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Leadville South Quadrangle Geologic Map, Lake County, Colorado

Authors' Notes

Includes Description of Map Units, Structural Geology, Geologic Hazards, Mineral Resources, and Ground-Water Resources

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Leadville South Quadrangle Geologic Map,
Lake County, Colorado

Panoramic photo of the northern half of the Leadville South quadrangle, looking northeast from the western boundary of the quadrangle at Half Moon Creek. The City of Leadville is visible at left center, and the Arkansas River flows from left to right across the middle of the photo. The high peaks of the Mosquito Range, visible in the distance, lie just northeast and east of the quadrangle boundaries. [UTM27 381270, 4339480]

by

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FOREWORD

The purpose of Colorado Geological Survey's (CGS) *Leadville South Quadrangle Geologic Map, Lake County, Colorado* is to describe the geology, mineral and ground-water resource potential, and geologic hazards of this 7.5-minute quadrangle located south of Leadville in central Colorado. Consulting geologists James P. McCalpin and Jonathan Funk, and field assistant David Mendel completed the field work on this project during the summer of 2008. Dr. McCalpin and Mr. Funk, the principal mappers and authors, created this report using field maps, photographs, structural measurements, and field notes generated by all three investigators.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and the CGS. USGS funding comes from the STATEMAP component of the National Cooperative Geologic Mapping Program, award number 08HQAG0094, authorized by the National Geologic Mapping Act of 1997, reauthorized in 2009. CGS matching funding comes from the Colorado Department of Natural Resources Severance Tax Operational Funds, from severance taxes paid on the production of natural gas, oil, coal, and metals in Colorado.

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ACKNOWLEDGMENTS

Numerous land owners and land managers granted us access to areas throughout the quadrangle. John Morrisey (District Ranger) and Nick Garrich (seasonal hydrologist), Leadville Ranger District of the San Isabel National Forest, assisted us in surveying the area between Iowa Gulch and Dry Union Gulch. Jim Moyer gave permission to cross his ranch at the mouth of Thompson Gulch. Mike Whittle, manager of Beaver Lakes Estates in Empire Gulch, assisted us in accessing roads in that area. Dan Jensen, manager of the Leadville Airport FBO, permitted access to the exposures in the airport grounds. Personnel of the Lake County Public Library in Leadville shared copies of their early government publications on the Leadville Mining District.

We enjoyed several days in the field with US Geological Survey personnel who were mapping the Leadville 1:100,000 sheet, including Cal Ruleman, Ralph Shroba, Bob Bohannon, and Mick Kunk. Shannon Mahan collected luminescence samples of lacustrine deposits for later dating. Dustyn Sale (Colorado School of Mines) assisted us in the field from July 23-25, 2008.

Figure 1. Google Earth view of the Leadville South quadrangle (outlines in red); view is to the north.

INTRODUCTION

PREVIOUS WORK

The Leadville South 7.5’ quadrangle (Figs. 1, 2) includes the southern half of the city of Leadville, Colorado, the highest city in the United States (official elevation 10,152 ft). The quadrangle lies within the old USGS Leadville 30’ quadrangle (e.g., Capps, 1909; Tweto and Case, 1972), and the NE quarter of the USGS Mount Elbert 15’ quadrangle (e.g., Tweto and Reed, 1973). Parts of the quadrangle had been previously mapped at scales larger than this map (1:24,000) as part of various mining districts (Table 1), and several adjacent quadrangles have been recently mapped at 1:24,000 scale (Fig. 3). More detailed mapping of the Quaternary geology was performed by the US Bureau of Reclamation in the late 1970s as part of studies for Twin Lakes Reservoir (USBR, 1981; Nelson and Shroba, 1998).

Table 1. Previously published geologic maps that cover parts of the Leadville South 7.5’ quadrangle.

Part of Quadrangle Mapped	Scale of Map	Reference
Extreme NE corner (Leadville Mining District)	1:4,800-1:9,600	Emmons, 1886; Emmons and Irving, 1907; Emmons and others, 1927
NE quadrant (west slope of Mosquito range)	1:12,000	Behre, 1953
Entire quadrangle (NE ¼ of the Mt. Elbert 15’ quadrangle)	1:62,500	Tweto and Reed, 1973
Entire quadrangle (compilation)	1:50,000	Cappa and Bartos, 2007

OVERVIEW OF GEOLOGIC SETTING AND FINDINGS

The Leadville South quadrangle lies in the valley of the upper Arkansas River, which is coincident with the Rio Grande rift in central Colorado. The quadrangle includes the eastern rift boundary where the Mosquito Range rises above the valley floor (frontispiece). The Mosquito Range is cored by Proterozoic granite, which outcrops all along the eastern part of the quadrangle except in the northeastern part. There, in the Leadville Mining District, basement rocks are overlain by a series of Paleozoic sedimentary rocks (carbonates and clastics) that are intercalated with Tertiary sills and dikes. These Tertiary intrusives and their contact aureoles with the Paleozoic host rocks are the source of the rich gold- silver-lead-zinc ores of the Leadville mining district. Proterozoic and Paleozoic rocks are faulted down to the west along a series of closely-spaced north-south-trending normal faults (step faults) that form the eastern boundary of the Rio Grande rift. The master fault of the eastern rift margin, the Mosquito fault, generally lies east of the quadrangle.

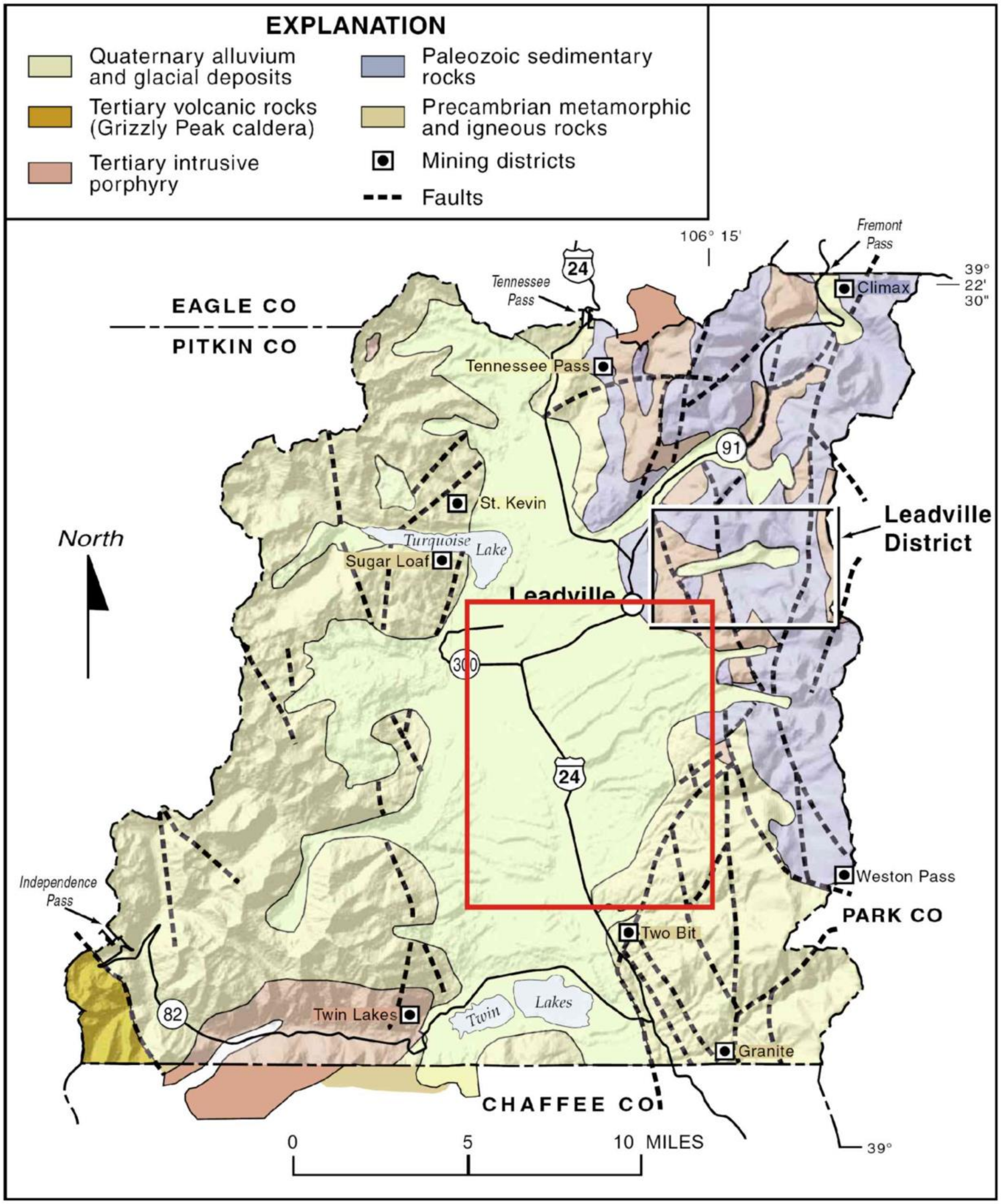

Figure 2. Simplified geologic map of Lake County, Colorado (from Cappa and Bartos, 2007), showing the location of he Leadville South quadrangle (red outline). The extreme northeast corner of the quadrangle overlaps the historic Leadville Mining District (rectangle).

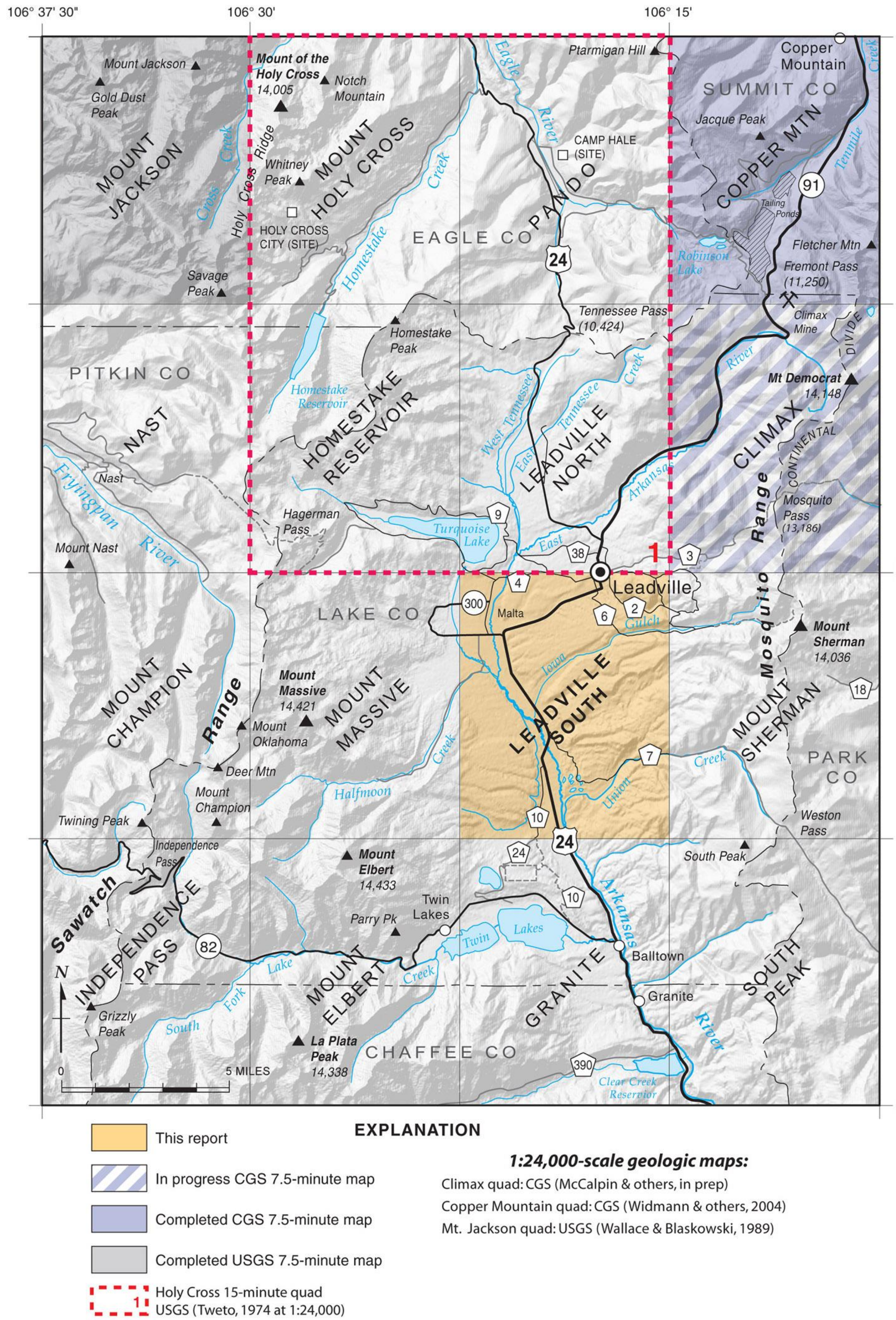

Figure 3. Location map and index of selected published geologic maps in the vicinity of the Leadville South quadrangle (yellow).

Pre-Tertiary rocks occupy an area of about 7.5 square miles along the eastern edge of the quadrangle (Fig. 2), covering only 13% of the total area of the quadrangle (57.6 square miles). The remainder of the quadrangle is underlain by semiconsolidated Tertiary rift-valley sediments (the Dry Union Formation, Miocene-Pliocene) and overlying unconsolidated Quaternary deposits. Tertiary sediments outcrop on the sides of high terraces flanking the Arkansas River. These terraces mark the early Pleistocene valley floor and have been incised several hundred feet by the Arkansas River and its tributaries during the middle-to late Pleistocene. Terraces are capped with Quaternary gravels that in some cases can be traced to terminal moraines of Pleistocene glaciers from the Sawatch and Mosquito Ranges. In late Quaternary time similar moraines downstream of the quadrangle temporarily dammed the Arkansas River, creating a series of paleolakes (collectively named Three Glaciers Lake, after Lee, 2005, 2008) that backed up to nearly 9500 ft elevation, covering the central quarter of the quadrangle. When these lakes drained rapidly, they created landslides along the lake rim, including the large complex at Mount Massive Lakes.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial (Quaternary) deposits are shown on the map if they form a continuous cover over bedrock, are more than 5 ft thick, and were deposited by some depositional process during the Quaternary (as opposed to being in-place weathered regolith). Thin or discontinuous Quaternary deposits (0-5 ft thick) are mapped as a “fractional” map unit, shown by a map unit abbreviation that lists the Quaternary deposit in the numerator and the underlying deposit in the denominator (e.g., Qpt/Tp). Artificial fills of limited extent were not mapped, although they may be numerous in urban areas such as the city of Leadville. Contacts between surficial units are often gradational but are mapped as definite contacts (solid lines) throughout. Mapped units may locally include smaller deposits of another unit.

The Quaternary deposits of the Leadville South quadrangle are generally not well exposed, due to the lack of artificial and natural vertical exposures. Therefore, the thickness of most units is estimated and descriptions of physical characteristics such as texture, stratification, and composition are based on observations at a small number of localities. Particle size is expressed in terms of the modified Wentworth scale (Ingram, 1989), and sorting is expressed in the terminology of Folk and Ward (1957).

