fluvial deposits of the Verdos Alluvium suggests that the older pediment deposits are younger than the older fluvial deposits (Machette, 1975).

Near the hogback belt, younger deposits of the Verdos Alluvium are as much as about 60 m above present streams. Tentative correlation with marine oxygen isotope stages and a nonlinear rate of stream incision in the Denver area since the deposition of the 640 ka Lava Creek B tephra suggest that the younger deposits may have accumulated between about 475 and 410 ka (table 1). Younger deposits of the Verdos Alluvium may be temporally correlative in part with shoreline and near-shore deposits that formed during a high stand of Lake Alamosa at about 450 ka in the San Luis basin in southern Colorado (Machette, 2006). If the age estimate for younger deposits of Verdos Alluvium is correct, it suggests limited deposition of terrace and pediment deposits during cold (glacial) climatic conditions of MIS 14 (about 570–533 ka) in the Colorado Piedmont near Denver. Alternatively, younger deposits of Verdos Alluvium may locally include alluvium deposited during MIS 14 as well as during MIS 12 (about 475–424 ka).

Cosmogenic dating (on ^{10}Be and ^{26}Al) of alluvial-fan deposits (typically ≤5 m thick; Knepper, 2005) that constitute the upper part of the Rocky Flats Alluvium at Rocky Flats indicates that they date from about 1.5 Ma (Dethier and others, 2001) or about 2–1 Ma (Riihimaki and others, 2006). However, the buried soil formed in the upper part of the unit at the type section (Scott, 1960) for the Rocky Flats Alluvium (Birkeland and others, 1996) suggests that the underlying valley-fill deposits (≤25 m thick; Knepper, 2005) that form the lower part of the unit may be much older. Morphologic and paleomagnetic properties of buried soils at a site about 3 km south of Rocky Flats geomorphic surface support the cosmogenic ages and suggest that the Rocky Flats Alluvium dates from at least 1.6–1.4 Ma (Birkeland and others, 1996), and possibly is about 2 m.y. old (Birkeland and others, 2003). Although the Coal Creek drainage basin (the source of the Rocky Flats Alluvium on Rocky Flats) was never glaciated, the Rocky Flats Alluvium may have been deposited during one or more glacial episodes. Considering the age constraints for the Rocky Flats Alluvium and the fact that no evidence has been found for a major glaciation in the United States between 1.5 Ma and 900 ka (Fullerton and Richmond, 1986; Richmond and Fullerton, 1986b, Chart 1), the Rocky Flats Alluvium may have been deposited after 2.5 Ma but before 1.5 Ma, the onset of major northern hemisphere glaciations (Shackleton and others, 1984; Prell, 1984; Thompson, 1991; Ravelo and others, 2006).

Eolian deposits are widespread east of the mountain front in the Colorado Piedmont. Age assignments, spatial distribution, and downwind fining of the particle size of eolian sand and loess in the Colorado Piedmont suggest a close relation between the genesis of these deposits and active aggradation of sparsely vegetated flood plains, chiefly during the Pinedale and Bull Lake glaciations. Some of the loess, and possibly some of the eolian sand, in and northeast of the map area were derived from bedrock sources (Scott, 1962; Madole, 1995; Aleinikoff and others, 1999). Much of the loess within the map area probably was deposited during two episodes during the Pinedale glaciation (about 20–14 ka and 13–10 ka; Muhs and others, 1999). Additional accumulation may have occurred during one or more episodes of the Bull Lake glaciation (about 150 ka; Forman and others, 1995). Much of the eolian sand within the map area probably was deposited during one or two episodes of flood-plain aggradation and eolian transport during the Pinedale glaciation (about 27–11 ka; Muhs and others, 1996) and possibly during a later episode following the Pinedale glaciation between 11 and 4 ka (Muhs and others, 1996) or 4.5 ka (Scott and Lindvall, 1970), prior to deposition of the Piney Creek Alluvium (about 4–1 ka; Madole, 1976; Madole and others, 2005).

