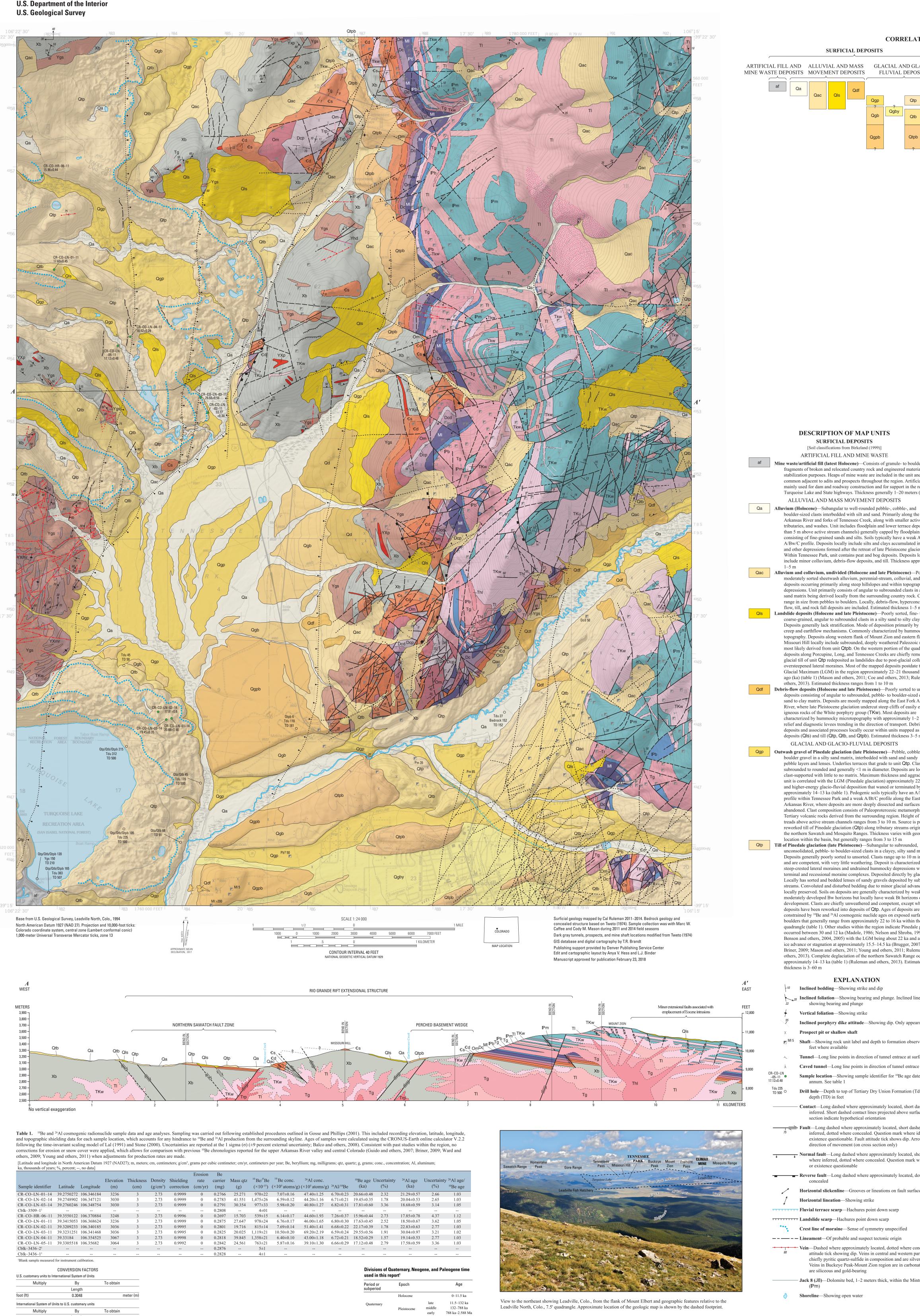
**Scientific Investigations Map 3400** 

## **U.S. Department of the Interior**



2.588-5.332 M

5.332-23.03 M

23.03-33.9 M

33.9-55.8 Ma

55.8–65.5 Ma

Ages of time boundaries are those of the U.S. Geological Survey Geologic Name

are expressed in ka for kilo-annum (thousand years) and Ma for mega-annum

Paleogene

foot (ft)

that, because of differences in rendering processes and pixel resolution, some slight

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**CORRELATION OF MAP UNITS** SURFICIAL DEPOSITS ARTIFICIAL FILL AND ALLUVIAL AND MASS GLACIAL AND GLACIO-MINE WASTE DEPOSITS MOVEMENT DEPOSITS FLUVIAL DEPOSITS PLIOCENE TO LATE CRETACEOUS INTRUSIVE ROCKS ➤ CRETACEOUS **PALEOZOIC SEDIMENTARY** ORDOVICIAN PROTEROZOIC IGNEOUS AND METAMORPHIC ROCKS MESOPROTEROZOI

**DESCRIPTION OF MAP UNITS** Outwash gravel of Bull Lake glaciation (late? and late middle Pleistocene)-SURFICIAL DEPOSITS Pebble, cobble, and boulder gravel in a silty sand matrix underlying terraces. [Soil classifications from Birkeland (1999)] Grades to unit Qtb. Clasts are subrounded to rounded and consist of ARTIFICIAL FILL AND MINE WASTE Paleoproterozoic metamorphic to Tertiary volcanic lithologies derived from the surrounding country rock. Height above stream level ranges from 5 m Mine waste/artificial fill (latest Holocene)—Consists of granule- to boulder-size in Tennessee Park to 20 m along the East Fork Arkansas River. Soils are agments of broken and relocated country rock and engineered material used for generally characterized as A/Bt/C profiles with stage I±II pedogenic carbonate stabilization purposes. Heaps of mine waste are included in the unit and are development. Thickness generally 1–15 m common adjacent to adits and prospects throughout the region. Artificial fill is Younger outwash gravel of Bull Lake glaciation (late? and late middle mainly used for dam and roadway construction and for support in the region of