The terminology used for divisions of Late Cenozoic (Neogene and Quaternary) time is shown in Fig.4. Numerical ages have not been obtained for any of the surficial units in the Leadville South quadrangle. The ages assigned to surficial units are estimates based principally on stratigraphic relations, geomorphic position, degree of erosional modification, differences in degree of weathering and soil development, and correlations with deposits elsewhere in the region whose ages have been determined by numerical-dating methods. For example, the two latest episodes of glaciation are correlated with the Pinedale (15-35 ka) and the Bull Lake (150-170 ka) glacial advances of the Rocky

Mountains (Pierce, 2003). We especially relied on the detailed mapping and soil profile descriptions of Nelson and Shroba (1998).

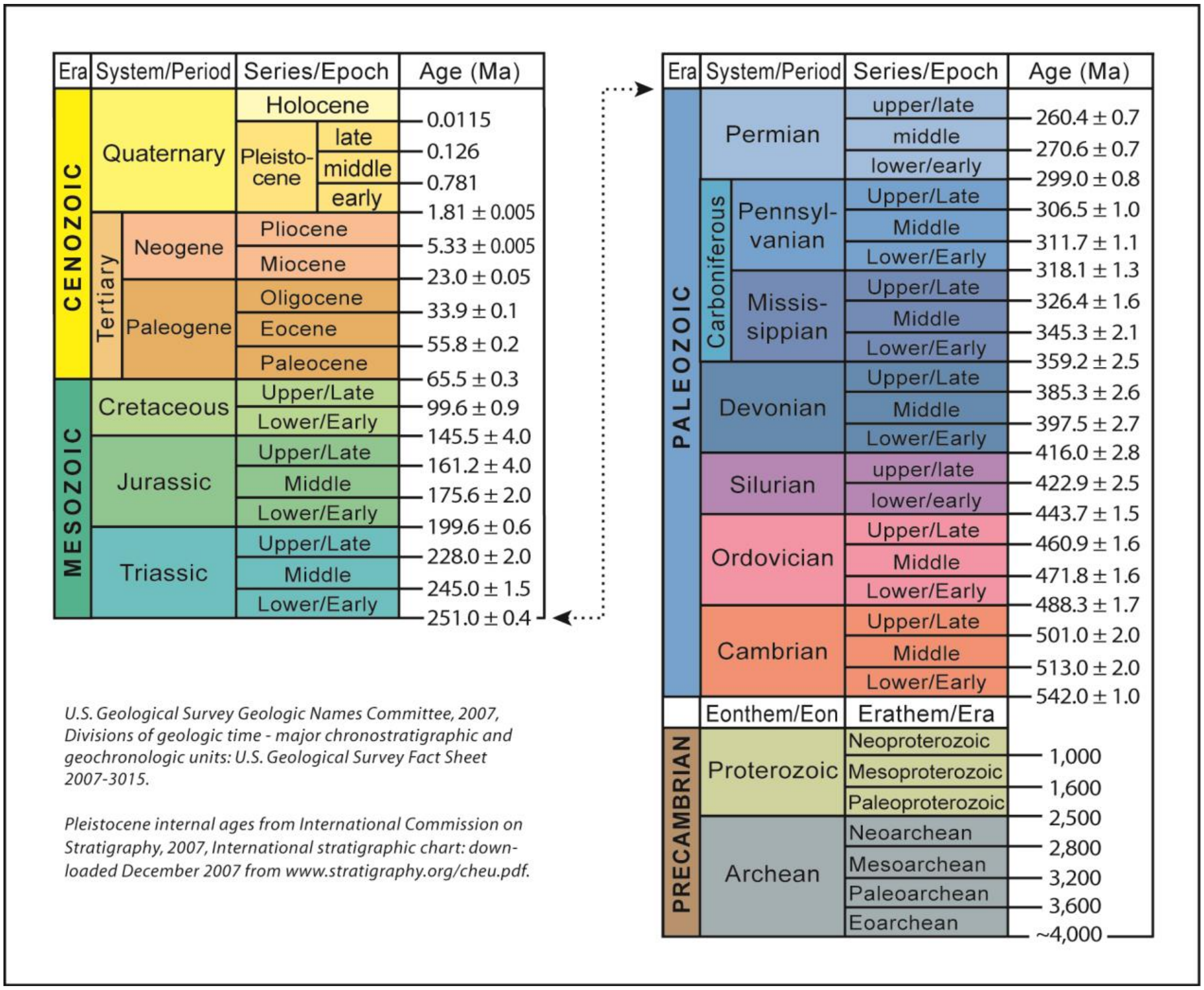

Figure 4. Geologic time chart used in this report. Within the Quaternary, we identify glacial deposits as "Pinedale" or "Bull Lake". Pinedale time is correlative to marine oxygen isotope Stage 2 of the Upper (Late) Pleistocene (from 11.8 ka to 35 ka), and is equivalent to the Latest Glacial Maximum (LGM) of current usage. Bull Lake time is correlative with marine oxygen isotope Stage 6 (ca.150-170 ka) and represents the second-oldest glacial advance commonly interpreted in the Rocky Mountains

HUMAN-MADE DEPOSITS

af **Artificial fill (latest Holocene)** – Unsorted silt, sand, and rock fragments deposited by humans during construction. Mapped where US highway 24 crosses the Arkansas River; the ends of the Leadville Airport runway; a small dam and the County landfill in Georgia Gulch; and small dams and graded fill in the bed of California Gulch. The average thickness of the unit is less than 50 ft. Artificial fill may be subject to settlement when loaded if not adequately compacted.

mw **Mine waste (latest Holocene) –** Unsorted silt, sand, and rock fragments deposited by humans during mining. Includes coarse-grained waste rock (spoil), fine-grained tailings, and areas of graded bedrock veneered with spoil. Mapped at the old townsite of Oro City; at the mouth of California Gulch (Apache Tailings; Fig. 5); Oregon Gulch tailings; and in the "Malta Gulch" tailings ponds west of Leadville and north of Stringtown. Small individual piles of mine waste east of Leadville are too numerous and small to map, and do not appear on the map. The average thickness of the unit is generally less than 50 ft. Mine waste may be subject to settlement when loaded if not adequately compacted.

Figure 5. Map of the Apache Tailings and Oregon Gulch mine tailings south of downtown Leadville (map unit mw), and constructed fills associated with the Yak Tunnel Water Treatment Facility (map unit af). Diamond-shaped cleared area at lower left is a gravel pit. Abbreviation "OU" stands for "Operable Unit" of the California Gulch Superfund Site (HDR, 2007).

ss **Smelter slag (latest Holocene) –** Solidified, black molten slag from smelters. Mapped in California Gulch. The average thickness of the unit is generally less than 30 ft. Smelter slag may contain high levels of heavy metals.

ALLUVIAL DEPOSITS

Qal **Stream-channel, flood-plain, and low-terrace alluvium (Holocene)** – Deposits are mostly clast-supported, pebble, cobble, and locally boulder gravel in a sandy silt matrix. The deposits are locally interbedded with and commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded, and their varied lithology reflects the diverse types of bedrock within their provenance. This unit includes modern stream-channel deposits of all perennial streams, adjacent flood-plain deposits, and low-terrace alluvium that lie a maximum of 10 ft above modern stream level. The largest mapped areas are in the channels and floodplains of the Arkansas River and its large tributaries (Lake Fork, Iowa Gulch, Empire Gulch, Big Union Creek, Halfmoon Creek), where channel facies is small pebble gravel and floodplain facies is medium to coarse sand. Smaller areas lie in the channels of intermittent streams (California Gulch, Thompson Gulch, Spring Creek, Box Creek). Deposits may be interbedded with colluvium or debris-fan deposits where the distal ends of fans extend into modern river channels and flood plains. Maximum thickness normally about 33 ft. Areas mapped as alluvium may be prone to flooding and sediment deposition. The unit is typically a good source of sand and gravel.

Qat **Low stream terrace alluvium (Holocene)** – Deposits are mostly clast-supported, pebble, cobble, and locally boulder gravel in a sandy silt matrix. Mapped on the floor of the Arkansas River and Lake Fork and some larger tributaries. The deposits are locally interbedded with and commonly overlain by sandy silt and silty sand. Clasts are subangular to well rounded, and their varied lithology reflects the diverse types of bedrock within their provenance. This unit includes alluvium of low terraces (5-8 ft) above the modern floodplain, and may have been deposited mainly as latest Pinedale glacial outwash. Maximum thickness probably less than 10 ft.

Qpoy **Pinedale outwash deposits, younger (late Pleistocene) –** yellowish-gray crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Mapped in Iowa Gulch (Fig. 6), and flanking the lower course of Halfmoon Creek (Fig. 7). Composed of Proterozoic metamorphic and igneous clasts (Halfmoon Creek), with an admixture of Tertiary intrusive and Paleozoic rocks (Iowa Gulch). Soil at top is weakly developed. Forms small fan-terraces 12 ft above stream level at Halfmoon Creek and also channels incised 15 ft deep into older fans (Fig. 7). Potentially a commercial source of gravel. Thickness probably 10-20 feet.

Qpoo **Pinedale outwash deposits, older (late Pleistocene) –** yellowish-gray, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Mapped in a 1 mile-wide outwash-fan surface south of Halfmoon Creek, which can be traced westward to the corresponding older Pinedale terminal moraine (Qpto). Also mapped in Iowa Gulch. Composed of Proterozoic metamorphic and igneous rocks. Soil at top is weakly developed. Forms outwash-fans and terraces 29 ft above Halfmoon Creek and channels incised into older fans channels 33 ft above the Arkansas River (Fig. 7). Mined as a source of commercial sand and gravel from two large County pits south of Halfmoon Creek. Thickness probably 10-30 feet.

Qpo **Pinedale outwash deposits, undivided (late Pleistocene) –** yellowish-gray, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Mapped

Figure 6. Gravel of younger Pinedale outwash (map unit Qpoy) exposed in a gravel quarry at the mouth of Iowa Gulch. Note consistent gravel imbrication indicating flow from left to right, and the Stage I calcium carbonate coatings on stone bottoms up to 0.04” thick. [UTM Z13, NAD27, 385430m E, 4338210m N].

along the Arkansas River and Lake Fork, where it forms small terraces 10-30 ft above stream level. Composed of Proterozoic metamorphic and igneous rocks, Tertiary igneous rocks, and minor Paleozoic rocks. Soil at top is weakly developed (A/C1ox/C2ox profile to A/2E/2Bw/Ck1/Ck2 profile 2.2 ft thick). Potentially commercial source of gravel. Thickness probably 10-30 feet.

Qboy **Bull Lake outwash deposits, younger (late middle Pleistocene) –** brown, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Mapped in a 1.5 mile-wide outwash-fan surface south of Halfmoon Creek, which can be traced westward to the corresponding younger Bull Lake terminal moraine (Qbty). Mapped between the Arkansas

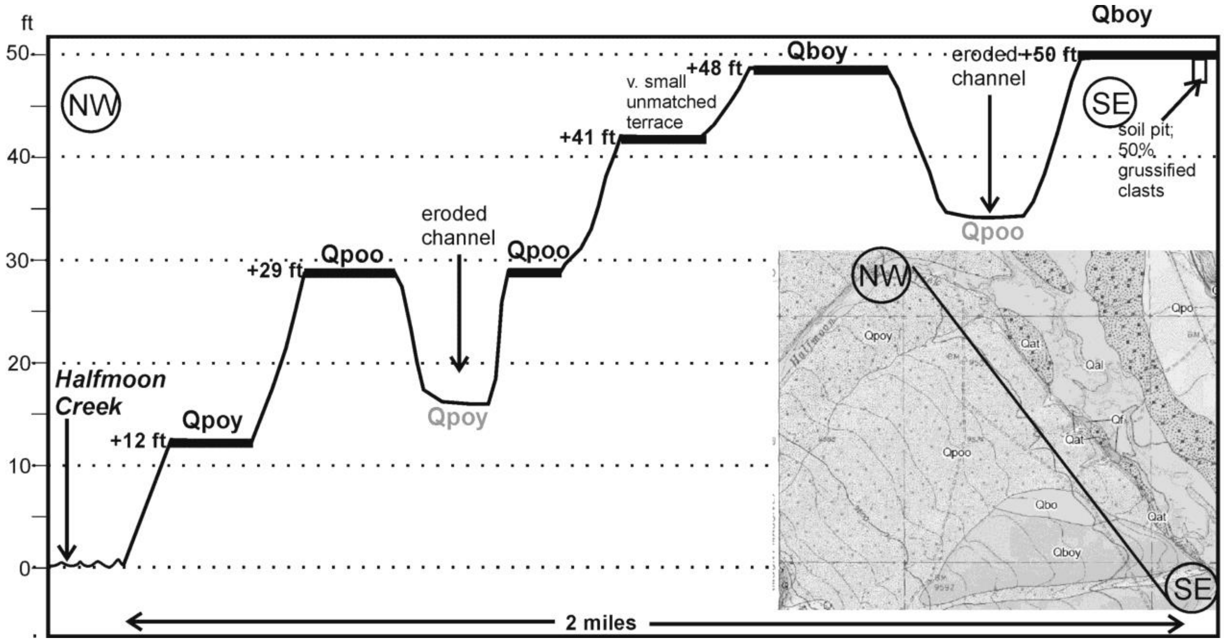

Figure 7. North-south topographic profile across the sequence of younger glacial outwash terraces of Halfmoon Creek. Qpoy, younger Pinedale outwash; Qpoo, older Pinedale outwash; Qboy, younger Bull Lake outwash. Gray labels indicate erosional channels that may have little or no backfill. All terrace heights (e.g., +12 ftm) are measured from the bed of Halfmoon Creek, except for Qboy at far right, which is measured above the Arkansas River.

River and Lake Fork, where the terraces stand 20 ft above river level. Also mapped west of Leadville and at the mouth of Thompson Gulch. Composed of Proterozoic metamorphic and igneous clasts (Halfmoon Creek), with an admixture of Tertiary intrusive and Paleozoic rocks elsewhere. Soil at top is moderately developed (contains textural B horizon). Forms outwash fans 47-50 ft above the Arkansas River (Fig. 8). Assigned to the early part of Bull Lake time (marine isotope stage 6), but could also correlate with isotope stage 4 (60-70 ka). Potentially commercial source of gravel, although upper gravel contains 50% grussified clasts, and there are no commercial pits. Thickness probably 20-50 feet.

Qboo **Bull Lake outwash deposits, older (late middle Pleistocene) –** brown, poorly stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Mapped in a 1.25 mile-wide, incised outwash pediment surface south of Halfmoon Creek, which can be traced westward to the corresponding older Bull Lake terminal moraine (Qbto). Terraces lie 100 ft above those of Qboy west of Arkansas River, and 120 ft above the Arkansas River near Malta. Composed of Proterozoic metamorphic and igneous clasts (Halfmoon Creek), with an admixture of Tertiary intrusive and Paleozoic rocks elsewhere. Soil at top is moderately- to well-developed containing textural B horizons. Too weathered to be a commercial gravel source. Thickness probably 10-50 feet.

Figure 8. East edge of younger Bull Lake outwash terrace (unit Qboy) overlooking the Arkansas River; view is to the southeast. [UTM Z13, NAD27, 384000m E, 4338070m N]

Qbo Bull Lake outwash deposits, undivided (late middle Pleistocene) – brown, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Mapped mainly on the north side of Iowa Gulch, where it forms a terrace 110-160 ft above the stream. Also mapped as thin alluvium in three channels eroded into the Qpbo pediment south of California Gulch (“Airport mesa”), which can be traced to the Qbt terminal moraine there. Composed mainly of resistant quartzites and fine-grained Tertiary intrusives at the surface, but contains more Proterozoic metamorphic and igneous clasts in the subsurface. Soil at top is moderately developed (contains textural B horizon). Thickness probably 10-50 feet.