Potential Geologic Hazards

Potential geologic hazards in the mountains, hogback belt, and piedmont of the Denver West quadrangle merit consideration, because urban growth and development in recent years commonly have occurred in parts of the landscape where geologic, topographic, and hydrologic conditions favor such hazards. Potential geologic hazards in the Denver West quadrangle include (1) mass movement, (2) expansive soils and bedrock and heaving bedrock, (3) compactable and compressible soils, (4) floods, (5) abandoned mines, (6) seismicity, (7) elevated radon, and (8) snow avalanches.

Mass Movement

Rock units and surficial deposits on moderate to steep slopes are prone to various forms of mass movement, including rock fall, debris flow, landsliding, and creep. Landslide deposits are common in areas of the Denver West quadrangle, particularly on steep slopes underlain by weak rocks such as Pierre Shale, Denver Formation, and locally on highly fractured and altered basement rocks. Landslides include material displaced chiefly by rotational rock slides, rotational earth slides, debris slides, earth flows, and earth slide–earth flows (as defined by Cruden and Varnes, 1996). Conditions and processes that promote sliding and other types of mass movement locally include (1) toe slopes over-steepened by erosion or human excavation; (2) gravitational spreading of mountain flanks (Varnes and others, 1989); (3) bedding, foliation, or other planes of weakness oriented parallel to slope; (4) deforestation resulting from logging, wildfires, and (or) construction of roads, buildings, and associated infrastructure; (5) high water content and elevated pore pressure due to intense or prolonged rainfall or rapid snow melt; (6) contrasts in material properties (such as dense, stiff material over plastic, easily deformed material); and (7) shrink-and-swell processes and low shear strength of clayey material (Cruden and Varnes, 1996). In addition to sliding, mass-movement deposits within the map area are also produced by rock fall, debris flows, and downslope creep. Debris flows are locally generated on steep (>30°) hillsides in small catchments during intense summer rainstorms (for example, Godt and Coe, 2007). They are particularly common in areas recently deforested and destabilized by wild fires (for example, Cannon and others, 1995; Soule, 1999; Cannon, 2001) and locally damage roads and structures.

Expansive Soils and Bedrock and Heaving Bedrock

Expansive soils and bedrock and heaving bedrock pose potential problems for roads, building foundations, and other man-made structures built on them. These problems are particularly serious at and near the western margin of the Colorado Piedmont where clayey sedimentary rocks and surficial deposits derived from these rocks have a high content of expansive clays (typically smectite and mixed-layer illite-smectite).

Expansive bedrock occurs in level to gently inclined, layered, clayey sedimentary rocks and commonly swells evenly and produces uniform heave at the ground surface; by contrast, heaving bedrock occurs in moderately to steeply inclined, layered, clayey rock and commonly swells unevenly and produces linear-heave features at the ground surface (Noe and others, 1997). Expansive clays in clayey rock units have the capacity to adsorb a substantial amount of water, which causes them to swell. During dry periods, clays in these units release adsorbed water and shrink. East of the Front Range, the Pierre Shale and Denver Formation are particularly susceptible to marked volume change, related to the gain and loss of adsorbed water, especially in layers of altered volcanic ash (Hart, 1974; Shroba, 1982). However, in the Blue River valley west of the Williams Range thrust, the Pierre Shale is apparently more indurated than Pierre east of the Front Range, possibly due in part to low-grade thermal metamorphism by Tertiary intrusive activity (W.A. Cobban, oral commun., 2000), and is likely to be less expansive.

Differential heaving of inclined bedrock is locally a problem in the outcrop belt of the Pierre Shale southeast of Green Mountain (Noe and others, 1999). In this area, the effects of heaving bedrock are manifest by the vertical growth of somewhat parallel ridges underlain by beds of expansive bedrock separated by swales underlain by beds of less expansive bedrock. Differential movement in excess of 0.6 m has occurred in a few areas within a few years after unloading of the bedrock due to excavation and subsequent wetting by natural processes and human activity. This differential movement has locally resulted in considerable damage to structures, roads, and utilities. Appropriate construction procedures help to stabilize and provide suitable drainage for roads, structures, and utilities built on expansive rock units and sediments. These procedures commonly include the installation of drilled-pier foundations, floating-slab floors, and over-excavation and replacement of expansive bedrock with at least 3 m of nonexpansive fill material in areas of heaving bedrock (Noe, 1997; Noe and Dodson, 1997; Noe and others, 1997).