Furquoise Lake and State highways. Thickness generally 1–20 meters (m) underlying terraces at elevations above and below units Qqp and Qqb. ALLUVIAL AND MASS MOVEMENT DEPOSITS respectively. Soils are generally characterized as those on unit Qgb. Unit mapped on southern margin of quadrangle where younger Bull Lake-age alluvium was Qa Alluvium (Holocene)—Subangular to well-rounded pebble-, cobble-, and deflected to the south by the Bull Lake-age glacier emanating from Mount boulder-sized clasts interbedded with silt and sand. Primarily along the East Fork Arkansas and Fremont Pass east of the map area. Estimated thickness is 1–15 m Arkansas River and forks of Tennessee Creek, along with smaller active streams, Till of Bull Lake glaciation (late middle Pleistocene)—Subangular to subrounded, tributaries, and washes. Unit includes floodplain and lower terrace deposits (less unconsolidated, nonsorted and lacking bedding and stratification, pebble to than 5 m above active stream channels) generally capped by floodplain deposits boulder gravel in a clay, silt, and sand matrix. Deposits generally lie downvalley consisting of fine-grained sands and silts. Soils typically have a weak A/C or from Pinedale terminal moraines (unit Qtp). The original depositional surface A/Bw/C profile. Deposits locally include silts and clays accumulated in kettles morphology has been eroded and smoothed. Boulders are partially to mostly and other depressions formed after the retreat of late Pleistocene glaciers. buried on the surface, and clasts are more weathered than those of unit Qtp. Within Tennessee Park, unit contains peat and bog deposits. Deposits locally Boulders in unit Qtb commonly have oxidized weathering rinds 3–5 millimeters include minor colluvium, debris-flow deposits, and till. Thickness approximately (mm) in thickness and are readily friable. In this northern region of the upper Arkansas Valley, soils on these deposits are generally A/Bt/C profiles with a Alluvium and colluvium, undivided (Holocene and late Pleistocene)—Poorly to 20–30-centimeter (cm)-thick argillic horizon oxidized to slightly red chromas. To moderately sorted sheetwash alluvium, perennial-stream, colluvial, and talus the south of the quadrangle, soils on deposits of this age commonly have stage II deposits occurring primarily along steep hillslopes and within topographic pedogenic carbonate development, but within the mapped quadrangle, Qtb depressions. Unit primarily consists of angular to subrounded clasts in a silty deposits typically have stage I carbonate development and locally discontinuous sand matrix being derived locally from the surrounding country rock. Clasts stage II pedogenic carbonate. Deposits are correlated with those dated in the range in size from pebbles to boulders. Locally, debris-flow, hyperconcentrated

flow, till, and rock fall deposits are included. Estimated thickness 1–5 m

creep and earthflow mechanisms. Commonly characterized by hummocky

coarse-grained, angular to subrounded clasts in a silty sand to silty clay matrix.

Deposits generally lack stratification. Mode of deposition primarily by surface

topography. Deposits along western flank of Mount Zion and eastern flank of

Missouri Hill locally include subrounded, deeply weathered Paleozoic rocks

most likely derived from unit Qtpb. On the western portion of the quadrangle.

deposits along Porcupine, Long, and Tennessee Creeks are chiefly remobilized

glacial till of unit Qtp redeposited as landslides due to post-glacial collapse of

oversteepened lateral moraines. Most of the mapped deposits postdate the Last

Glacial Maximum (LGM) in the region approximately 22–21 thousand years

**Debris-flow deposits (Holocene and late Pleistocene)**—Poorly sorted to unsorted

others, 2013). Estimated thickness ranges from 1 to 10 m

ago (ka) (table 1) (Mason and others, 2011; Coe and others, 2013; Ruleman and

deposits consisting of angular to subrounded, pebble- to boulder-sized clasts in a

sand to clay matrix. Deposits are mostly mapped along the East Fork Arkansas

River, where late Pleistocene glaciation undercut steep cliffs of easily eroded

characterized by hummocky microtopography with approximately 1–2 m of

deposits and associated processes locally occur within units mapped as landslide

relief and diagnostic levees trending in the direction of transport. Debris flow

deposits (Qls) and till (Qtp, Qtb, and Qtpb). Estimated thickness 3–5 m

Outwash gravel of Pinedale glaciation (late Pleistocene)—Pebble, cobble, and

boulder gravel in a silty sand matrix, interbedded with sand and sandy

pebble layers and lenses. Underlies terraces that grade to unit Qtp. Clasts are

subrounded to rounded and generally <1 m in diameter. Deposits are locally

clast-supported with little to no matrix. Maximum thickness and aggradation of

unit is correlated with the LGM (Pinedale glaciation) approximately 22-21 ka

approximately 14–13 ka (table 1). Pedogenic soils typically have an A/Bw/C

profile within Tennessee Park and a weak A/Bt/C profile along the East Fork

Tertiary volcanic rocks derived from the surrounding region. Height of terrace

treads above active stream channels ranges from 3 to 10 m. Source is primarily

reworked till of Pinedale glaciation (Qtp) along tributary streams originating in

the northern Sawatch and Mosquito Ranges. Thickness varies with geomorphic

unconsolidated, pebble- to boulder-sized clasts in a clayey, silty sand matrix.

and are competent, with very little weathering. Deposit is characterized by

steep-crested lateral moraines and undrained hummocky depressions within

Locally has sorted and bedded lenses of sandy gravels deposited by subglacial

moderately developed Bw horizons but locally have weak Bt horizons of stage I

development. Clasts are chiefly unweathered and competent, except where older

streams. Convoluted and disturbed bedding due to minor glacial advances is

locally preserved. Soils on deposits are generally characterized by weak to

deposits have been reworked into deposits of Qtp. Ages of deposits are

boulders that generally range from approximately 22 to 16 ka within the

ice advance or stagnation at approximately 15.5–14.5 ka (Brugger, 2007:

approximately 14–13 ka (table 1) (Ruleman and others, 2013). Estimated

**EXPLANATION** 

**Inclined bedding**—Showing strike and dip

showing bearing and plunge

Vertical foliation—Showing strike

Prospect pit or shallow shaft

depth (TD) in feet

thickness is 3-60 m

constrained by <sup>10</sup>Be and <sup>26</sup>Al cosmogenic nuclide ages on exposed surface

occurred between 30 and 12 ka (Madole, 1986; Nelson and Shroba, 1998;

quadrangle (table 1). Other studies within the region indicate Pinedale glaciation

Benson and others, 2004, 2005) with the LGM being about 22 ka and a possible

Briner, 2009; Mason and others, 2011; Young and others, 2011; Ruleman and

others, 2013). Complete deglaciation of the northern Sawatch Range occurred by

Inclined foliation—Showing bearing and plunge. Inclined lineation arrow

Inclined porphyry dike attitude—Showing dip. Only appears on unit Tg

Shaft—Showing rock unit label and depth to formation observed in shaft in

Caved tunnel—Long line points in direction of tunnel entrace at surface

**Sample location**—Showing sample identifier for <sup>10</sup>Be age dates in kilo-

**Drill hole**—Depth to top of Tertiary Dry Union Formation (Tdu) and total

— **Contact**—Long dashed where approximately located, short dashed where

section indicate hypothetical orientation

Fault—Long dashed where approximately located, short dashed where

direction of movement (on cross section only)

Normal fault—Long dashed where approximately located, short dashed

**Reverse fault**—Long dashed where approximately located, dotted where

Horizontal slickenline—Grooves or lineations on fault surface

• Vein—Dashed where approximately located, dotted where concealed. Vein

attitude tick showing dip. Veins in central and western parts of map

— Jack 8 (J8)—Dolomite bed, 1–2 meters thick, within the Minturn Formation

chiefly pyritic quartz-sulfide in composition and are silver bearing.