Qpboy Pre-Bull Lake outwash deposits, younger (middle Pleistocene) – brownish-red, poorly stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Underlies a 1.5 mile-wide incised outwash pediment surface west of the Arkansas River, which can be traced westward to the corresponding younger pre-Bull Lake terminal moraine (Qpbty). The pediment stands 40 ft higher than the Qboo outwash surface to the north, and about 250 ft above the Arkansas River. Also forms the highest mesa surface west of Stringtown, which lies about 150 ft above the Arkansas River. Composed of resistant quartzites and fine-grained Tertiary intrusives at the surface, but contains more Proterozoic metamorphic and igneous clasts in the subsurface. Soil at top is well developed (1-2 ft-thick textural B horizon). Too weathered to be a source of commercial gravel. Thickness probably 10-50 feet.

Qpbo Pre-Bull Lake outwash deposits, undivided (middle to early Pleistocene) – brownish red crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Underlies most of the high terrace surfaces south of California Gulch, including the "Airport mesa", and thus forms the "high terraces" defined by Emmons and Capps in their early papers (Fig. 9). Composed of glacial outwash from pre-Bull Lake-age glaciers in Iowa Gulch and Empire Gulch. Terrace surface lies about 140 ft above the Arkansas River at Malta, where it is underlain by the "Malta gravel" of Tweto (1961; Fig. 10). The high terrace surface rises to the south, reaching 300 ft above the River at the mouth of Empire Gulch. The contact of this unit with pre-Bull Lake till at the head of the terraces can only be located approximately, due to the smoothed and eroded topography. Composed of resistant quartzites and fine-grained Tertiary intrusives at the surface, but contains more Proterozoic metamorphic and igneous clasts in the subsurface. Soil at top is well developed (up to 4.4 ft-thick textural B horizon on Airport Mesa). Too weathered to be a source of commercial gravel. Thickness probably 10-50 feet.

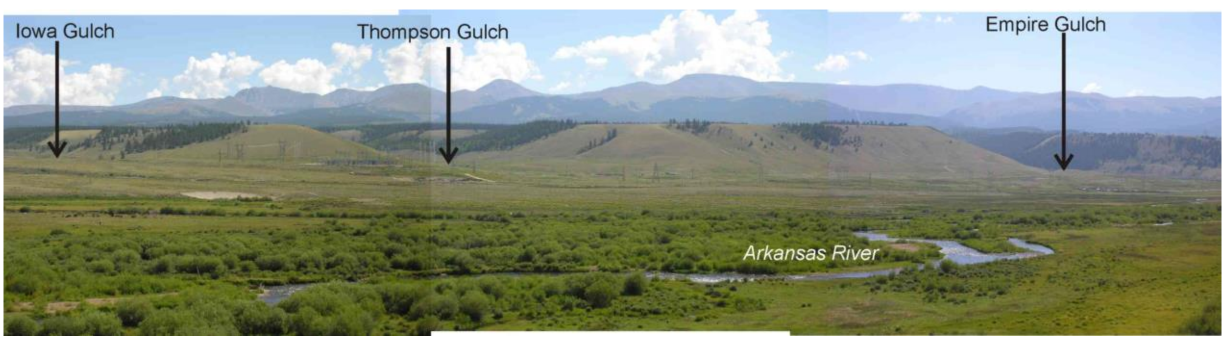

Figure 9. High terraces (mesas) east of the Arkansas River, incised by Iowa Gulch, Thompson Gulch, and Empire Gulch. Photo taken from younger Bull Lake outwash terrace (unit Qboy) of Halfmoon Creek, which stands 50 ft above the Arkansas River. [UTM Z13, NAD27, 384000m E, 4338070m N].

Figure 10. Photograph of the type locality of the "Malta gravel" of Tweto (1961) (our map unit QTa), in an old cut at the Malta railroad siding. [UTM Z13, NAD27, 383530m E, 4342580m N].

Qao **Older alluvium, undivided (middle to early Pleistocene) –** brownish-red, crudely stratified alluvium containing well-rounded to subrounded boulders, cobbles, pebbles, and sand. Occurs as isolated patches of alluvium on small terraces and benches many tens of feet above modern streams, and cannot be associated with any terminal moraine. Composed mainly of resistant quartzites and fine-grained Tertiary intrusives at the surface, but contains more Proterozoic metamorphic and igneous clasts in the subsurface. Soil at top is moderately- to well-developed (1.5 ft-thick textural B horizon below Toledo Street). Generally too thin, too inaccessible, and too weathered to be a source of commercial gravel. Thickness probably 10-50 feet .

QTa **Quaternary-Tertiary alluvium, undivided (early Pleistocene to late Tertiary) –** brownish-red to yellowish-red, crudely- to well-stratified alluvium containing cobbles, pebbles, sand, and silt. Mapped in two places: (1) along the base of the high terraces from Malta to Iowa Gulch, including the "Malta Gravel" of Tweto (1961; Fig. 10), and (2) as a lag deposit on the surface of the "high terraces" south of Empire Gulch, overlying the Tertiary Dry Union Formation. At Malta and southward along US Highway 24, excavations show the deposit to be primarily fine-grained (sand and silt), with gravels not exceeding large pebble size. Tweto and Case (1972, p. C10) call the Malta gravel "outwash from a pre-Bull Lake glaciation", but the grain size belies this contention, and a connection with moraines cannot be definitely established. Possibly some or all of this unit is pre-Quaternary and belongs in the uppermost Dry Union Formation, but it is undated at present. Maximum exposed thickness of the Malta gravel was estimated by Tweto and Case (1972) as 300 ft.

The high terraces south of Empire Gulch lie about 500 ft above the Arkansas River at the mouth of Dry Union Gulch, higher than the Qpbo surface to the north, and are capped by non-glacial gravels we include in unit QTa. The deposit is highly disrupted by landsliding, particularly on the walls of Empire Gulch and south of Dry Union Gulch. At the surface the deposit is composed of subrounded cobbles of resistant quartzites, silicified Paleozoic carbonates, and fine-grained Tertiary intrusives at the surface (Fig. 11), but contains more Proterozoic metamorphic and igneous clasts in the subsurface. The soil profile at top is well developed (>3 ft-thick textural B horizon upslope of the Yak Tunnel Treatment Plant). Deposit is too weathered to be a source of commercial gravel. Measured thickness of QTa gravel beneath the QTa terrace south of Empire Gulch is 43 ft; elsewhere probably 10-50 feet.

ALLUVIAL AND COLLUVIAL DEPOSITS

Qac **Alluvium and colluvium, undivided (Holocene to late Pleistocene)** – Unit primarily consists of a mixture of alluvial deposits of ephemeral, intermittent, and small perennial streams, and of colluvial deposits deposited from valley sides. Interfingers with and is gradational with stream alluvium (Qal), alluvial-fan deposits (Qf), and colluvium (Qc). Alluvium is typically composed of poorly to well sorted, stratified, interbedded, pebbly sand, sandy silt, and sandy gravel. Colluvium may range from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to relatively well-sorted sand composed of disintegrated granitic rocks (grus). Clast

Figure 11. Photo of QTa gravels on the high terrace between Empire Gulch and Dry Union Gulch. [UTM Z13, NAD27, 387190m E, 4336340m N]. The grain size of this lag deposit is much larger that observed between Malta and Iowa Gulch.

lithologies vary and are dependent upon the bedrock or surficial unit from which the deposit was derived. Maximum thickness of the unit is approximately 20 ft.

Qfy **Alluvial fan deposits, younger (late Holocene) –** Moderately sorted sand- to boulder-size gravel in undissected, fan-shaped deposits from tributary streams. Mapped at mouths of selected tributaries where they enter main valleys, if there was evidence of recent deposition, or if part of the fan is inset within an older fan. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependent upon local source rock. Sediments are deposited by debris flows, hyperconcentrated flows, streams, and sheetwash. Deposit overlies and thus post-dates Pinedale outwash and till deposits. The maximum thickness may exceed 20 ft. Extreme precipitation events are likely to trigger future deposition on these young alluvial-fan deposits. Fan deposits may be prone to collapse (hydrocompaction) when wetted.

Qf **Alluvial fan deposits, undivided (Holocene to late Pleistocene) –** Moderately sorted sand- to boulder-size gravel in undissected, fan-shaped deposits from tributary streams. Mapped where narrow, steep, intermittent and ephemeral tributaries debouch into wider, lower-gradient master stream valleys. This undivided unit is mapped where deposition has occurred over a long time period, beginning (in places) as early as early- to middle-Pleistocene time and continuing into the Holocene. Deposits typically composed of both matrix-supported beds (debris flow facies) and clast-supported beds (streamflow facies), often interbedded. Clasts are mostly angular to subround with varied lithologies dependent upon local source rock. Sediments are deposited by debris flows, hyperconcentrated flows, streams, and sheetwash. Debris-fan deposits commonly grade from boulder- and cobble-size fragments at the head of the fan to sandier deposits near the fan terminus. The maximum estimated thickness is less than 33 ft. Extreme precipitation events may trigger future deposition on alluvial fans. Debris-fan deposits may be prone to collapse when wetted or loaded.

GLACIAL DEPOSITS

Qpt **Pinedale till, undivided (late Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal, lateral, and ground moraines at Turquoise Lake and in Iowa and Empire Gulches. May also include localized lenses of material transported by melt-water adjacent to ice, and post-glacial alluvium in stream courses too small to map. Areas where till is a thin or discontinuous mantle over bedrock are mapped as fractional units. Deposits are light olive gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Lithologies include mainly resistant Proterozoic crystalline rocks, but also include minor Tertiary porphyries and Paleozoic rocks in the Leadville mining district. Small kettle holes and hummocky topography are common. Soils comprised of moderately well-developed A-horizon and weakly developed C-horizon. Lack of clast weathering, limited soil development (A/AC profile 1.5 ft thick, N lateral moraine of Iowa Gulch), and hummocky surface morphology suggest a late Pleistocene age (Pinedale equivalent, 12-35 ka). Maximum thickness is unknown.

Qpto **Pinedale till, older (late Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal, lateral, and ground moraines in Halfmoon Creek, Iowa Gulch (Fig. 12), and Empire Gulch. Forms moraine ridges separate from, and either farther downvalley or outboard of, Qpt moraines. May also include localized lenses of material transported by melt-water adjacent to ice, and post-glacial alluvium in stream courses too small to map. Deposits are light olive gray, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Clasts are typically angular to rounded and unweathered. Small kettle holes and hummocky topography are common. Soils comprised of moderately well-developed A-horizon and weakly developed C-horizon. Lack of clast weathering, limited soil development, and hummocky surface morphology suggest a late Pleistocene age (early Pinedale equivalent, 22-35 ka). Maximum thickness is unknown.

Qbty **Bull Lake till, younger (late middle Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped only at Halfmoon Creek and Iowa Gulch, where they comprise the younger of two older moraine ridges. Deposits are tan to brown, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and

Figure 12. View up Iowa Gulch looking east, with the modern stream flowing in the willows of the valley floor. At lower center the older Pinedale outwash terrace (Qpoo) is a densely forested flat 10-15 m above stream level. The small hill directly behind the forested terrace is the older Pinedale terminal moraine (Qpto). [UTM Z13, NAD27, 387101m E, 4340820m N].

cobble gravel in a silty-sand matrix. Most clasts are subangular to rounded and slightly weathered, but Proterozoic schist clasts rich in biotite may be rounded and partly disintegrated. Generally, exposed boulders are half buried below surface of moraine. Moraine is only slightly hummocky and crest is rounded. Soils are moderately developed and have a weakly developed argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest a pre-Pinedale age (either marine isotope stage 4 or 6). Maximum thickness is unknown, but may be as much as 66 ft.

Qbto **Bull Lake till, older (late middle Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped only at Halfmoon Creek and Iowa Gulch, where they comprise the older of two older moraine ridges. Deposits are brown to reddish-brown, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Most clasts are subangular to rounded and moderately weathered, but Proterozoic clasts rich in biotite or other mafic minerals are rounded and partly disintegrated. Generally, exposed boulders are half buried below surface of moraine. Moraine is slightly hummocky to smooth and crest is wide and rounded. Soils are moderately- to well-developed and have a textural B-horizon. Degree of clast weathering, soil development, and surface morphology suggest an age of 150-170 ka (marine isotope stage 6). Maximum thickness is unknown, but may be as much as 66 ft.

Qbt **Bull Lake till, undivided (late middle Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped in Empire Gulch (south lateral moraine), Iowa Gulch, Empire Gulch, and south of Turquoise Lake, where it is not possible to distinguish two ages of older moraine ridges. Deposits are brown to reddish-brown (Fig. 13), poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Most clasts are subangular to rounded and moderately weathered, but Proterozoic schist clasts rich in biotite are rounded and partly disintegrated. Generally, exposed boulders are half buried below surface of moraine. Moraine is only slightly hummocky and crest is rounded. Soils are moderately developed and have a moderately developed argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest a late middle Pleistocene (Bull Lake, 150-170 ka) age for these deposits. Maximum thickness is unknown, but may be as much as 66 ft.

Figure 13. Bull Lake till (unit Qbt) exposed in a gravel pit south of Turquoise Lake. [UTM Z13, NAD27, 382140m E, 4344790m N].

Qpbty **pre-Bull Lake till, younger (middle Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped only in the SW corner of the quadrangle north of Box Creek, and in the city of Leadville (Capitol Ridge), although part of Capitol Ridge may be very old outwash (correlative to high terraces south of California Gulch).

Deposits are brown to reddish-brown, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Surface clasts are 90% quartzite (resistant lag), all other lithologies in the deposit having disintegrated into small fragments. In the subsurface clasts are subangular to rounded and highly weathered to disintegrated. Boulders are completely to nearly completely buried below surface of moraine. Moraine is smooth and lacks primary constructional topography; what relief exists is mainly erosional. Soils are well developed and have a strong, thick argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest a middle Pleistocene (pre-Bull Lake, >>170 ka) age for these deposits. Maximum thickness is unknown, but may be as much as 66 ft.

Qpbt **pre-Bull Lake till, undivided (middle to early Pleistocene) –** Heterogeneous deposits of gravel, sand, silt, and clay deposited by ice in terminal and lateral moraines. Mapped only on the heads of "high terraces" at Airport mesa south of Leadville, and between Iowa Gulch and Empire Gulch. Deposits are brown to reddish-brown, poorly sorted, unstratified or poorly stratified, matrix-supported, boulder, pebble, and cobble gravel in a silty-sand matrix. Surface clasts are 90% quartzite, all other lithologies having disintegrated into small fragments. In the subsurface, clasts are subangular to rounded and highly weathered to disintegrated. Boulders are completely to nearly completely buried below surface of moraine. Moraine surface morphology is smooth and lacks primary constructional topography; what relief exits is mainly erosional. Soils are well developed and have a strong, thick argillic B-horizon. Degree of clast weathering, soil development, and surface morphology suggest an early to middle Pleistocene (pre-Bull Lake, >>170 ka) age for these deposits. Correlative to the "ancient glacial drift" of Tweto (1968), who estimated a maximum thickness of 150 ft.