Compactable and Compressible Soils

Silty and slightly silty eolian sediments (loess and eolian sand), organic-rich, silty sediments, such as Piney Creek Alluvium, and poorly compacted deposits of artificial fill are common in the eastern part of the Denver West quadrangle. When placed under a heavy load, these deposits commonly decrease in total volume due to particle compaction. Organic-rich mineral deposits, such as Piney Creek Alluvium and some artificial fill, also undergo compression under load due to reduction of the open structure of organic material. Both compaction and compression can result in excessive and non-uniform decrease in volume, which results in differential settlement at the ground surface, especially when these deposits become water saturated by natural processes or human activity (Simpson, 1973; Shroba, 1982). The lower the density and the higher the content of the organic material, the more likely deposits are to compact and (or) compress, and undergo differential settlement. Other factors, such as moisture content and possibly the amount and type of clay-size material and shape and orientation of the silt- and clay-size particles, influence the amount of consolidation of loess (Shroba, 1982). If either compactable or compressible material is present at a site, foundations can be designed to transmit the load to more competent material at depth, or the material can be removed or replaced with satisfactory fill material (Simpson, 1973).

Floods

Intense summer downpours or rapid melting of thick snowpack during unusually warm spring thaws may cause localized stream flooding in and near stream channels, and localized sheet erosion and sheet flooding on slopes. Floods commonly are restricted to low-lying areas. Roads, structures, and utilities built on historical flood plains and low (<5 m) terraces east of the mountain front may be susceptible to stream flooding during periods of high runoff. Construction of buildings and roads decreases the area available for infiltration of rainfall and increases the magnitude of periodic flash floods, due chiefly to increased runoff. In mountainous areas, unusual intense summer thunderstorms, such as those that formed above the upper part of the Big Thompson Canyon (about 40 km north of the map area) and other nearby canyons during July 31–August 1, 1976, can produce 25 cm of precipitation in a few hours (McCain and others, 1979) in areas that normally receive about 30–35 cm for an entire year (Hansen and others, 1978). In the 1976 Big Thompson instance, the ensuing devastating flash floods resulted in significant loss of life, destruction of property, and geomorphic change (Shroba and others, 1979). Heavy rainfall from intense summer thunderstorms generated by orographic uplift and convective instability commonly falls at elevations of about 2,100–2,750 m (Cole, 2004). As a result, low-lying areas on the east flank of the Front Range and in the adjacent piedmont at or below an elevation of about 2,750 m are susceptible to local summer thunderstorm-induced stream and sheet flooding. In addition to flooding, these storms locally initiate sheet erosion, landslides, debris flows, and rockfall, any or all of which can locally cause considerable damage to roads, buildings, and other structures in mountain valleys and adjacent slopes (Shroba and others, 1979).

Abandoned Mines

Collapse and subsidence of abandoned mine portals and stopes pose a potential hazard in areas mined during the latter part of the 19th and early part of the 20th centuries. Precious metals, copper, lead, zinc, and tungsten were mined in the Colorado mineral belt near the towns of Central City, Idaho Springs, Georgetown, Empire, and Nederland; and coal was mined in the Colorado Piedmont near Marshall and Louisville. Drainage from mines in the Colorado mineral belt tends to be acidic, due to oxidation of sulfide minerals (mostly pyrite), and commonly contains toxic levels of heavy elements such as zinc, cadmium, lead, and arsenic in areas near the sources (Ficklin and Smith, 1994; Emerick and others, 1994). Soil contaminated by acidic mine drainage may be corrosive to untreated metal and concrete, pose a hazard to building foundations, and locally render nearby surface and subsurface water unsuitable for human use and consumption. Differential subsidence is locally a problem for structures built on fill material in reclaimed clay pits near Golden (Noe and others, 1999).