Veins in Buckeye Peak-Mount Zion region are in carbonate rocks and

Horizontal lineation—Showing strike

are siliceous and gold-bearing

Shoreline—Showing open water

Landslide scarp—Hachures point down scarp

Fluvial terrace scarp—Hachures point down scarp

Crest line of moraine—Sense of symmetry unspecified

inferred. Short dashed contact lines projected above surface in cross

inferred, dotted where concealed. Ouestion mark where identity or

existence questionable. Fault attitude tick shows dip. Arrows show

where inferred, dotted where concealed. Question mark where identity

**Tunnel**—Long line points in direction of tunnel entrace at surface

Deposits generally poorly sorted to unsorted. Clasts range up to 10 m in diameter

location within the basin, but generally ranges from 3 to 15 m

Arkansas River, where deposits are more deeply dissected and surfaces are

abandoned. Clast composition consists of Paleoproterozoic metamorphic to

and higher-energy glacio-fluvial deposition that waned or terminated by

GLACIAL AND GLACIO-FLUVIAL DEPOSITS

igneous rocks of the White porphyry group (TKw). Most deposits are

Landslide deposits (Holocene and late Pleistocene)—Poorly sorted, fine- to

others, 2002). Thickness varies based on geomorphic position, but is generally estimated to be 5–20 m Outwash gravel of pre-Bull Lake glaciations (middle and early? Pleistocene)— Light brownish-gray to light reddish-brown and orangish brown, weakly stratified, pebble, cobble, and boulder gravel in a clayey, silty sand matrix underlying terraces grading to pre-Bull Lake till (Qtpb). Clasts are subrounded to rounded and generally deeply weathered and grussified. Proterozoic granitic and metamorphic clasts are especially easy to disaggregate by hand. West of Leadville, the unit consists of a few old remnant surfaces preserved on deposits that prograded westward from the Mosquito Range. Surfaces generally lack any original depositional morphology and are buried by greater than about 1 m of loess, leaving few to no boulders and clasts exposed at the surface. Glacial outwash of pre-Bull Lake age that emanated from the Sawatch Range into Tennessee Park is presumed buried by younger deposits due to continuous displacement along the dominantly east-dipping northern Sawatch fault zone. Based on drill hole data of Tweto (1974), deposits of unit Qgpb appear to lie unconformably on the Dry Union Formation and Malta Gravel of Tweto (1961) and mark a dramatic shift in depositional systems at the contact from deposits related to lower-energy, episodic depositional systems (for example, debris flow and alluvial fan deposition) below to weakly bedded and stratified, subrounded to rounded, and sorted glacio-fluvial gravels above. Pedogenic carbonate development is not consistently preserved in these deposits within the quadrangle, but carbonate accumulation and cementation within the gravels is noted to be locally pervasive in adjacent areas (Behre, 1953). Richmond (1983) places the Malta Gravel above and younger than the Lava Creek B ask bed (approximately 640 ka, Lanphere and others, 2002) and older than Bull Lake moraine (approximately 200–130 ka), making these the first definitively recognized glaciogenic deposits in the upper Arkansas River valley to be middle

**Pleistocene**)—Pebble, cobble, and boulder gravel in a silty sand matrix

adjacent Front Range of Colorado with <sup>10</sup>Be and <sup>26</sup>Al cosmogenic radionuclide

exposure minimum age estimates of 101±21 ka and 122±26 ka (Schildgen and

River enters Tennessee Park, Tweto (1974) described older pre-Bull Lake till buried beneath pre-Bull Lake outwash by several meters at most (see geologic map). Thickness varies, but may be as much as 20 m Till of pre-Bull Lake glaciations (middle and early? Pleistocene)—Unsorted, unstratified, deeply weathered boulder gravel in a clayey, silty sand matrix lacking original depositional morphology. Surface clasts are typically absent on the landform and, where exposed, are deeply weathered and easily pulverized in the hand. Mapped at Leadville along the East Fork Arkansas River extending beyond both Pinedale and Bull Lake glacial limits. Deposits mapped at and proximal to Tennessee Pass are interpreted as older till and differentiated from unit Qd to the south based on the geomorphic position to Mount Zion and glaciated No Name Gulch. Minor drainages south of No Name Gulch and north of the East Fork Arkansas River appear to be unglaciated and associated older pre-Bull Lake deposits (unit Qd) adjacent to the range front are interpreted as debris-flow deposits. Thickness varies from 1 to 40 m Diamicton (middle and early? Pleistocene)—Unsorted, unstratified boulder gravel in a clavey, silty sand matrix. Deposits are deeply weathered with almost complete erosion of original depositional landform. Depositional process unknown, but deposits resemble pre-Bull Lake till deposits within the quadrangle. Two possible explanations for the deposits exist. The sediments were either deposited by glaciers emanating from Mt. Zion and the northern Sawatch Range, as part of a previously unrecognized, more regionally extensive ice field, or by debris flows shed off the western flank of Mount Zion within