LACUSTRINE DEPOSITS

Qlg **Shoreline gravel deposits (middle Pleistocene) –** Coarse gravel deposited on poorly-preserved shoreline platforms of Pleistocene moraine-dammed lakes ("Three Glaciers Lake" of Lee, 2008) between about 9,400 and 9,480 ft elevation. Deposits are well sorted, well stratified, clast-supported, small pebble to small cobble gravel. Clasts are subround and slightly weathered on the surface, although this may be a resistant lag overlying more weathered gravel in the subsurface. Occasional boulders exist that may have rolled down onto the active platform from the wave-cut cliff; these are partly buried by colluvium. Shoreline platforms range in morphology, from gently-sloping benches eroded into the high terraces, to flat hilltops planed off by wave action on landslide complexes (Fig. 14) such as the Mt. Massive Lakes complex. Thickness ranges from near zero (a thin gravel lag) to as much as 5 ft. Three Glaciers Lake was probably dammed by the Pine Creek glacier (south of the quadrangle) in pre-Bull Lake time (Nebraskan, ca. 1.4 Ma; Kansan, ca. 600 ka), Bull Lake time (ca. 150 ka), and Pinedale time (35 ka to 15 ka) (Scott, 1984; Lee, 2005, 2008).

Qlgs **Littoral sand and gravel deposits (middle Pleistocene) –** Lacustrine sand, silt, clay, and minor gravel deposited in shallow water below the shorelines of Three Glaciers Lake between about

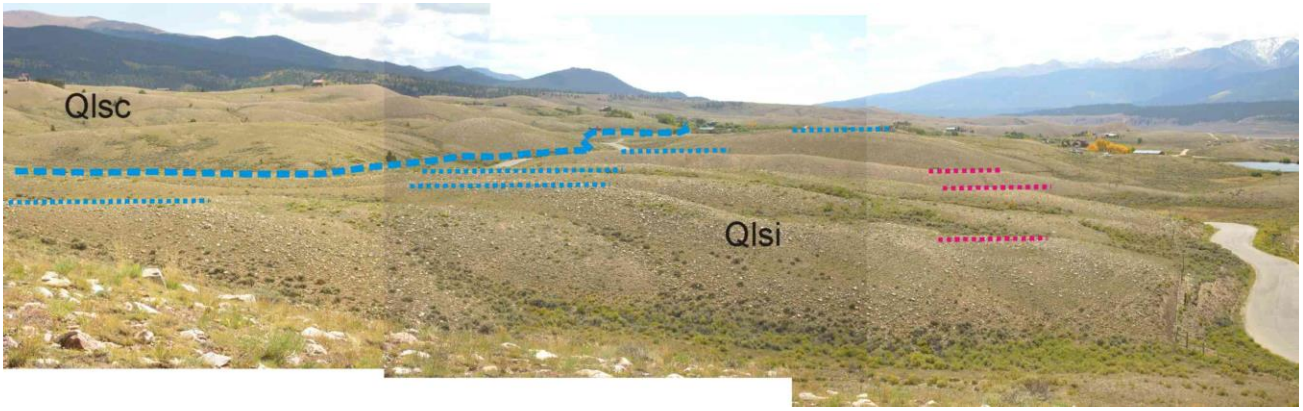

Figure 14. View of beveled, gravel-capped hilltops on the western flank of the Mt. Massive landslide complex, planed off by wave action of Three Glaciers Lake. View is to south from the northwest corner of the landslide complex (Qlsc, Qlsi); note County Road 7 at far right. Thick blue line shows upper limit of lake erosion (ca. 9480 ft elevation); thin blue dots and thin pink dots show two different shoreline levels. [UTM Z13, NAD27, 386880m N, 4336040m N].

9,340 and 9,480 ft elevation. Deposits are well sorted, well stratified, generally clast-supported. Alternating beds of green-gray clayey sand to sandy clay; cross-bedded coarse sand and granules; small pebble gravel. Mantles all the slopes in the Box Creek reentrant in the southwest corner of the quadrangle below 9,480 ft, which erodes into badlands and gullies (Fig. 15). May correlate with “older lacustrine deposits” that lie beneath the Pinedale terminal moraine of Lake Creek (south of the quadrangle) as described by Nelson and others (1984, p. 10).)Also present east of the Arkansas River. Dated by optically-stimulated luminescence at 143-146 ka near top (Bull Lake age), and 204 ka near middle. Exposed thickness is up 33 ft.

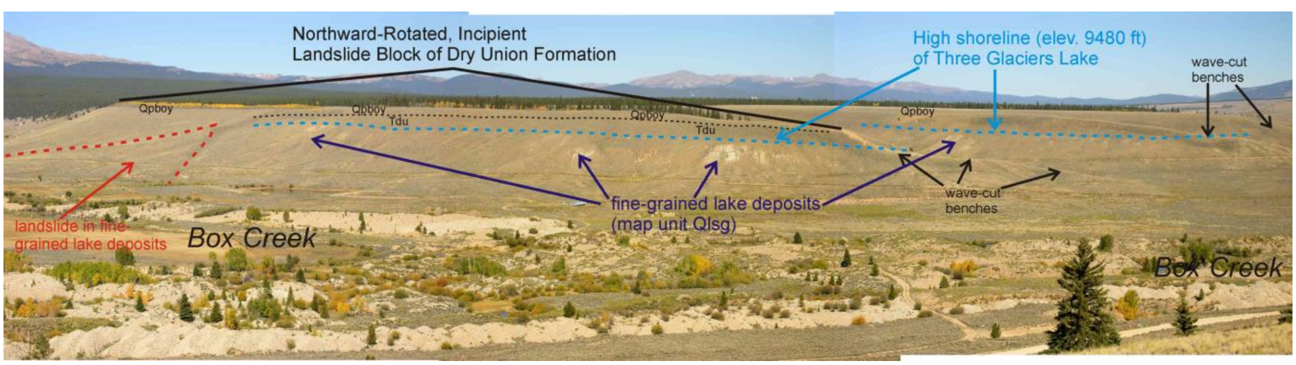

Figure 15. Annotated photo showing fine-grained lacustrine deposits (our map unit Qlgs) of Three Glaciers Lake mantling mesa sideslopes in the valley of Box Creek. View is to the north. Deposition rates were high in this valley because it formed a shallow reentrant bay in the lake that was fed by large meltwater streams from Sawatch Range paleoglaciers. By comparison, slopes at the same elevation east of the Arkansas River have discontinuous lacustrine deposits or erosional landforms. [UTM Z13, NAD27, 384660m E, 4331000m N].

MASS-WASTING DEPOSITS

Qc **Colluvium (Holocene to late Pleistocene)** – Includes weathered bedrock fragments that have been transported downslope primarily by gravity. Mapped mainly in small areas at the base of steep slopes in major canyons. Colluvium ranges from unsorted, clast-supported, pebble to boulder gravel in a sandy silt matrix to matrix-supported gravelly, clayey, sandy silt. It is generally unsorted to poorly sorted and contains angular to subangular clasts. Colluvial deposits derived from glacial or alluvial deposits contain rounded to subrounded clasts. Clast lithology is variable and dependent upon types of rocks occurring within the provenance area. Locally, this unit may include debris-fan deposits that are too small or too indistinct on aerial photography to be mapped separately at 1:24,000 scale. Colluvium commonly grades into and interfingers with alluvial, debris-fan, landslide, talus, glacial, and sheetwash deposits. Maximum thickness of this unit is probably about 30 ft; however, thickness may vary. Areas mapped as colluvium are susceptible to future colluvial deposition and locally are subject to debris flows, rockfall, and sheetwash. Colluvial deposits may be a potential source of aggregate.

Qlsy **Landslide deposits, younger (Holocene) –**Chaotically arranged debris ranging from clay to boulder size (diamicton), associated with slumps and slides of weak bedrock or till on steep slopes. Mapped on both sides of Iowa Gulch near eastern map boundary; on the south side of Thompson Gulch, opposite the pre-Bull Lake terminal moraine; includes small reactivated slumps within the Empire Gulch and Mt. Massive Lakes landslide complexes (Qlsc); on upper Spring Creek, where it partly blocks the drainage; and in the SW corner of the quad, derived from Dry Union Formation (Td). Surface of deposit is hummocky, and source area of landsliding is easily identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). May be more than 33 ft thick.

Qlsi **Landslide deposits, intermediate age (late to middle Pleistocene) –**Chaotically arranged debris ranging from clay to boulder size (diamicton). Mapped only between about 9300 ft and 9500 ft elevation, where the rapid drawdown of water level in Three Glaciers Lake destabilized the shores of the lake (mainly in Bull Lake time). Surface of deposit is generally hummocky, but hummocks may be planed off flat by later wave erosion. Source area of landsliding is generally identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). May be more than 33 ft thick.

Qlso **Landslide deposits, older (middle to early? Pleistocene) –** Chaotically arranged debris ranging from clay to boulder size (diamicton). Mapped as the oldest parts of the Empire Gulch and Mt. Massive Lakes landslide complexes. Distinguished from younger landslide deposits by its subdued surface topography, lack of closed depressions, well integrated drainage network, and difficulty in distinguishing the headscarp, toe bulge, and margins from other non-landslide landforms. May be more than 66 ft thick.

Qlsc **Landslide complex deposits (Holocene to late Pleistocene) –** Chaotically arranged debris ranging from clay to boulder size (diamictons). Includes large interconnected areas of landslides of various ages and sizes which are too small to map individually at 1:24,000 scale. Mapped only in the Empire Gulch and Mt. Massive Lakes landslide complexes (Fig. 16), both derived from the

Figure 16. Panoramic photograph of the Mt. Massive Lakes landslide complex, looking south from the top of the headscarp near its western end. The lakes shown in the center distance are artificial, created by diverting runoff from Big Union Creek into ditches which then flow into a series of closed depressions on the landslide surface.

Tertiary Dry Union Formation. Surface of deposit is hummocky and contains springs, and source area of landsliding is easily identifiable (linear pull-away scarps indicated by thick dashed lines with ticks in direction of sliding). May be more than 66 ft thick).

Qls **Landslide deposits, undivided (Holocene to late Pleistocene) –** Chaotically arranged debris ranging from clay to boulder size (diamicton). Mapped throughout the quadrangle, including a lake-level-related landslide on the southern map boundary. Surface of deposits commonly hummocky, and source area of landsliding is generally identifiable (top of scarp area indicated by thick dashed lines with ticks in direction of sliding). Larger landslide deposits may be more than 50 ft thick.

Qdf **Debris flow deposits (late Holocene) –** Poorly sorted debris ranging from clay to boulder size, deposited by rapidly-moving slurries of water, mud, and larger debris (debris flows). Mapped where historic debris flows have cut through the railroad grade SW of Stringtown, and on the south valley wall of Iowa Gulch. Surface of deposit is hummocky and marked by channel-margin levees of chiefly composed of boulders. Probably ranges from 3-5 ft thick.

BEDROCK UNITS

Bedrock units of the Leadville South quadrangle include Tertiary sedimentary rocks and intrusive rocks, Paleozoic sedimentary rocks, and Proterozoic igneous and metamorphic rocks. The stratigraphic column for Lake County, which includes all the mapped units in the Leadville South quadrangle, is shown in Fig. 17. Geologic units and faults in the northeast corner of the quadrangle (former Leadville mining district) were mainly adapted from Emmons and others (1927) and Behre (1953).

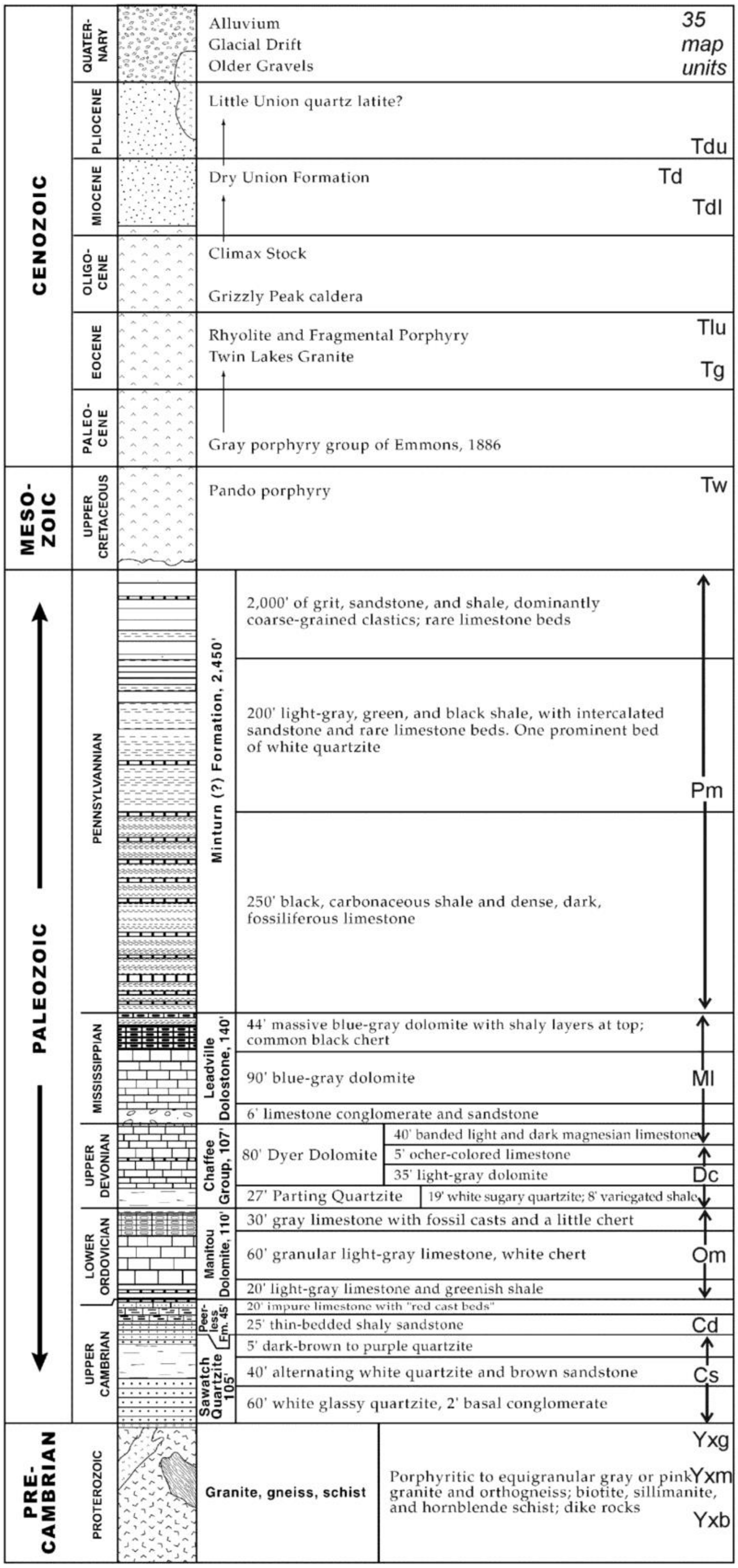

Figure 17. Generalized stratigraphic column of Lake County, Colorado (from Cappa and Bartos, 2007). Bold letters at right show the map unit abbreviations used on the Leadville South quadrangle. Our age assignment of Eocene for the Little Union quartz latite is based on regional relationships and contradicts Cappa and Bartos' (2007) age assignment of late Pliocene.