Seismicity

Large-magnitude historical earthquakes have rarely occurred in and near the Front Range. An earthquake of inferred magnitude 6.5 was widely felt in parts of Colorado, Wyoming, Utah, and Kansas in 1882 and caused local structural damage in the northern part of the Front Range (Kirkham and Rogers, 1986, 2000). Scattered earthquakes of smaller magnitude periodically shake the region, such as the magnitude 2.8 earthquake near Conifer in 1981 (Butler and Nichols, 1986).

Inferred seismogenic faults in and near the map area locally displace Quaternary deposits. Quaternary sediments and faults exposed in an exploratory trench about 200 m east of the Golden fault near the town of Golden document 5.5 m of vertical displacement since the deposition of Verdos Alluvium and the overlying Lava Creek B tephra (about 640 ka), but prior to the development of a soil formed in colluvium that is similar to soils formed in Slocum Alluvium (Scott, 1970; Kirkham, 1977). However, interpretation of this structure is equivocal and the displacement may be due to gravitational processes. Another possible seismogenic fault is located near Valmont Butte, just north of the map area (Scott and Cobban, 1965), where Slocum Alluvium is displaced (Scott, 1970).

Historical records and geologic investigations (Scott, 1970; Kirkham, 1977) suggest that the probability for damaging earthquakes in the Denver West quadrangle is low compared to more seismically active areas of the country (http://nationalatlas.gov/natlas/Natlasstart.asp).

Radon

Radon is a naturally occurring gas that can damage lung tissue and may increase the risk of lung cancer if it is inhaled at a certain level over a period of time. Radon is radioactive and is one of the byproducts of radioactive decay. Elevated radon is of concern, especially in confined areas such as homes and other structures. Most of Colorado, including the area of the Denver West quadrangle, has elevated radon values compared to those in other parts of the country due to uranium- and thorium-rich crystalline rocks and sediments. One out of three homes in Colorado have radon values greater than 4 picocuries per liter (pCi/L), the cutoff value for allowable household radon determined by the U.S. Environmental Protection Agency. Mitigating action is recommended for homes with values greater than 4 pCi/L (Environmental Protection Agency, 1993). Granite and felsic gneiss are relatively radiogenic compared to most other rocks, and surficial deposits, such as alluvium and till derived from Proterozoic bedrock, may have elevated radon values (Otton and others, 1993). The hazard increases with increased permeability; therefore, weathered rock and loose sediment may have a higher radon risk than fresh rock and well-consolidated sediment. Shale (particularly black shale, as in the lower part of the Pierre Shale) can also have elevated radon values (Dubiel, 1993). Testing for radon is relatively easy, and inexpensive remedial procedures are available to mitigate the hazard (Environmental Protection Agency, 1993).

Snow Avalanches

Ever since gold was first discovered in the Front Range west of Denver during the late 1850s, snow avalanches have posed a serious hazard to prospectors, miners, and mine structures. In recent decades, snow avalanches in the mountains have posed an ever-increasing hazard to human life and property due primarily to accelerated growth in both winter-sport activities and the construction of mountain homes (Ives and others, 1976). Snow avalanches can occur anywhere that (1) slopes are steeper than about 25° (90 percent of snow avalanches develop on slopes of 30°–45°), (2) snow accumulates to a sufficient depth, (3) a weak layer or layers develop at depth within the snowpack, and (or) (4) triggering mechanisms initiate snowslides (Colorado Avalanche Information Center, 2000). The prevailing winds in the region are from the west and northwest and most slides start on the lee (downwind) or east side of ridges where snow commonly accumulates. Large avalanches can flow across a valley and move hundreds of meters up the opposite valley side. Triggers for snow avalanches might be a skier, an animal, or a sonic boom, but most avalanches are caused simply by the weight of accumulated snow; avalanches commonly occur when shear stress exceeds shear strength along a weak layer within the snow pack. Established avalanche tracks are commonly devoid of large living trees; broken tree trunks and limbs litter the paths of recurrent avalanches. Snow avalanches locally contain fragments of trees and rocks.

For additional information on geologic hazards, as well as on the environmental geology of the region, refer to reports by Rogers and others (1974), Hansen and Crosby (1982), and other reports cited in this section.

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