unglaciated drainages. If these deposits are sourced from the west, then

displacement along the northern Sawatch fault zone has downdropped and buried

these deposits with younger glacial and glacio-fluvial deposits below Tennessee

Pleistocene (788–132 ka; Richmond and Fullerton, 1986), not early Pleistocene

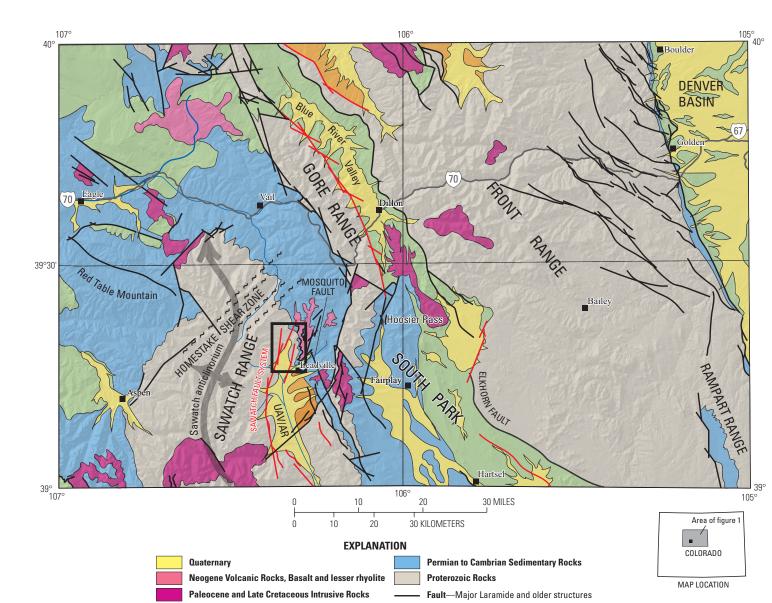
(2.59 Ma–788 ka; Richmond and Fullerton, 1986). Where the East Fork Arkansas

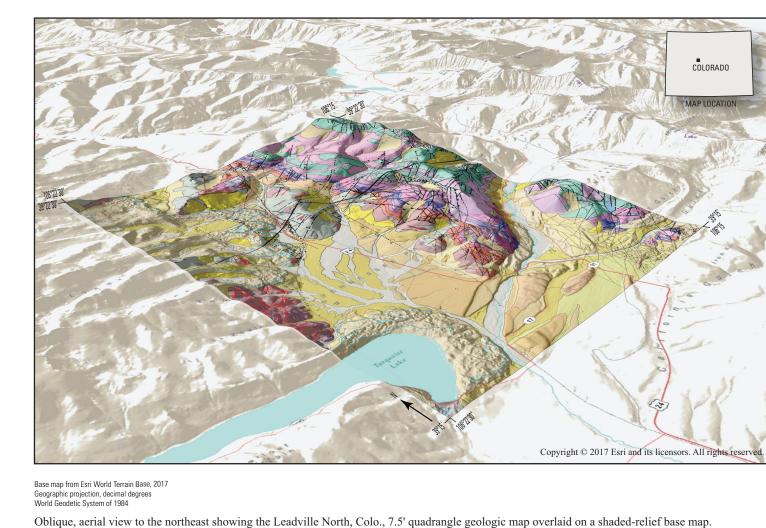
Park, as noted by Tweto (1974) (see unit **Qgpb** description). Estimated thickness PLIOCENE TO LATE CRETACEOUS INTRUSIVE ROCKS **Rhyolite (Pliocene? or Miocene?)**—White to light-gray, fine-grained rhyolite with minor amounts of black vitrophyre. Unit associated with rhyolite breccia in the Leadville region and was emplaced at very shallow depths. The only definitively recognized Tr dikes within the quadrangle lie approximately 1 kilometer (km) east of downtown Leadville on the western flank of Canterbury Hill. Regionally,

dikes tend to be found along the northern Sawatch fault zone and other range-bounding faults Rhyolite porphyry (Oligocene?)—Light-yellow to pinkish-brown, fine-grained rhyolite porphyry with abundant, large (>5 mm) quartz phenocrysts. Secondary phenocrysts consist of sanidine, potassium feldspar, and biotite. Unit is exposed along the southwest side of Tennessee Pass and farther to the north, off the quadrangle. Unit is only exposed within and proximal to normal faults and sheared zones interpreted to be associated with regional extension. Trp is correlated with the approximately 29 million years ago (Ma) Chalk Mountain Porphyry (McCalpin and others, 2012) based on texture and composition in hand specimen, and thus correlative herein. Crosscutting relationships and age constraints in the adjacent Climax, Colo., 7.5' quadrangle (McCalpin and others, 2012) demonstrate that unit is younger than Cretaceous to Eocene igneous intrusive rocks. Close proximity of exposures to rift-related normal faults within the quadrangle and to the north within the Camp Hale region further supports an Oligocene age and rift-related emplacement. Due to structural and hydrothermal alteration, exposures of unit within quadrangle are not optimal for dating or

chemical analyses Hornblende latite porphyry (Eocene?)—Pink-gray to dark greenish-gray, porphyritic granodiorite sills and dikes mapped on the southwestern ridge of Mount Zion. Based on composition, unit correlated with the Eagle River Porphyry and assigned an Eocene age. However, no absolute age has been determined and the Gray porphyry group (Tg) is intruded by Thl, suggesting unit Thl could be as young as Oligocene Tg Gray porphyry group (Eocene)—Includes the Evans Gulch, Johnson Gulch, and Mount Zion Porphyries of Emmons and others (1927) and Behre (1953) and the

Sacramento Gulch and Eagle River Porphyries of Tweto (1974). Widely exposed along the western flank of Mount Zion as a domed laccolith and accompanying sills within the Minturn Formation (Pm). All of these porphyries are generally gray to greenish-gray, and locally bluish-gray, porphyritic monzogranite or granodiorite with phenocrysts of plagioclase, quartz, and biotite <10 mm in diameter in a microcrystalline groundmass. Locally contains large hornblende phenocrysts <5 mm. Generally weathers as plates and slabs that are light yellowish brown to grayish white in color. The youngest pluton of this sequence, the Johnson Gulch Porphyry, has a zircon fission-track age of 43.1±4.3 Ma (Thompson and Arehart, 1990) and a recent U-Pb zircon age of 39.5±0.6 Ma (Kellogg and others, 2017) from adjacent areas outside the quadrangle. Previous work separated these individual stocks and plutons based on geographic location and local minor variations in petrology and appearance. Herein, these units are combined to illustrate the local extent of late Eocene magmatic activity expressed as sills and laccoliths intruded into the Paleozoic country rocks. Tweto (1974) originally described the Sacramento Gulch Porphyry as being cut by the Lincoln Porphyry (TI), but crosscutting relationships east of Tennessee Pass demonstrate that the Lincoln Porphyry is older. Locally contains inclusions of White porphyry group (TKw) and Lincoln Porphyry (TI), which further complicates the interpretation of structural and intrusive relationships. Similar approximately 40 Ma biotite K-Ar and zircon-sphene-apatite fission-track ages have been documented to the east, at the northern end of South Park (Bryant and Naeser, 1980; Bryant and others, 1981; Ruleman and others, 2011)