TERTIARY SEDIMENTARY ROCKS

Tdu **Dry Union Formation, upper part (Pliocene?) –** Mapped below the tops of the high terraces (mesas) of the Arkansas Valley, from the base of the Quaternary pediment gravels, downward for about 100 ft on the mesa-flanking slopes (i.e., from 40 to 140 ft beneath the terrace surface). On airphotos unit is portrayed by smooth tones, light brown to white north of Big Union Creek, and reddish-brown south of Big Union Creek. Slopes are generally covered by friable gravelly colluvium, suggesting a high gravel component. Rarely exposed in outcrop, except on south-facing slopes north and south of Dry Union Gulch where it is the type locality of Tweto (1961), dominated by fluvial overbank/eolian sands, fluvial channel gravels (cemented into ledges), and rare paleosols (Fig. 18). Probably correlative to the lower part of the "Wash" defined by early publications of Emmons and Capps, but may partly correlate with the stratified "Lake Beds" unit of the same authors. Correlative with unit Tdu2 of USBR (1981), described as "sand and gravel series, consisting of gravels in a tan to brown clay-silt-sand matrix with some crude stratification." Fluvial channel beds strike N60°E and dip 5°NW, but have probably been rotated by landslide movement. Exposed thickness ranges from about 100 ft in the northern part of the quad to more than 250 ft at the type locality south of Dry Union Gulch (Fig. 19).

Figure 18. Photograph of the type locality of the Dry Union Formation (Tweto, 1961), on the headscarp of the Mt. Massive Lakes landslide, south of lower Dry Union Gulch. View is to the east. The lower 30 ft of the exposure is mantled with slopewash and is not part of the measured stratigraphic section in Fig. 18. The cemented fluvial channel gravels at center strike N60°E and dip 5°NW. However, the pediment gravel surface at the top of the headscarp (ridge between headscarp and Dry Union Gulch) now dips 10°N, so the entire ridge has presumably been rotated 10° by incipient landslide movement. If so, this implies that the pre-rotation dip of the Dry Union Formation was about 5°S, similar to dips measured in Dry Union strata in Empire Gulch (this report) and at Mt. Elbert Forebay (USBR, 1981).

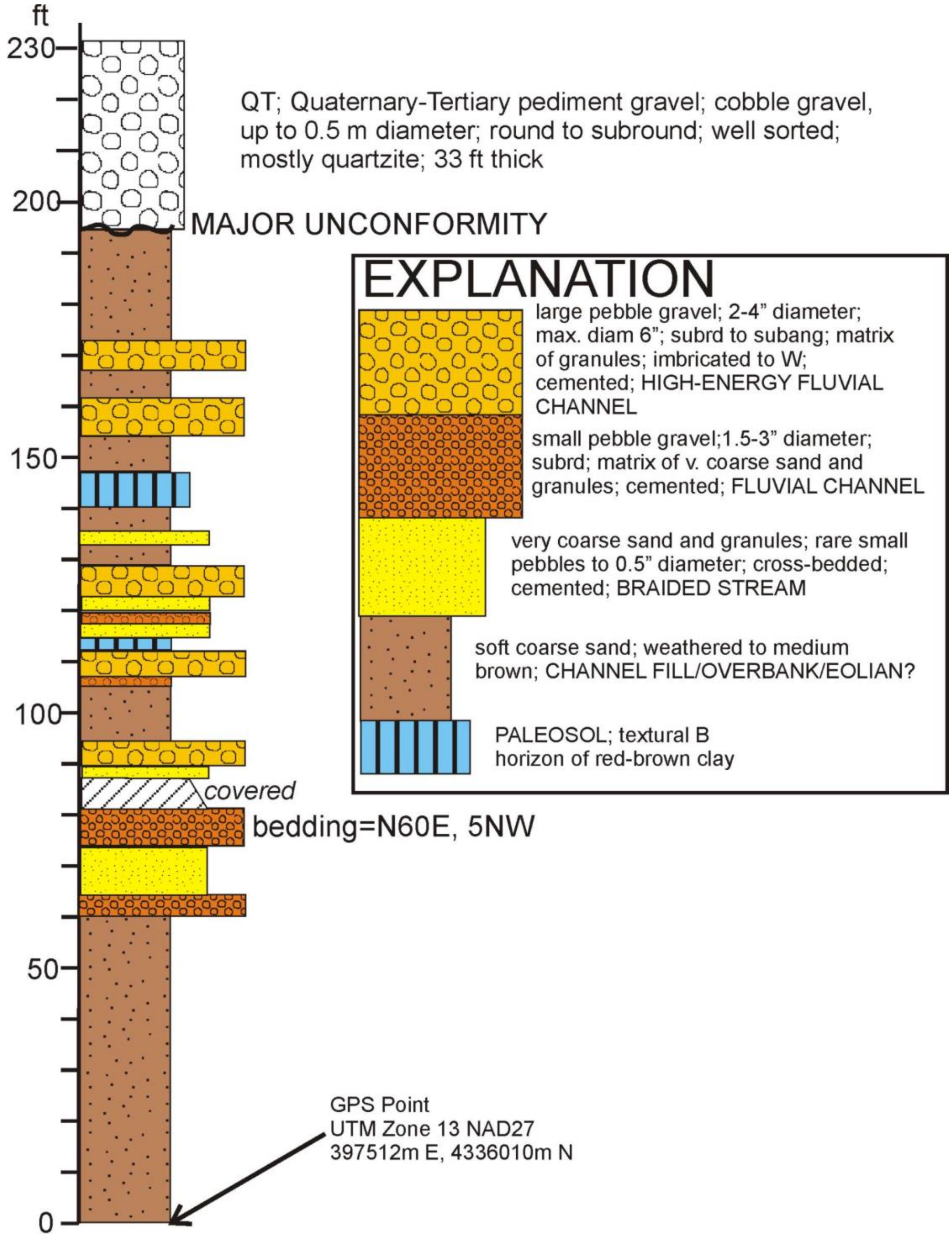

Figure 19. Measured section 233 ft thick at the type locality of the Dry Union Formation (Tweto, 1961), on the headscarp of the Mt. Massive Lakes landslide, south of lower Dry Union Gulch. This exposure is part of the upper part of the Dry Union Formation (Tdu) as defined in this report, correlative with the upper part of the Dry Union Formation ("sand and gravel series") defined by USBR (1981). Degree of cementation is indicated by width of bed. Fluvial channel development and cementation here is anomalously strong, compared to other outcrops of the upper Dry Union Formation.

Tdl **Dry Union Formation, lower part (Miocene to Pliocene?) –** Mapped south of Empire Gulch, where it underlies the coarser upper part of the Dry Union Formation. On airphotos it is recognized by its higher drainage density, particularly south of Big Union Creek where it is characterized by gullies and badlands. On airphotos, unit displays mottled tones; white north of Big Union Creek, and green south of Big Union Creek. Rarely exposed in outcrop, except on north-facing stream-cut slopes on the south side of Union Gulch. Probably correlative to the lower part of the stratified "Lake Beds" of Emmons and Capps. Correlative with the "clay-silt series" of the Dry Union Formation defined by USBR (1981), consisting of "grey sandy silts and clays… and yellow-green ashy sands." This unit contains the failure planes of all the landslides in the southern half of the quadrangle. Exposed thickness is up to 150 ft on the south wall of Big Union Creek, but may be as much as 2000 ft thick (Tweto, 1961).

Td **Dry Union Formation, undivided (Miocene to Pliocene) –** Mapped on forested slopes of mesas, where the upper and lower parts of the Dry Union Formation cannot be differentiated. Tweto and Case (1972) and Tweto (1978) cite a maximum thickness of 2000 ft and 3000 ft, respectively.

TERTIARY IGNEOUS ROCKS

Since there are few, if any, outcrops of these units within the quadrangle, mapping was derived from Emmons and others (1927) and Behre (1953) who had the advantage of entering the mines while they were still operational. For this project, rock types were confirmed from the mine dumps found on the ground outside the mines, but nothing was discovered that gave reason to doubt any of the mapping done by the aforementioned authors.

Tlu **Little Union Quartz Latite (Eocene)** - Medium to dark gray, fine-grained, phaneritic porphyritic rock with small (<5mm) phenocrysts of subhedral to euhedral biotite and quartz (up to 50% of the rock) with lesser altered feldspars. Originally described by Behre (1953); found as small (<100ft wide) outcrops that define a body mapped south of Empire Gulch. Displays flow-parallel partings and foliation (Fig. 20). Contains xenoliths of Gray porphyry which suggests it is younger, but an absolute age in unavailable. Petrologic similarity to Gray porphyry suggests that they are genetically related. Mapped under the title "Felsite and Quartz Porphyries" by Tweto and Reed (1973).

Tg **Gray Porphyry (Eocene) –** Medium to dark gray groundmass with small (<1cm) altered feldspar, quartz, and biotite phenocrysts that can make up to 50% of the rock. Found only in mine dumps and appears to have been a principal mining target. Includes the Johnson Gulch porphyry (first described by Behre, 1953) which appears denser and finer grained but is still medium gray and not separated as distinct here. The Johnson Gulch porphyry was dated by Thompson and Arehart (1990) to be 43.1 Ma. Emmons and others (1927) and Behre (1953) differentiate between multiple subdivisions throughout the Leadville district. Cappa and Bartos (2007) summarize and compare these divisions for occurrences throughout Lake County.

Figure 20. Natural exposure of the Little Union quartz latite (map unit Tlu) - note parting fractures and foliation. UTM27, 390777mE, 4337821mN.

Tw **White Porphyry (Late Cretaceous) -** White to light-gray, weathers to buff; typically porphyritic, but at times, completely devoid of phenocrysts. Where porphyritic, contains large (<2cm) subhedral to euhedral, quartz phenocrysts, that can make up to 30% of the rock, in an aphanitic groundmass. Does not occur in outcrops but only in mine dumps and as scattered piles of thin (<6") plates. Occasionally, associated with thick (<2 ft) quartz veins that appear to be genetically related. For this map, Tw includes a small area in the extreme northeast corner of the quadrangle mapped by Behre (1953) as rhyolite.

White Porphyry was divided into early and late varieties by Behre (1953), but only the Early white porphry was mapped in this quadrangle. Cappa and Bartos (2007) correlated the Early white porphyry to the Pando porphyry (described by Tweto, 1951, 1954) from the Gilman District to the north-west. An age of 71.8 Ma for the Early white porphyry was reported by Pearson and others (1962) followed by Cunningham and others (1994), using K-Ar in biotite. Detailed petrologic descriptions of white porphyry are summarized by Cappa and Bartos (2007) with references therein.

PALEOZOIC SEDIMENTARY ROCKS

Like the Tertiary intrusive units, outcrops of Paleozoic sedimentary rocks are mostly non-existent and mapping follows the work done by Emmons and others (1927) and Behre (1953). Besides the rarity of samples, most of these rocks have undergone some degree of alteration and/or mineralization due to Tertiary intrusions, and they can therefore be quite different from their counterparts described in other areas. As well, the measured thicknesses of these units are unattainable as the Tertiary sills have inflated the entire sequence.

Ml **Leadville Limestone (Mississippian)** - Blue-gray to black dolomite and limestone that is both massively bedded and karstic. Is one of the principal ore bearing formations in the Leadville district. Does not outcrop but can be found in mine dumps where it often occurs as breccia (with clasts <2”) and a gray and white striped dolomite known as “zebra rock” (Fig. 21); both of which were the dominant mining targets as they are often mineralized. Is pervasively intruded by sills of Tertiary intrusive rocks. Originally known as the “blue limestone” and thoroughly investigated by Emmons and others (1927) and Behre (1953), it is also summarized by Cappa and Bartos (2007).

Figure 21 - (*left*) Breccia of the Leadville Limestone (specimen is approx. 7” across) varies between clast-supported (top) to matrix-supported (bottom) and clasts are always subangular to angular. (*right*) Leadville Limestone “zebra rock” (specimen is approx. 11in. across) consists of thin stripes and lenses of coarse-grained, white dolomite in a fine-grained dark dolomite.

Dc **Chaffee Group - Dyer and Parting Formations, undivided (Devonian)**

Dyer Formation - Maroon, ochre and gray, often strongly silicified, dolomite breccia. Is also an ore bearing formation that does not outcrop but is found in mine dumps and as glacial erratics. In areas where silicified, is very resistant to erosion. Besides large (<1.5ft.) clasts of white and pink quartzite and grey dolomite, at times contains large (<6in.) dissolution vugs.

Parting Formation - Purple to tan, fine- to medium-grained sandstone, conglomerate, and pinkish white quartzite. Does not outcrop but is abundant in float and as glacial erratics. Rare samples are found in mine dumps. Detailed sedimentary attributes have been described by Emmons and others (1927), Behre (1953), and summarized by Cappa and Bartos (2007); however, the paucity of available occurrences on this quadrangle precludes such description here.

Om **Manitou Formation (Ordovician)** - White to light gray, thin to thick bedded, limestone and dolomite. Known as the "white limestone" by Emmons and others (1927), it was also an ore-bearing formation. Is notably crumbly and friable, which Cappa and Bartos (2007) attribute to the dissolution of intercrystalline calcite. Is very susceptible to weathering and is only found in mine dumps and as dissolving patches of white ground exposed by prospect pits. Bedding 0.5-12" thick and thin (<0.04") laminations are also present.

Cd **Dotsero Formation (Cambrian)** - Maroon to tan, thinly bedded, sandstone that is often shaly and/or dolomitic. Was originally called the "Peerless Formation" (Emmons and others, 1927 and Behre, 1953) but has since been included in the Dotsero Formation by Myrow and others (2003). Is very thin in this area and is therefore rare, but is relatively resistent to weathering. Does not occur as a measurable outcrop but as small piles near prospect pits. Is often present as partly fused, coarse sandstone with cement removed. Observed samples are similar to the Sheep Mountain member described by Myrow and others (2003).

Cs **Sawatch Quartzite (Cambrian)** - White to pink, thick bedded, medium grained sandstone, poorly sorted conglomerate, and quartzite. Where not completely fused into quartzite, grains are mostly well rounded quartz. Crops out only as small cliffs south of Empire Gulch, but it is also found in mine dumps and prospect pits. As float or glacial errata, it is difficult to discern from the Parting Formation. The rarity of outcrops on this quadrangle preclude detailed correlation to individual units within the Sawatch Formation found elsewhere throughout Colorado, which are described in Behre (1953), Myrow and others (2003), and Cappa and Bartos (2007).

PROTEROZOIC IGNEOUS AND METAMORPHIC ROCKS

Descriptions of the following rock units are based on hand sample analysis and field relations.

YXm **Migmatite, biotite gneiss, and schist (Proterozoic)** - Refers to narrow zones (<60 ft wide, but 100s of feet long) that are presumably of tectonic origin and are likely related to the emplacement of YXg. Typically, zones grade from migmatite to biotite gneiss then biotite schist. Rarely, migmatite is absent, and small (<1 ft) pods of mylonite are found, suggesting movement in a more brittle (lower temperature) fashion than those with migmatite. Migmatite grades from highly contorted with more felsic material where nearest to granite, to well foliated and more mafic where it grades into gneiss. Gneiss is dark-gray to black with white stripes, fine to medium-grained, strongly foliated, and composed primarily of biotite, quartz, and plagioclase. Biotite schist is also strongly foliated and at times contains sillimanite (Fig. 22). Weakly foliated

Figure 22. Natural exposure of Proterozoic biotite gneiss and schist (map unit YXm,center) approximately 4ft. wide, flanked by Proterozoic granite (map unit YXg, reddish). [UTM27, 391433mE, 4334606mN].

YXg immediately adjacent to YXm is often stained red, and along with thin (<6” wide) quartz veins, is concordant with the foliation of YXm.

YXg **Granite and granodiorite with associated pegmatite and aplite, undivided (Proterozoic)** - Is typically a homogenous, orange to pink, medium to coarse grained, non- to weakly foliated, equigranular granite consisting of quartz, potassium feldspar, plagioclase and lesser biotite. Rare variations have gradational contacts with the typical form and include porphyritic with <1.5” feldspar phenocrysts and very coarse grained equigranular textures. Granodiorite is noted where the rock has a higher biotite content. Where weakly foliated, biotite is the dominant aligned mineral. Muscovite is also present but sparse. Pegmatite and aplite are infrequent and quartz veins are more common. Outcrops are ubiquitous and occur as large, strongly weathered, bouldery masses (exhumed corestones?) surrounded by thick deposits of grus.