Paleocene to Jurasic Sedimentary Rocks —— Active fault—Definitive Pleistocene activity Figure 1. Geologic setting of the Leadville North, Colo., 7.5' quadrangle. Black box indicates location of mapped quadrangle. Major Laramide and older structures shown by heavy black lines. Faults having definitive Pleistocene activity shown by heavy red lines. [UAV, Upper Arkansas

Lincoln Porphyry (Eocene)—Exposed as a main sill body on Cooper Hill and the western flank of Buckeye Peak and Chicago Ridge in northeastern part of quadrangle. Gray to light pinkish-gray porphyritic monzogranite with phenocrysts of mainly orthoclase and quartz <1 cm long and rare biotite and hornblende (Behre, 1953). Unit is crosscut by the Gray porphyry group (Tg), but the age is problematic. Earlier biotite K-Ar ages of 62 Ma (Pearson and others, 1962) and 64.6 Ma (McCalpin and others, 2012) are in conflict with a more recent biotite K-Ar age of 44.1±1.6 Ma (Marvin and others, 1989) and fission-track dates of 36.7±3.9 Ma and 48.6±6.6 Ma on apatite and 40.1±3.9 Ma and 41.5±3.7 Ma on zircon (Mach, 1992) on rocks of very similar composition and appearance. Based on geologic mapping by Tweto (1974) and the complex intrusive history of the region, which leads to difficulty in differentiating units, we interpret the older Paleocene ages as measurements of xenolithic bodies and inclusions of the older White porphyry group (TKw) within the Lincoln Porphyry, Region stippled on the west flank of Buckeye Peak indicates whe strong secondary, shallow fluid-rock, deuteric alteration occurred TKu Undivided porphyries (Paleocene and Upper Cretaceous)—Generally white, red, yellow, and brown, highly altered and sheared porphyries of varying composition. Unit exposed within shear zones and faults associated with Late

Valley; AR, Arkansas River]

Cretaceous and Paleocene deformation along the western flank of Missouri Hill and within a dike along the southern flank of Mount Zion TKW White porphyry group (Paleocene and Upper Cretaceous)—White to yellowish brown, cryptocrystalline to aphanitic porphyritic rhyolite and monzogranite. Composed primarily of visible quartz and biotite <2 mm in a fine-grained groundmass of quartz, biotite, and plagioclase. Common accessory minerals include magnetite, zircon, apatite, and hornblende (Cappa and Bartos, 2007). Exposed along the western flank of Mount Zion as sills subparallel to bedding within the Minturn Formation (Pm). Intrusive body thickens to the southsoutheast into domed sills and small stocks in the Mount Sherman quadrangle (Bohannon and Ruleman, 2013). Unit includes the Pando Porphyry of Tweto (1951, 1974) with biotite K-Ar ages of 70 Ma (Pearson and others, 1962) and 71.8 Ma (Cunningham and others, 1994) and a more recent U-Pb zircon age of 64.1±0.9 Ma (Kellogg and others, 2017).

PALEOZOIC SEDIMENTARY ROCKS The Paleozoic section of sedimentary rocks crops out in the eastern part of the quadrangle. Most exposures are very limited except in the northeastern area within the Eagle River drainage and the western flank of Chicago Ridge and Mount Zion. Much of the detailed bedrock mapping is based on float on colluvial slopes and adit, prospect, and shaft data (see geologic map for locations) collected by Ogden Tweto during the years 1948–1953. Descriptions of units are from local exposures of units and extrapolated from concealed subsurface exposures (Tweto, 1974) and adjacent regions where exposure is more extensive (McCalpin and others, 2012; Bohannon and

Minturn Formation (Middle Pennsylvanian)—Predominantly light-gray to grayish-brown, fine- to coarse-grained arkosic sandstone interbedded with pebble-cobble conglomerate and calcareous shale. Calcareous shale and thin limestone beds occur towards the base of the formation. Weathers grayish-brown to reddish brown. Clasts in conglomerate are predominantly quartzite and chert. Section of the Minturn within quadrangle is mainly that of the "gray-brown facies" of Bohannon and Ruleman (2013), a section named for its diagnostic weathering and (or) alteration color around the Mount Sherman area to the east, but not diagnostic within this quadrangle. Tweto (1974) subdivided eight limestone members within the formation. Some of these members higher in the stratigraphic section are not within the quadrangle, but have been mapped in adjacent regions (Widmann and others, 2004, 2005; Widmann and others, 2006; McCalpin and others, 2012). The base of the Minturn Formation is defined as a coarse-grained sandstone and pebble conglomerate overlying the Belden Formation (Pb) black shale sequence. This coarsening upward sequence in the Minturn Formation, above the Belden Formation, was originally called the Weber Formation by Emmons (1886) and Behre (1953). In the northeast quadrant of the map, the 1–2 m-thick Jack 8 dolomite bed (J8) (Tweto, 1974) is a red-, green-, and light brown-mottled, coarse-grained dolomite with abundant chert and jasper grains occurring approximately 150 m above the base of the Minturn in the region. Thickness of the Minturn Formation is estimated to range from approximately 1,000 to 1,200 m within the quadrangle, but is unknown due to the profuse intrusive history and magmatic inflation of the region Belden Formation (Middle and Lower Pennsylvanian)—Dark gray to black, aminated to massively bedded shale interbedded with thin-bedded gray to dark gray limestone and dolomite. Shale is commonly calcareous and (or) carbon-

contain layers of fossil hash. Contains minor amounts of interbedded light gray to olive-gray, fine-grained, arkosic sandstone. Locally, shale layers contain plant fragments and petrified wood. Formation generally forms a subtle swale in topography within the stratigraphic section. Lies unconformably above the Mississippian Leadville Limestone (MI) on an irregular, karst-erosional surface (Tweto, 1974) with moderate pre-existing topographic relief (<10 m), which contributes to the irregular thickness of the formation. Within the quadrangle, thickness varies due to extensive replacement and remobilization of shales during the Paleocene to Oligocene intrusive sequence, but is generally 20–30 m. The Belden Formation thickens substantially to the east and southeast to as much as 360 m in the Jones Hill 7.5' quadrangle (Widmann and others, 2011) and 230 m in the Fairplay West 7.5' quadrangle (Widmann and others, 2006). Within the Climax 7.5' quadrangle (McCalpin and others, 2012), the Minturn and Belden Formations were mapped as a single unit eadville Limestone (Lower Mississippian)—Medium-gray, micritic limestone and pitted dolomite grading down section into bluish-black, fine-grained dolomite containing abundant well-rounded and fragmented black chert pebbles and cobbles. Bedding is generally massive and irregular. Brecciated zones are found throughout the unit and are interpreted as evidence for paleokarst activity

aceous within the quadrangle. Limestone beds are locally fossiliferous and

quartzite with limestone rip-up clasts called the Gilman Sandstone member of the Chaffee Group (Tweto and Lovering, 1977; Kirkham and others, 2012). Formation unconformably overlies the Devonian Chaffee Group (Dc). Thickness ranges from 40 to 50 m Chaffee Group, undivided (Upper Devonian)—I Parting Sandstone of Chronic (1964) described below. Units mapped as a group where exposure and structural relationships obscure the stratigraphy. Total thickness ranges from 30 to 50 m **Dyer Dolomite**—Fine-grained, sparry, thin- to massive-bedded dolomite. Generally, unit grades from light gray to dark gray and weathers to a mottled yellowish-gray to brownish-gray color. Locally contains thin lenses (<5 mm) of