Tweto (1979) mapped YXg as Early Proterozoic (Xg) and grouped it with the Denny Creek Batholith of the Routt Plutonic Suite (1.7 Ga), which is found in the southern Mosquito range. However, Tweto (1987, p. A36) included granitoid rocks within mine workings at Leadville as part of the St. Kevin Batholith of the Berthoud Plutonic Suite (1.4 Ga), which lies predominantly to the north and west. Cappa and Bartos (2007) concluded that YXg was part of the Cross Creek Granite (Early Proterozoic - Routt Plutonic Suite), which is located north of Tennessee Pass near Minturn. However, Shaw and Allen (2007) note that the Homestake Shear Zone is the southern boundary of the Cross Creek granite and they therefore label YXg as a part of the Denny Creek

Granite. With regard to overall geologic characteristics, YXg is quite different from the Denny Creek granodiorite (Xgd) and is more similar to the area mapped as YXg of the Marmot Peak quadrangle to the south, by Houck and others (in prep.).

YXb **Biotite schist** - Dark gray to black, fine to medium grained, non- to moderately foliated, biotite-rich schist that is present as xenoliths with varying degrees of assimilation by the surrounding granite. Contacts vary from "cold" with no assimilation but often forming a breccia (Fig. 23) to gradational, forming elongated, foliated schlieren <2 ft wide. Often cut by veins of pegmatite, aplite, and very coarse grained granite. Interpreted as either relicts of the 1.7Ga metasedimentary country rock or an early crystallization phase of YXg.

Figure 23. Brecciated, non-assimilated Proterozoic biotite schist (map unit YXb, black) in a matrix of Proterozoic granite (map unit YXg). Brunton compass is 2.75" wide.

STRUCTURAL GEOLOGY

The Leadville South quadrangle is situated on the eastern flank of the broadly antiformal Sawatch uplift, comprised today of two basement-cored mountain ranges, the Sawatch Range on the west and the Mosquito Range on the east. Between these two ranges lies the Upper Arkansas Valley, a topographic and structural basin belonging to the Late Cenozoic Rio Grande rift. The rift, which extends 1000 km to the south, split and foundered the eastern flank of the Sawatch uplift beginning in the early Miocene (Tweto, 1961). The Leadville South quadrangle lies just east of the rift axis, so that most of the structures shown on our map are west-dipping normal faults related to the Late Cenozoic development of the rift. Tweto and Case (1979, Fig. 8) show that a deep, local gravity low lies in the north-central part of the quadrangle, with the center (20 mgal closure) lying 1/3 mile due north of the confluence between the Lake Fork and the Arkansas River (1.2 mi SSW of Malta). They call this gravity low (-330 mgal Bouger anomaly) the “deepest known [gravity] low in the conterminous United States.” Using assumed rock densities, they estimate the Tertiary-Quaternary graben fill sediments are 3000-4000 ft thick here.

Unfortunately, due to the thick sequence of sediments that overlie them, the faults responsible for creating this deep low are not visible at the surface. The eastern third of the quadrangle does contain a series of north- to northeast-trending normal faults, mainly down-to-the-west, in a zone of step-faulting that comprises the broad eastern margin of the rift. In the northeast quadrant, these step-faults displace the entire Paleozoic stratigraphic section and interbedded Tertiary sills of the Leadville Mining District, leading to many repeated sections (Fig. 24). In the southeast quadrant the faults trend more northeasterly, and displace Proterozoic crystalline rocks, and in some places, the Dry Union Formation.

There is also evidence in the quadrangle for several older (pre-Late Cenozoic) periods of structural development. The oldest period(s) were responsible for the high-grade metamorphism and faulting of Proterozoic metamorphic rocks, but little is known of that period. Minor episodes of uplift punctuated the deposition of the Paleozoic sequence, as indicated by unconformities/ hiatuses during the Silurian and Mississippian (paleo-karst).The next major orogeny in central Colorado was the Ancestral Rockies orogeny (Pennsylvanian), which led to the deposition of thick clastic sequences such as the Fountain, Maroon, and Minturn Formations. Although adjacent quadrangles contain thick sections of the Minturn Formation, there is none exposed in the Leadville South quadrangle. In late Cretaceous time the quadrangle was affected by the Laramide orogeny, characterized by basement-cored vertical uplifts. During the Laramide the Sawatch anticlinorium developed, and Paleozoic strata were broadly folded in the Leadville Mining District (Fig. 22). The latest deformation predating the rift was the latest Cretaceous to Oligocene development of the Colorado Mineral Belt, associated with intrusion of acidic to intermediate stocks, dikes, and sills. In the Leadville South quadrangle these sills intruded the folded Paleozoic section and gave rise to the rich gold-silver-lead-zinc ores of the Leadville Mining District.

LATE CENOZOIC FAULTS

Because the rift-related Late Cenozoic faults dominate the quadrangle, and determine the degree of seismic hazard, we describe them in more detail herein. The following discussion is based on the

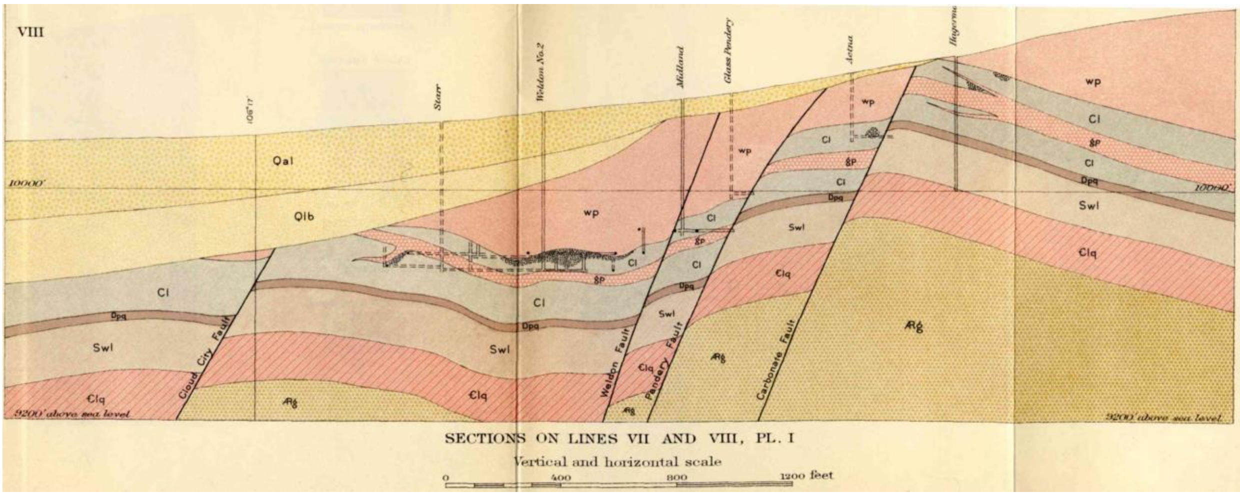

Figure 24. Cross-section across the Late Cenozoic normal step-faults at Carbonate Hill, just east of downtown Leadville, from Emmons and Irving, 1907 (from left to right, Cloud City fault, Weldon fault, Pendery fault, Carbonate fault). The latter three faults merge into a single Pendery fault just south of this section line. Although not shown in this section, the Pendery fault displaces the Late Cenozoic “Lake Beds” (lower part of the Dry Union Formation?) farther to the north (Section IV of Emmons and Irving, 1907). Qal, the “Wash” (our units Qpbo, Qboo, Qboy); Qlb, the “Lake Beds” (nowhere exposed at the surface); wp, White Porphyry (our unit Tw); Cl, Carboniferous limestone (our unit Ml, Leadville Dolostone); gp, Gray Porphyry (our unit Tg); Dpq, Parting Quartzite (our unit Dc); Swl, White Limestone (Manitou Dolomite of modern usage, Om); Clq, lower quartzite (Sawatch Quartzite of modern usage, Cs); ARg, Archean granite (our unit YXg).

Quaternary Fault and Fold Database of Colorado (QF&FDB) published by the Colorado Geological Survey (Widmann and others, 1998; http://geosurvey.state.co.us/Default.aspx?tabid=270) and the US Geological Survey (http://earthquake.usgs.gov/regional/qfaults). (see Fig. 25)

Fault 2303—Mosquito Fault

The Mosquito fault is the easternmost, and largest, rift-related fault on the eastern side of the Rio Grande rift. Two northeast-trending fault strands associated with the Mosquito fault by Widmann and others (1998) lie in the Leadville South quadrangle. The northern strand is 4 miles long and parallels the course of Big Union and Little Union Creeks. This fault does not connect with the main Mosquito fault trace as mapped by others, and its inclusion as part of the named “Mosquito fault” by Widmann and others (1998) appears to have been made for convenience only. USBR (1981) defined this fault, which continues southwest across the Arkansas River, as the northern of three “cross-valley” normal faults that trend NE and cross the rift (i.e., they did not consider it a part of the Mosquito fault).

The fault is exposed as displacing the upper and lower parts of the Dry Union Formation on the south bank of Big Union Creek in Sec. 35, T. 10 S., R. 80 W. According to USBR (1981) the fault, “*trending through Dry Union Formation, separates gravelly sands on the southeast* [our unit Tdu] *from yellow-green ashy sands* [our unit Tdl] *on the northwest. It has at least 45 m (150 ft) of stratigraphic offset in*

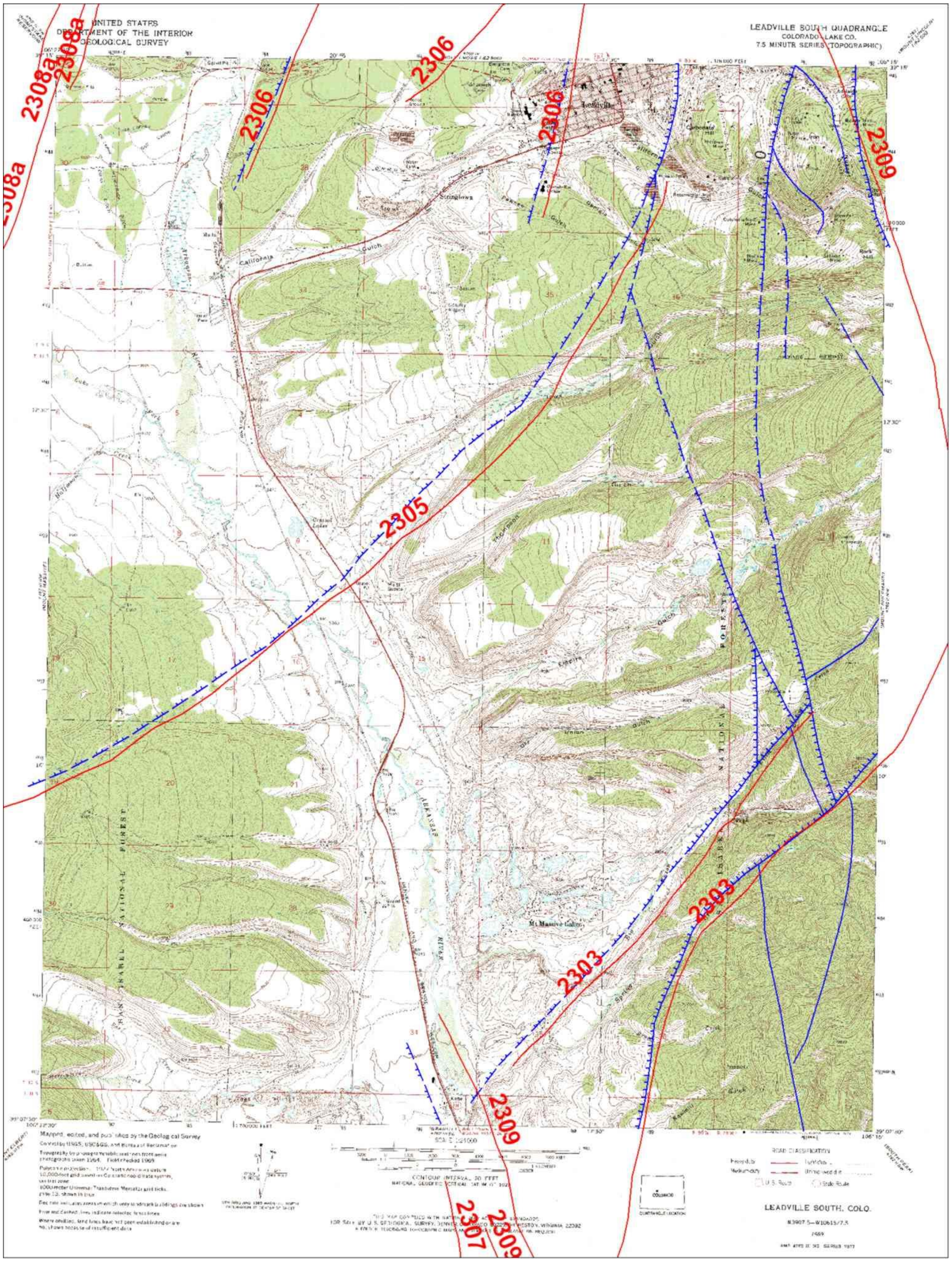

Figure 25. Map of Quaternary faults from the QF&FDB (red) and faults mapped by Tweto and Reed (1973)(blue). 2303, Mosquito fault; 2305, unnamed faults south of Leadville; 2306, unnamed faults northwest of Leadville; 2307, unnamed faults near Twin Lakes Reservoir; 2308, Sawatch fault, northern section; 2309, Northeast boundary fault system (of the Rio Grande rift).

this exposure, where it strikes N 42°E and dips 67°W….. To the southwest, the … fault is inferred to continue across the valley and through the Mt. Elbert Forebay area. Preliminary correlation of wire-line logs … shows a down-to-the-north offset of about 15 m (50 ft) in the Dry Union coincident with a straightline projection of the fault from its exposure east of the river. The well log picks include three ash beds within the Dry Union Formation and are reliable within the area mapped. The key beds dip generally 9° south to southeast, roughly parallel to the ground surface…. While this offset is far less than expected on a major graben-bounding fault, it does suggest the presence of a down-to-the-north fault at this locality."

We conclude that this fault is part of a major down-to-the-northwest fault zone, based on the observations just described, and the fact that Proterozoic basement rocks do not appear on the valley floor northwest of it. The south- to southeast dips of Dry Union Fm. cited by USBR (1981; and measured by us on the north wall of Empire Gulch) suggest that the Dry Union Formation has either a primary (depositional) or secondary (tectonic) dip southward toward this fault zone. We map most of the length of this fault as concealed beneath Holocene alluvium of Big Union Creek, so its latest period of movement can only be constrained as post-Dry Union and pre-Holocene.

Tweto and Reed (1973) and the Widmann and others (1998) show a second, longer strand of the Mosquito fault to the SE of the strand described above. This curvilinear fault is entirely contained within Proterozoic crystalline rocks and thus its throw cannot be estimated. The fault does not coincide with a topographic break, and its curvilinear shape is at odds with the rectilinear NW-SW fault pattern that we map. Therefore, we do not include this fault on our map. We do map a nearby NE-trending fault in Spring Creek, but that fault does not curve to the south as does fault 2303, but continues SW in a linear fashion to the southern boundary of the quadrangle. The fault does not displace Holocene alluvium, and we infer it also has not experienced movement in late Quaternary time.

Fault 2305—Unnamed Fault South of Leadville

This single, northeast-trending fault crosses the quadrangle from its western boundary at a latitude of 39°10', continues across the Arkansas River and parallels Iowa Gulch, crosses California Gulch, and ends just east of the Oregon Gulch tailings area. For its entire length fault 2305 coincides with an inferred fault mapped by Tweto and Reed (1973); that fault is never observed and does not outcrop, so the evidence for its existence is unknown.

Fault 2305 ends to the NE just where the Pendery fault ends to the SW, so it does not include the Pendery fault as mapped in the Leadville Mining District. The Pendery fault is the major down-to-the-west step fault in the Downtown District of Leadville (Emmons and Irving, 1907). The Pendery fault (Fig. 22) is one of the few faults known to displace Late Cenozoic deposits in the subsurface. Emmons and Irving (1907) state: ""*The direct evidence of [*Late Cenozoic] *movement observed by the writer was confined to two places, one in the Walcott mine, the other in the Elk mine, both of them along the Pendery fault and in the depression of lower Stray Horse Gulch. In each place the rock face on the foot or east wall of the fault, which stands at 65° or 70°, has been lifted up across the* [Tertiary] *Lake beds, which adjoin it on the west. In the Elk mine the brownish clay that constitutes the Lake beds shows a distinct* *sheeting parallel to the fault planes, and a selvage of this clay material carries in places a fault breccia that still clings to the limestone foot wall, which it could not have done had this wall constituted a cliff against which the lake beds were deposited…. The aggregate amount of such displacements can not be accurately determined. In the Elk mine it is certainly as much as 100 feet, and possibly 150 feet."*

Thus, it is odd that fault 2305, for which there is no clear evidence of its existence, is mapped as a Quaternary fault, yet the Pendery fault, a known fault which does have evidence for Late Cenozoic movement, is not. The authors of this report doubt the existence of fault 2305, since the gravity map of the Leadville area shows no anomalies along its trace, and in fact the fault is not shown on Tweto and Case's (1972) Plate 1.

<u>Fault Group 2306—Unnamed Faults Northwest of Leadville</u>

This group of six faults was interpreted by Tweto (1974) from subsurface data and nearby surface exposures and was considered approximate or conjectural. Tweto and Case (1972) mapped these as inferred faults in Cenozoic deposits. Three of the 2306 group faults enter the north-central part of the Leadville South quadrangle, and were apparently projected into the quad from the trend of faults mapped in the Holy Cross 15' quadrangle to the north. All three faults are entirely concealed by Quaternary deposits at the surface, which show no evidence of faulting, and the existence of faults in the subsurface is conjectural. Thus, the authors of this map do not believe that the faults are late Quaternary faults (if they exist at all), and we do not map them.

<u>Fault Group 2309—Northeastern Boundary faults</u>

The Northeastern Boundary fault system forms the northeastern margin of the upper Arkansas Valley graben between Leadville and Buena Vista. This group of eight faults lies mainly east and south of the Leadville South quadrangle. Only the northern tips of two faults enter the quadrangle, the Mike fault (extreme NE corner of the quad) and an unnamed fault at Kobe (south-central boundary of the quad). The Mike fault was described by Emmons (1886, p. 226-227) as "passing into an anticlinal fold on the west slope of Empire Hill" at its south end. On its north end "it cannot be traced north of Adelaide Park". These constraints limit the length of the Mike fault to about 3 miles, or much shorter than the 15 miles shown in Widmann and others (1998). Emmons also mentions that the Mike fault is a scissors fault, being downthrown to the west in its central part (maximum throw 1000 ft) but downthrown to the east in its northern part (maximum throw 300 ft). Neither Emmons (1886), Emmons and Irving (1907), or Emmons and others (1927) mention any evidence of Late Cenozoic movement on the Mike fault, and we doubt that it is a late Quaternary fault.

An unnamed, NNW-trending fault was mapped as extending 1 mile into the Leadville South quadrangle at Kobe by Tweto and Reed (1973. They show this fault as truncating a 4 mile-long, NE trending fault that ascends Big Union Creek and Little Union Creek (strand of the "Mosquito fault"). According to Widmann and others (1998), fault 2309 extends an additional 16 miles to the SSE, parallel to the Arkansas River. However, the cross-cutting relationships shown by Tweto and Reed (1973) between faults 2309, 2303, and the southern continuation of the Iron fault indicate that fault 2303 is oldest, being truncated by the two other faults (2309 and the Iron fault). This age sequence contradicts Widmann and others (1998), which lists fault 2303 as Quaternary and the Iron fault as pre-Quaternary. We do not map fault 2309 at all, not finding evidence for it in the field, although we did map fault 2303.

GEOLOGIC HAZARDS

Potential geologic hazards in the Leadville South quadrangle fall into four categories: 1) landslides, 2) floods and debris flows, 3) abandoned mined lands, and 4) seismicity and active faulting.

LANDSLIDES

Landslide deposits are relatively rare in the higher parts of the quadrangle where bedrock lies close to the surface, and exist only on the steep walls of incised drainages such as Iowa Gulch, and also sporadically in the Proterozoic granite terrain in the SE part of the quad. For example, in upper Iowa Gulch there is an opposing pair of slump-type landslides involving Pinedale till (and the underlying bedrock?), which in this area is the White Porphyry (Tw). Normally the White Porphyry does not landslide, so it is likely there is a fault at one or both landslide sites, which has weakened the bedrock and formed a conduit for groundwater underflow to saturate the till.

By far the largest landslides in the quadrangle occur in the Dry Union Formation in upper Empire Gulch (1.8 square miles) and between Dry Union Gulch and Big Union Creek (Mt. Massive Lakes landslide, 2.5 square miles). These large complexes include many slide lobes of different age, although the main style of landsliding seems to be retrogressive slumping. The failure plane is not exposed in either slide complex, but presumably lies within the lower part of the Dry Union Formation (Tdl), which is dominated by fine-grained, ashy deposits that may have altered to montmorillonite (USBR, 1981). The morphology of the Mt. Massive Lakes landslide suggests that the failure plane dips at a very shallow angle to the south, because the slide is clearly retrogressing to the north. USBR (1981) observed a 9° south- to southeast dip in the Dry Union near Mt. Elbert Forebay just west of our quadrangle. The apparent northwest dip of 5° in the headscarp of the Mt. Massive Lakes landslide at the Dry Union type locality has almost surely been rotated about 10-15° by landslide movement of the ridge south of Dry Union Gulch. This rotation is indicated by the 15° northward slope of the originally-horizontal pediment surface (QTa) mentioned earlier, and by the recent opening of headscarp tension cracks in the bed of Dry Union Gulch, which has created an 8 ft-deep arroyo parallel to, but separate from the water-eroded channel (Fig. 26). This pull-apart gash suggests that the entire ridge of Dry Union Formation south of Dry Union Gulch has slid about 2.5 m southward and 0.7-1.5 m downward relative to the terrain to the right. Presumably this slip reflects landslide movement on the incipient (new) headscarp failure plane of the Mt. Massive Lakes landslide, which has now retrogressed northward to the bed of Dry Union Gulch. A similar phenomenon is visible on the southernmost part of the high terrace west of the Arkansas River, directly north of Box Creek. Here a 2000-ft wide piece of the Dry Union Formation and overlying gravels (Qpboy) has detached and slid to the southward, rotating such that the pediment surface now dips 8° N (Fig. 27).

Figure 26. Photo looking west down the axis of a fresh tension crack that opened up in the bed of Dry Union Gulch, prior to 2005. There is no evidence of erosion by water in this crack. Note the water-eroded natural channel at left. County Road 52 is at far right. [UTM Z13, NAD27, 387500m E, 4336320m N].

The final category of landslide deposits is that of small to large hummocky masses that lie at the foot of nearly all the high terraces (Qboo, Qpbo, Qta) between about 9,400 and 9,500 ft elevation. The largest of these straddles the southern boundary of the quadrangle west of the Arkansas River and was named the "Kobe landslide" by Lee (2008). These landslides are peculiar for several reasons. First, there is no obvious arcuate landslide scar upslope of them. Second, their width is much greater than their length, which is anomalous for landslides. Third, at some mesas the deposits form a nearly-continuous rimming belt of hummocky topography, but are restricted to an elevation band below about 9,500 ft. These characteristics suggest that the landslides were thin, "sliver-type" failures of the mesa flanks, of the type that is commonly observed on reservoir margins after a rapid water drawdown (e.g., Schuster and Embree, 1980). Based on their elevation and association with paleo-shorelines of Three Glaciers

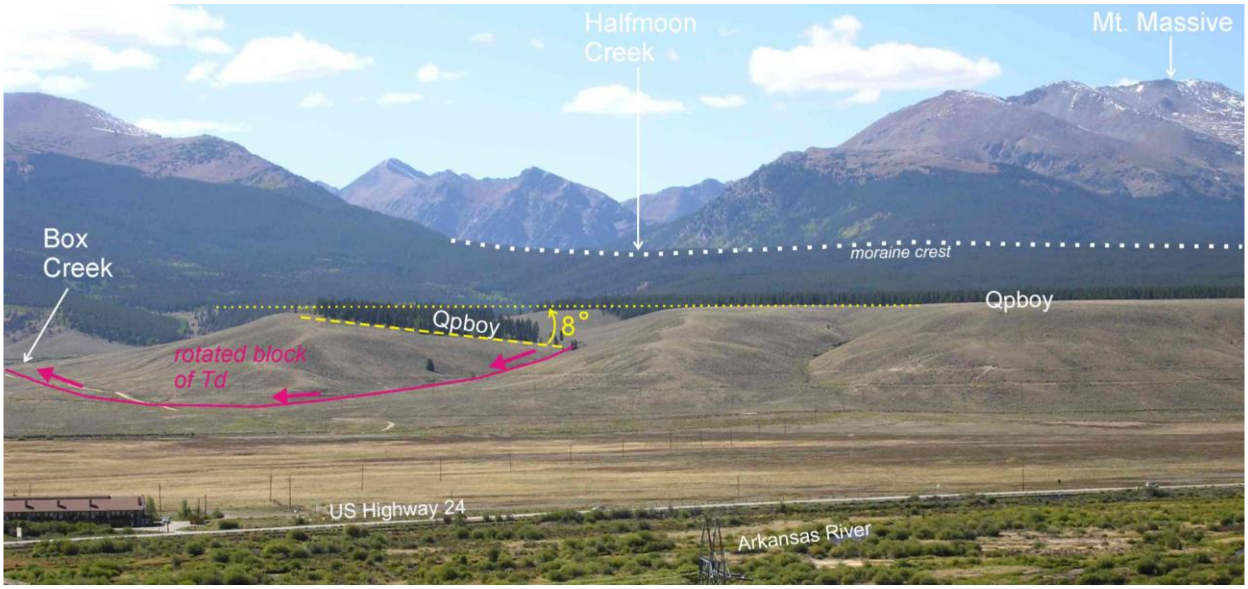

Figure 27. Telephoto view looking west at the rotated slump block (pink) involving the southernmost part of the high terrace (Qpboy) on the west side of the Arkansas River, opposite Kobe. Note the backtilt (down to the north) of the forested pediment surface. The failed slope was mostly submerged by the highstand of Three Glaciers Lake, thus the slump may have been triggered by rapid drawdown.

Lake, we agree with Lee (2005, 2008) that these deposits formed by failure of the mesa edges during rapid lowering of Three Glaciers Lake, caused by catastrophic draining of the lake(s) in the late Pleistocene.

FLOODS AND DEBRIS FLOWS

Intense summer rainstorms or rapid melting of deep snowpack during unusually warm spring thaws may cause localized flooding and debris-flow activity. For example, most of the area mapped as Holocene alluvium (Qal) in the quadrangle lies on modern floodplains and is potentially subject to flooding. A related hazard is that of sheetwash and sheetfloods at the heads of small drainages, debris flows in ephemeral and intermittent streams, and resulting deposition on alluvial fans. Such areas are generally mapped herein as alluvium/colluvium (Qac). All undissected Holocene alluvial fans (Qf, Qfy) are potentially subject to debris-flow deposition over most of their surfaces). Obvious historic debris flows have been placed in a separate debris-flow units (Qdf).

ABANDONED MINES

Collapse of abandoned mine shafts, tunnels, and excavated highwalls poses a potential hazard in the NE part of the Leadville South quadrangle, which lies in the historic Leadville Mining District (Emmons and others, 1927). Several deep vertical shafts are still open at the ground surface and pose a hazard to trespassers. Numerous shallow prospect pits are also present in the quadrangle, but most of these are partly filled with local slopewash and do not present a collapse hazard.

SEISMICITY AND ACTIVE FAULTING

The Leadville South quadrangle lies in the axis of the Rio Grande rift, a zone of Neogene crustal extension. The level of historic seismicity is low in the Colorado portion of this rift. A search of the USGS/NEIC Internet catalog of earthquakes "Preliminary Determination of Epicenters" (1973-2003 A.D.) reveals no instrumental or historical earthquakes within a 6 mile radius of the center of the quadrangle .

Despite this lack of historical seismicity, there are several Late Cenozoic faults in the quadrangle, all of which are normal faults associated with the Rio Grande rift (described in the Structural Geology section). The largest and arguably most active of the faults is the Mosquito fault (fault 2303). Previous work (Tweto, 1978; cited in Kirkham and Rogers, 1981) suggested that the Mosquito fault may have been active in late Quaternary time. However, Tweto's best evidence for recent movement was disproved by McCalpin and others (in prep.) in the Climax quadrangle. R.M. Kirkham (pers. comm.., 2008) alleges that Bull Lake moraines in the Mt. Sherman quadrangle have been faulted by the Mosquito fault. If true, this is the only evidence for middle to late Quaternary movement on the Mosquito fault, or on any other fault in the Leadville South quadrangle. By the common definitions used in the USA for an active fault (movement in the past 11,000 years) or a potentially active, capable fault (movement within the past 50,000 years), neither the Mosquito fault nor any of the other faults in the quadrangle qualify as active.

MINERAL RESOURCES

Metallic Minerals

Lode Mines of The Leadville Mining District

The Leadville Mining District, part of which lies in the NE part of the quadrangle, is one of the great metal producing districts of the world, having yielded 3.3 million oz of gold; 265 million oz of silver; 2,354 million pounds of lead; 1,936 million pounds of zinc; and 110 million pounds of copper (Cappa and Bartos, 2007). The ores are found in a 2,660-ft-thick section of Paleozoic sedimentary rocks that overlies Proterozoic basement and is intruded by Tertiary sills and dikes. Virtually all of the sedimentary rocks host ore, but the principal ore hosts are the three carbonate units: the Mississippian Leadville Limestone, the Devonian Dyer Formation, and the Ordovician Manitou Formation. The Leadville Limestone is by far the predominant host for carbonate replacement ore, containing approximately 80 percent of the total. A karst surface and associated karst-fill deposits (Molas Formation) mark the top of the Leadville Limestone and served to localize ore in some places. The stratigraphic section is rarely found intact within the district. Rather it is extensively intruded by a series of igneous dikes, sills, and plugs that can “inflate” the Paleozoic stratigraphy to two or three times its normal thickness, or segment it into islands or isolated blocks engulfed by porphyry.

The ore bodies in the Leadville district have been classified according to form into veins, stockworks closely related to veins, replacement deposits, and placers. The first two classes are found primarily in the siliceous rocks of the Minturn Formation and the Proterozoic crystalline rocks. The third class is found in the carbonate rocks mentioned above. The ore bodies of the first group are generally found in contact with sills of porphyry which were consolidated and fractured prior to deposition of the ore. This group is the least important commercially. The veins of the second group have been worked since 1868, but have also been of minor economic importance. Only a few stockworks have been found and they may be regarded as variations of the veins. The area of Proterozoic rocks is riddled with numerous small mines and prospect pits, the targets and yields of which are unknown.