(Maslyn, 1977; Beaty and others, 1990). Grades down section to a basal

yellowish-brown to white, thin-bedded, discontinuous-bedded sandstone and

shale and (or) chert. Considered part of the "Blue Limestone" at Leadville by Tweto (1974). Conformably grades from the underlying Parting Sandstone (Dcp) (Chronic, 1964). Thickness 20–30 m Parting Sandstone—White to light-gray, fine- to medium-grained, well-rounded, well-sorted quartzite and sandstone with minor interbeds of dolomitic sandstone. Finer-grained dolomitic sandstone beds weather a reddish-yellow brown and quartzite layers weather bright white. Typically contains a coarse pebble conglomerate at the base. Locally contains thin layers and lenses of shale and (or) chert. Thickness varies, but is generally 10–20 m Ianitou Dolomite (Lower Ordovician)—Light-yellowish-gray to dark-gray, thin- to thick-bedded sandy dolomite and dolomite. Weathers yellowish- to reddish-brown and commonly has rough, angular surfaces (Tweto, 1974). Commonly contains whitish-gray to black laminated chert nodules, blebs, and

stringers. The lowermost 1–3 m have been called the "red cast beds" (Emmons, 1886) and were formerly considered the upper member of the Peerless Formation (Behre, 1953). However, more recent paleontologic investigations place these beds within the Taylor Pass Member of the Manitou Dolomite (Myrow and others, 2003). The Taylor Pass Member section is characterized by thick (about 1 m), tabular dolomite beds with oxidized red spots that are <0.5 cm in diameter. Locally contains crinoids, gastropods, echinoderms, nautiloids, and trilobite fragments (Houck and others, 2012). The Manitou Dolomite pinches out to the north towards Tennessee Pass where it is unconformably overlain by the Devonian Chaffee Group (Dc). Thickness averages between 30 and 40 m **Dotsero Formation (Upper Cambrian)**—Interbedded fine- to medium-grained sandstone grading upward to dolomitic sandstone and silty, sandy dolomite. Generally weathers to a reddish-brown and purple-brown color. Formerly mapped as the Peerless Formation (Behre, 1953; Tweto, 1974). Beds within the lower, more quartzose section are tabular and typically 0.5–1.0 m in thickness. Beds thin upwards into the more dolomitic section and are generally wavy, subparallel, and range from a few centimeters to 25 cm in thickness. Overall thickness is 20–30 m

Sawatch Quartzite (Upper Cambrian)—Fine- to coarse-grained, medium- to thick-bedded, white, light-vellowish-brown, and reddish-brown quartzite and finer-grained sandstone unconformably overlying Mesoproterozoic and Paleoproterozoic rocks on a planar to low-relief surface (Tweto, 1974). Sandstone is locally glauconitic. Generally moderately to well-sorted, and grains are subrounded to rounded. Typically has a 10 cm-1 m-thick hasal conglomerate with well-rounded, quartz-pebble clasts. Beds range in thickness from 1 cm to 1 m and are distinguished by variations in resistance and color. Thickness ranges from 30 to 40 m

## PROTEROZOIC IGNEOUS AND METAMORPHIC ROCKS

Yhd Hornblende diorite dike (Mesoproterozoic?)—Gray to dark gray to green, medium-grained, hornblende-rich diorite dikes on the north side of Missouri Hill. Truncates Paleoproterozoic host-rock foliations. Hosts metalamprophyres and St. Kevin batholith within the Homestake Reservoir region to the west St. Kevin Granite (Mesoproterozoic)—Medium- to coarse-grained, gray to light-pinkish-gray and pinkish-brown, euhedral equigranular to porphyritic, massive to locally weakly foliated biotite-muscovite monzogranite, with local gradational and facies changes to granodiorite and other textural variations (Pearson and others, 1962; Tweto and Pearson, 1964; Tweto, 1974, 1987). The main batholith is characterized by a central region of coarse-grained trachtytic monzogranite grading outward into medium-grained monzogranite and eventually to fine-grained, foliated monzogranite and granodiorite with seriate-to-porphyritic texture commonly having Carlsbad twinning in aligned microcline phenocrysts. Within the map area, medium-grained, euhedral monzogranite is the common phase of the main plutonic body. Batholith has been previously assigned to the Silver Plume intrusive event (Stark and Barnes, 1935; Behre, 1953). Rb-Sr isochron age is 1,390±60 Ma (Pearson and others, 1962), and a more recent U-Pb age from outside the quadrangle is 1,444±15 Ma (Moscati and others, 2012)

egmatite and aplite (Mesoproterozoic? and Paleoproterozoic?)—Fine- to coarse-grained to megacrystalline, white to light-pink and red, inequigranular quartz-feldspar-biotite-muscovite rock that intrudes all metamorphic and igneous Proterozoic rocks in the quadrangle. Biotite is the predominant mica. Forms zoned, linear dikes and veins typically with fine-grained, "chilled," aplitic textures formed towards the margins and within latest-phase intrusions. Also forms concentrated blebs, pods, and stringers as much as 10 m in width. Pegmatites within and proximal to the St. Kevin batholith generally contain sparse black tourmaline and beryl (Tweto, 1974). Pegmatite and aplite are similar in composition, but aplite is generally light pinkish-brown to gray, fineto medium-grained, and leucocratic, which can be similar in appearance to

Mesoproterozoic St. Kevin Granite (Ygs)-associated rocks, especially the finer-grained, marginal phases. Crosscutting relationships indicate that pegmatite and aplite are associated with late-stage intrusive processes and occur within both the Paleoproterozoic Routt Plutonic Suite (about 1,700 Ma) and

Mesoproterozoic Berthoud Plutonic Suite (about 1,400 Ma) of Tweto (1987). Pegmatite and aplite rocks mapped within the quadrangle appear to be undeformed Ionzogranite, granodiorite, biotite gneiss and schist, and pegmatite, undivided (Mesoproterozoic and Paleoproterozoic)—Medium-gray to black, grayish-pink, light-pinkish-brown to light-brown, fine- to coarse-grained biotite gneiss and schist profusely intruded by phases of predominantly units Ygs and YXp. Mineralogy is generally consistent with the parent rock and younger intrusive complexes consisting of biotite, hornblende, plagioclase, microcline, and quartz. Unit is mapped around the peripheries of the St. Kevin batholith and associated stocks and other textural and (or) gradational phases where the ntrusive component and country rock are in relatively equal volumetric proportions. Exposures show complicated intrusive relationships and assimilation of country rock, which consists predominantly of unit Xb in this region. Ptygmatic folding, boudinage, and sigmoidal structures are commonly found. Xenolithic bodies have diffuse boundaries and locally internal, intense ptygmatic folding. Unit was mapped in adjacent regions to distinguish profusely intruded country rock from areas of more distinct metamorphic and igneous rocks (Ruleman and others, 2011; Bohannon and Ruleman, 2013). Due to complex intrusive and petrologic relationships associated with plutonic metamorphism and assimilation of the country rock, unit is commonly confused with other "migmatitic" rocks in the region that were formed by older regional, burial dynamothermal metamorphism

Biotite gneiss (Paleoproterozoic)—Light-gray to black, fine- to coarse-grained, weakly foliated to strongly foliated and layered gneiss and schist. Mineralogy composed chiefly of quartz, plagioclase, microcline, biotite, and hornblende. Sillimanite is common. Common accessory minerals include rutile, sphene, apatite, garnet, and zircon. Locally, garnets are as much as 1 cm in diameter. Unit Xb contains minor amounts of interlayered amphibolite, hornblende gneiss, quartzite, and calc-silicate rock, especially within the northwest part of the quadrangle. Rocks are predominantly of metasedimentary and metavolcanic origin (Tweto, 1987). Correlated with similar metasedimentary rocks within the adjacent Gore and Front Ranges, with detrital zircon U-Pb ages ranging from approximately 1,785 to 1,750 Ma (Kellogg and others, 2008, 2011). Wallace (1993) concluded that the rocks were deposited between 1,770 and 1,700 Ma and metamorphosed between 1,750 and 1,670 Ma

## GEOLOGIC FRAMEWORK AND HISTORY

The U.S. Geological Survey (USGS) Leadville North quadrangle lies at the northern end of

the Upper Arkansas Valley (UAV; fig. 1), where the Continental Divide at Tennessee Pass creates a low drainage divide between the Colorado and Arkansas River watersheds. The quadrangle includes portions of the San Isabel and White River National Forests within Lake County. In the eastern half of the quadrangle, the Paleozoic sedimentary section dips generally 10–30° east towards the Mosquito fault (McCalpin and others, 2012), a high-angle, west-dipping, Neogene normal fault cutting the eastern margin of the Sawatch anticlinorium. This broad, north-south trending antiformal uplift, is cut by high-angle, axial reverse faults, and extends northsouth about 120 kilometers (km) from approximately Vail to Salida, Colo., and east-west about 70 km from approximately Fairplay to Aspen, Colo. (Tweto, 1975). Minor displacements along high-angle, east- and west-dipping Laramide-age reverse faults occurred in the core of the northblunging anticlinorium along the western and eastern flanks of Missouri Hill in the north-center of the map. Mesoproterozoic and Paleoproterozoic metamorphic and igneous rocks are uplifted along the generally east-dipping, high-angle Sawatch fault system and are overlain by at least three generations of glacial deposits (units Qtpb, Qtb, and Qtp) in the western part of the quadrangle. The Paleoproterozoic rocks within the quadrangle are chiefly composed of biotite gneiss and schist (unit Xb) and are part of the Paleoproterozoic Colorado province (Bickford and others, 1986). These metamorphic rocks were originally deposited and (or) intruded as marine sediments interlayered with mafic and felsic rocks along the southern margin of the Archean North American craton between 1,780 and 1,730 Ma (Bickford and others, 1986; Boardman and Condie, 1986; Aleinikoff and others, 1993; Reed and others, 1993; Chamberlain, 1998; Mueller and Frost, 2006; Premo and others, 2007). These rocks were accreted to the present southern border of Wyoming as a series of island arcs and back-arc basin deposits during the Medicine Bow orogeny of Chamberlain (1998) between 1,780 and 1,740 Ma.

Following this continental suturing event, Mesoproterozoic rocks of the Berthoud Plutonic Suite (Tweto, 1987) intruded the region as large batholiths. The St. Kevin Granite (U-Pb age 1,444±15 Ma; Moscati and others, 2012) is one in this quadrangle. All of the Mesoproterozoic granitic rocks in the region are very similar in mineralogy and texture, indicating a period in which large, regional batholiths were emplaced. Areas mapped as mixed rock (unit YXmr) surrounding the igneous bodies of the St. Kevin Granite were originally called migmatite by Tweto (1974). However, upon closer examination, they show more intrusive relationships than depth burial metamorphism. We interpret these areas to be country rock of chiefly unit Xb that has been extensively intruded and partially assimilated into stocks and plutons of the St. Kevin Granite. Pegmatites in the quadrangle are within and crosscut all Paleoproterozoic and Mesoproterozoic rocks, demonstratng complex relationships between multiple Proterozoic, and possibly younger, geologic events. With the onset of the Paleozoic era, shallow seas extended across this region and most of North America. Sedimentary rocks within the quadrangle associated with this period begin with the transgressive Upper Cambrian Sawatch Quartzite (CS), lying unconformably on a relatively flat Neoproterozoic or Early Cambrian erosional surface, and end with the Middle Pennsylvanian Belden Formation (Pb). Interim Paleozoic transgressive-regressive marine sequences are preserved within the Dotsero Formation (Cd) through the Leadville Limestone (Ml). During the Middle Pennsylvanian, the orogeny that formed the Ancestral Rockies began (De Voto, 1980), uplifting Proterozoic basement rock and eroding the overlying Paleozoic sedimentary section. Uplift associated with this orogenic event is generally marked by Middle Pennsylvanian Minturn (Pm) and Permian Maroon Formations unconformably overlying Proterozoic rocks. Within the quadrangle, the only evidence for the Ancestral Rockies orogenic episode is the regressive, coarser clastic Minturn Formation overlying the Belden Formation. Following the event that formed the Ancestral Rockies, the region underwent a long interval

encroachment of the Western Interior Seaway and deposition of thick, Cretaceous marine sediments. During the Late Cretaceous to Paleocene Laramide orogeny, contractional deformation formed the broad Sawatch anticlinorium, and the White porphyry group (TKw) (71.8–64.1 Ma; Tweto, 1974), which includes the Pando Porphyry, was emplaced. Based on the amount of displacement within the Laramide-age (Paleocene-Cretaceous), basement-cored structure (as observed occurred on faults in this uplift, and structural change was mainly regional upwelling on a broad arch. Igneous activity continued from the Paleocene into the Eocene, lasting from 62 to 40 Ma (Pearson and others, 1962; Kellogg and others, 2017). Within the quadrangle, these 62–40 Ma intrusive units include the Lincoln Porphyry (TI) and Gray porphyry group (Tg), which have been subdivided during previous mapping into various geographic location names (Behr, 1953; Tweto, 1974), but have no substantial compositional distinction from one another. As the Laramide orogeny and associated igneous activity waned in the Eocene (Tweto, 1975), broad erosional surfaces began to form across central Colorado and the southern Rocky Mountains (Epis and Chapin, 1975). Remnants of these broad erosional surfaces are not found within the quadrangle, but these relict surfaces are preserved farther south along the southern end of the Mosquito Range and to the east in South Park and in the Front Range (Epis and Chapin, 1975; Chapin and Cather, 1983; Chapin and Kelley, 1997; Kirkham and others, 2006; Ruleman and others, 2011; Houck and

of erosion that lowered the topography. By Late Jurassic, the region was relatively flat, allowing

others, 2012; Kirkham and others, 2012). Following the late Eocene erosional interval, regionally extensive Oligocene volcanism began, and is generally associated with inception of the Rio Grande rift and extensional deformation in the region (Tweto, 1979; Kirkham and Rogers, 1981; McCalpin and others, 2012). This is represented in the quadrangle by normal faulting, uplift, and exhumation of the Sawatch anticlinorium. Oligocene volcanic rocks (Trp) have very limited exposure within the quadrangle. Based on the regional spatial distribution of Oligocene volcanic centers in adjacent and more northerly locations (for example, hypabyssal rocks of unit Trp about 29 Ma at Camp Hale and down the Eagle River Valley; McCalpin and others, 2012), it is possible that a larger, buried Oligocenesourced pluton and (or) stock exists in the subsurface of the quadrangle. Tweto and Case (1972) attempted to differentiate the pluton sequence in the subsurface using geophysical data to differentiate Cretaceous–Eocene intrusives from the country rock and the extensive St. Kevin batholith. Higher resolution gravity and aeromagnetic data, coupled with the extensive drill-hole data in the region, would be needed to better constrain these interpretations of significant rift-related, Oligocene intrusive activity in the subsurface.

The western margin of the upper Arkansas Valley graben is bound by the east-dipping northern Sawatch fault zone (NSFZ). Discontinuous lineaments and linear bedrock escarpments occur along the trace of the NSFZ west of Tennessee Pass. No displacement of late Pleistocene, or Last Glacial Maximum (LGM) (about 22 ka), deposits and landforms was identified on the NSFZ south of the quadrangle by Widmann and others (1998) and Ostenaa and Nelson (2002), nor was any identified during this mapping effort. However, relict bedrock escarpments, lineaments, and depressions suggestive of prior Quaternary displacement are present to the west of Tennessee Pass and generally trend north-northwest. During the Pleistocene, multiple glacial cycles eroded and exhumed older rock units. Within

the quadrangle, glacial deposits associated with three Marine Oxygen Isotope Record stages (MIS; 2, 6, and possibly one definitive glacial episode during MIS10-8 [about 374-243 ka]; Lisiecki and Raymo, 2005) have been identified. Immediately west-northwest of the town of Leadville, glacial deposits of the oldest stage (pre-Bull Lake) extend much farther west than subsequent glaciations and most likely converged with the pre-Bull Lake Turquoise Lake terminal complex. Later Bull Lake and Pinedale glaciations (MIS 6 and MIS 2, respectively) were less extensive and glacial complexes from the Mosquito and Sawatch Ranges did not converge west of Leadville at the Turquoise Lake terminal moraine complex. New cosmogenic ages presented herein are generally consistent with ages of other LGM (about 22-21 ka) and deglaciation (about 14-13 ka) deposits in the region (Young and others, 2011). Madole (1986) defines the LGM to have occurred between 30-12 ka. Two outlying ages of  $29.55\pm0.6$  and  $30.04\pm0.97$  ka for  $^{10}$ Be and  $^{26}$ Al, respectively (table 1, sample CR–CO–LN–03–11), were determined from boulders on the LGM terminal moraine approximately 8 km below its source-region cirque, yielding a glacial growth-and-advance rate from circue headwall to terminal moraine from about 30 to 22 ka of 1 meter per year (m/yr). This rate is strikingly similar to the LGM deglaciation rate from recessional moraines on the eastern flank of Mount Massive proposed by Mason and others (2011) and Ruleman and others (2013) of 1 m/yr from 22 to 14 ka.

## FAULT MAPPING AND SUBSURFACE DATA

Surficial faults have been mapped based on displaced surficial deposits and disrupted geomorphic landforms, drainages, and fluvial trends along discontinuous lineaments of suspect tectonic origin. Original bedrock faults of Tweto (1974) were field checked and remapped for lateral continuity, displacement of consecutive units, and structural significance. Based on this work, bedrock faults have been simplified and organized into a structural framework, in an attempt to eliminate the confusing myriad of minor faults and fractures produced from tectono-magmatic emplacement processes clearly having occurred in the region. Stratigraphic relationships and subdivision of units and contacts within the Paleozoic section were originally mapped by Tweto (1974) as part of an extensive subsurface survey during 1948-1959. Underneath the town of Leadville, the complex fault and fracture pattern of Tweto (1974) was retained on this map to demonstrate the complexity involved in any future structural or hydrologic modeling of the area. Elsewhere, conealed and inferred fault projections from Tweto (1974) across newly mapped areas of surficial deposits have been simplified to eliminate over interpretation of fault linkage and improve geologic map clarity. Subsurface depth measurements and locations are shown on the map and the unit nomenclature, labeling, and interpretation of Tweto (1974) has been updated to include new tectonic interpretations of aggradation of sequential glacial deposits (for example, Tweto's unit Qd, "Diamicton," to a depth of 200 feet in the subsurface is changed to Qtp, Qtb, and Qtpb)

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