Replacement deposits of the third group consist of large masses of sulfide minerals that were formed primarily in the Leadville Limestone (the “Blue Limestone” of Emmons and others, 1927), with secondary deposits found in the Manitou Formation (the “White Limestone” of Emmons and others, 1927). The replacement bodies commonly occur at certain horizons, locally called “contacts”, where structural conditions have controlled the mineralizing solutions and consequently, the concentration of the ore. The number of “contacts” varies with the number of porphyry sills and shale beds that act as impermeable boundaries to the ore bodies. In some places, ore has been mined at as many as ten or eleven “contacts”.

The ores are believed to have been deposited by high to moderate temperature magmatic waters during the multiple porphyry intrusive stages during the Tertiary. Large quantities of ore-bearing solutions accumulated in the magma reservoirs and rose upwards as faulting and fracturing allowed. Several periods of ore-solution activity are suggested by moderate temperature sulfide veins crosscutting higher temperature deposits. Differences in mineral composition of the deposits were determined largely by the types of rocks which the solutions passed and by the temperature at which reaction with the rocks took place.

Unfortunately, the Leadville district is inactive and all the historic mines were inaccessible when this report was written (except for the Black Cloud Mine in the Mt. Sherman quadrangle). Most of the preceding data were thus taken from Emmons and others (1927), Behre (1953), and the excellent summary by Cappa and Bartos (2007).

__Placers of the Leadville Mining District__

Two placer areas have yielded precious metals in the Leadville South quadrangle. The largest and earliest was California Gulch, where placer gold was discovered in 1860. The site of the tent city established by the placer miners (Oro City) lies in the bottom of California Gulch at the eastern boundary of the quadrangle. As noted by Cappa and Bartos (2007), the gold rush was over within a few years; however, placer operations continued through the 1930s (Parker, 1974, p. 12–28). Henderson (1926, p. 176) estimated the value of gold placer production from 1859 to 1867, mostly from California Gulch, as

$5.272 million (approximately 164,000 oz of gold at an average price of $32 per ounce during the Civil War years).

The placer gold was mined in California Gulch from both modern alluvium (Qal, Qat) and high-level terrace gravels (Qboy, Qboo, Qpboy). The irregular gold flakes and nuggets came mostly from the prolific lode deposits of Printer Boy Hill, which lies on the south side of California Gulch directly east of the eastern boundary of the quadrangle. California Gulch gravels do not contain placer gold upstream of Printer Boy Hill. Cerussite ($PbCO_3$) occurred in the placer deposits of upper California Gulch, and it interfered with gold recovery from the sluice boxes. When it was finally identified, it guided prospectors to the rich lead-zinc-silver lode deposits of the Leadville district (Parker, 1974).

Other nearby gulches on the west flank of the Mosquito range were also prospected for placer gold (e.g., Evans Gulch, Iowa Gulch), but these had been scoured by Pleistocene glaciation that removed the gold placers; only California Gulch had significant quantities of alluvial gold. Today the bed of California Gulch is all disturbed with mine waste and artificial fill from Oro City down to Leadville, and then a mixture of fill, mine waste, slag, and tailings, and rare undisturbed alluvium down to the Arkansas River. Due to the existence of the California Gulch Superfund Site, it is unlikely that any future placer mining can be accomplished there, even if there were a gold resource.

The second placer area in the quadrangle is the Derry Ranch placer on Box Creek, located near the southern boundary of the quadrangle west of the Arkansas River (labeled “dredge tailings” on the base map). According to Parker (1974, p. 50-64), placer mining commenced in 1915 with the construction of a 6-cu-ft dredge for the Empire Dredging Company. The Company stated that the gravels (map unit Qal at the surface, but probably contains Pinedale outwash below) were 35 ft thick and had a value of $0.20 per cu yd (at a gold price of $20.67 per ounce). The basal gravels lay on a bed of clay correlated by Parker (1974) with the Lake Beds of Emmons and others (1927), although it is possible that the clays are actually much younger Quaternary lacustrine deposits from Three Glaciers Lake. 80% of the gold was found within 6” of the gravel/clay contact. The dredge worked these gravels until 1932 when it was dismantled. Other companies worked these Derry Ranch placers until 1951, contributing to an estimated total production >$1.3 million, or roughly ¼ the yield of the California Gulch placers.

Industrial Minerals

Although gravel is abundant in the Upper Arkansas Valley, the gravel deposits of the high terraces (Qboo, Qpboy, Qoa, QTa) are all too weathered to be of much use in construction except as bulk fill. Present and past gravel pits developed for aggregate have been restricted to the younger terraces (Qboy, Qpoo, Qpo, Qat) and the modern floodplain (Qal). For example, the two largest operating gravel pits in the quadrangle are located on the older Pinedale outwash fan of Halfmoon Creek. Glacial till deposits have been quarried for bulk fill in the past (e.g., Figs. 1, 12), but they tend to include finer-grained material along with sand and gravel and would require washing and processing for many construction uses.

GROUND-WATER RESOURCES

Groundwater resources in the Leadville South quadrangle include groundwater in bedrock formations along the eastern third of the quadrangle, and groundwater in Quaternary deposits in the western two-thirds of the quadrangle. Although the largest area of exposed bedrock in the quadrangle lies in the Proterozoic granite terrain of the SE quadrant, there are no wells in that terrain and we know no details about its hydrologic regime. In contrast, there was considerable previous work done on the groundwater regime in Paleozoic/Tertiary rocks of the Leadville Mining District , because of the importance of dewatering the mines. The southern termini of both the Leadville Drainage Tunnel and the Yak Drainage Tunnel lie within the quadrangle.

Groundround-Water in Bedrock of the Leadville Mining District

The following is summarized from Turk and Taylor (1979). Groundwater in the Leadville Mining District occurs in granite, quartzite, limestone, sandstone, and porphyry dikes. These rocks form a single aquifer because the formations are hydraulically connected through physical contact (superposition), fracturing, faulting, and numerous mine workings and exploratory boreholes. In the area of the Leadville Drainage Tunnel, the southern end of which lies1.15 miles east of Harrison Avenue on the northern boundary of the quadrangle, the water level in wells stood 40-50 ft below the ground surface in 1978. This compares to water level depths of 65-161 ft in 1940-1944, which were probably depressed somewhat by artificial pumping of mines.

The bedrock aquifer is recharged by precipitation at and above Leadville and water moves mainly westward (parallel to surface contours), and also slightly toward California Gulch (the deepest incised gulch) and probably towards Evans Gulch. Groundwater discharges out of the bedrock aquifer into the valley of California Gulch, either to the channel itself or to the valley-fill alluvium beneath the channel (the relative proportions are unknown). Groundwater levels in wells east of downtown Leadville seasonally rise 7 to 15 ft due to influx of spring snowmelt and summer rainfall. Pump tests in mine shafts indicate that the combined bedrock aquifer has a bulk transmissivity of 400-1100 ft^2/day at a drawdown of 733-891 ft (cited in Turk and Taylor, 1979).

Ground-water in Quaternary Deposits of the Upper Arkansas Valley

The following discussion is based on data from 377 water wells in the quadrangle that have information on well depth, depth to water level, or yield (Fig. 28). In general, the depth to groundwater in Quaternary deposits is directly proportional to how high the well head lies above the nearest stream, that is, the local topographic relief. The yield of a well is directly proportional to the gravel content and inversely proportional to the clay content of the deposit, the latter of which generally increases with age. As a result, on young geomorphic surfaces near stream level, such as Holocene terraces (unit Qat) and Pinedale outwash terraces (unit Qpo), depth to water level is shallow (less than 20 ft in 2/3 of the wells) and well yields are high (80% of wells have yields of 15 gpm or higher; 20% have yields of 30 gpm

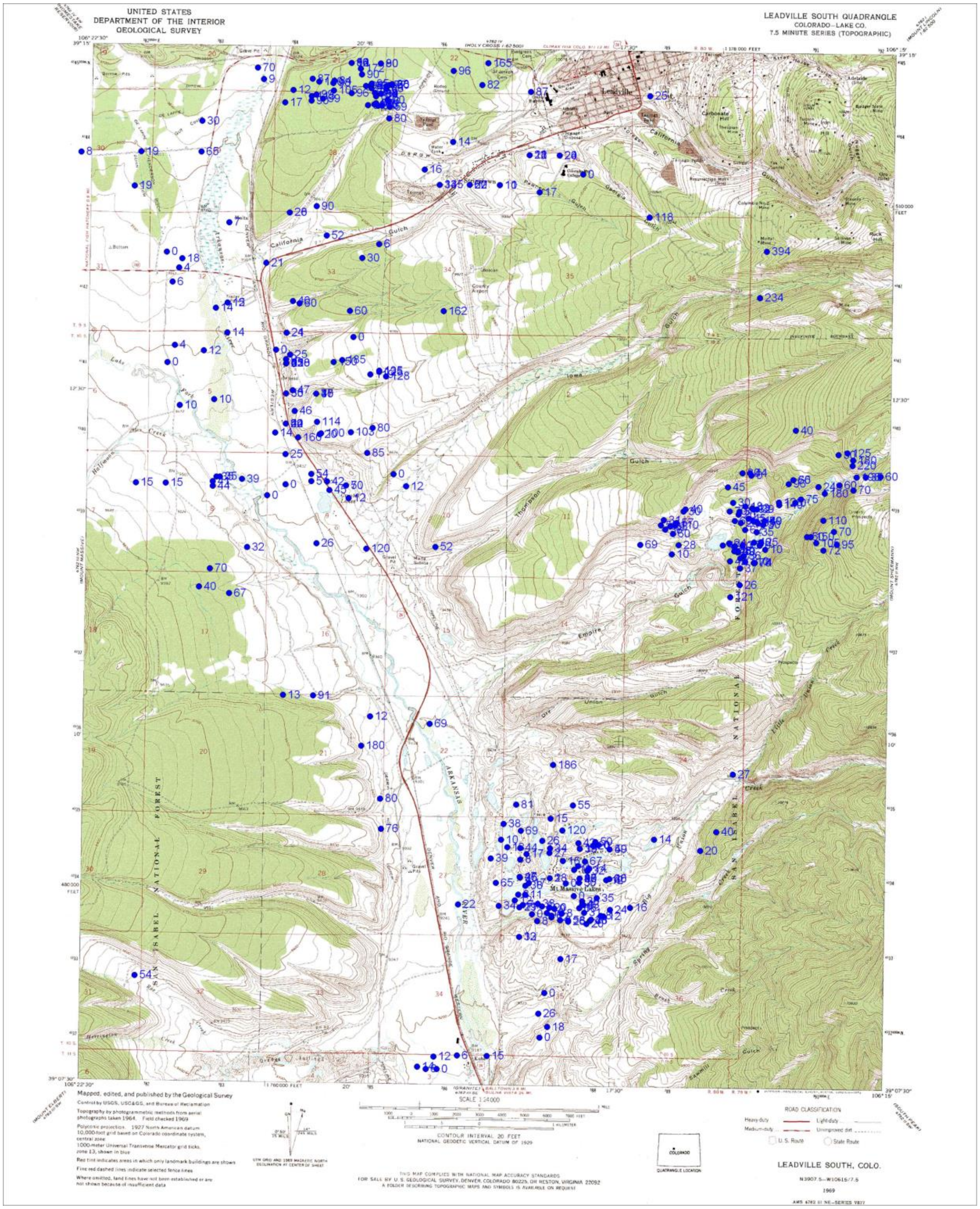

Figure 28. Map of 377 water wells in the quadrangle, labeled with depth of static water level below ground surface. Data from Colorado Division of Water Resources, 2009.

or higher). On slightly higher and older terraces (unit Qboy), water levels are slightly deeper (12-24 ft) and yields lower (1-38 gpm). More details are given in Table 2. According to Turk and Taylor (1979), Pinedale and Bull Lake till and outwash deposited in the south lateral moraine complex of the East Fork Arkansas River, just north of the quadrangle, have horizontal hydraulic conductivity of about 50 ft/day, transmissivity of 2300 ft2/day, and specific yield of 0.3.

Table 2. Water well data from the Leadville South quadrangle, grouped by the geologic map unit containing the wellhead (listed from youngest to oldest). The rows in this table represent clusters of wells representing 272 of the 377 wells in the quadrangle. The remaining wells are scattered widely throughout the quadrangle and among many map units.

Map Unit Abbrev.[1]	Location	Number of Wells with Good Data	Depth to Water Level (ft)		Yield (gpm)		Depth of Well (ft)	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Qat, Qpo	Low terraces of the Arkansas River, Lake Fork, Halfmoon Creek	35	23	21	21	19	63	33
Qpt	Beaver Lake Estates	4	139	82	6.8	5.6	258	99
Qpt	Iowa Gulch	2	314		6.5		373	
Qbt	Beaver Lake Estates	7	114	67	7.3	2.6	202	100
Qlsc	Beaver Lake Estates	56	42	23	11	4	99	46
Qlsc	Mt. Massive Lakes	90	26	21	11	6	66	33
Qpbo	W edge of "Airport mesa" high terrace	27	83	51	14	6	132	62
Qboo, Qpbo	West of Leadville	51	83	34	12	7	123	35

[1] Qat, Holocene terrace; Qpo, Pinedale outwash; Qpt, Pinedale till; Qby, Bull Lake till; Qlsc, landslide complex; Qboo, older Bull lake outwash; Qpbo, pre-Bull Lake outwash.

On the high terraces (units Qboo, Qpbo, QTa) water levels are normally deep (averaging 83 ft with a large standard deviation of 34-51 ft), reflecting the deep topographic incision by local streams into the mesas. However, some wells apparently produce water from local water bodies at depths of only 40-60 ft, probably from water perched at the erosional unconformity between coarser Quaternary gravels and the underlying Dry Union Formation. Well yields are moderate to low (12±7 gpm on surfaces west of

Leadville; 14±6 gpm on the Airport surface SW of Leadville), due to the stronger weathering and higher clay content of the old alluvium, and/or the uppermost part of the underlying Dry Union Formation.

The largest concentrations of water wells in the quadrangle (157 wells) are found in two mountain subdivisions, Beaver Lakes Estates in Empire Gulch (67 wells) and Mt. Massive Lakes subdivision north of Big Union Creek (90 wells). Both subdivisions are built on giant landslide complexes (map unit Qlsc). Depth to water tends to be shallower at Mt. Massive Lakes (26±21 ft) than at Beaver Lakes (42±23 ft), probably because the former lies closer to stream level and groundwater levels are kept high by an extensive system of artificially-fed lakes. Well yields in the two landslide complexes are moderate and essentially identical (11±6 gpm at Mt. Massive Lakes, 11±4 gpm at Beaver Lakes).

The lowest well yields in the quadrangle are encountered in glacial till, such as Pinedale till at Beaver Lakes (6.8±5.6 gpm) and Iowa Gulch (6.5 gpm), and Bull Lake till at Beaver Lakes (7.3±2.6 gpm). These low yields probably reflect two factors: (1) the high amount of matrix clay in the tills, reducing their permeability, and (2) the fact that the wells are so deep on average, that much of their production may be coming from relatively tight Dry Union Formation beneath the till. Due to the high elevation difference between the moraines and the nearby incised streams, wells in moraines have the greatest depth to water of any in the quadrangle, averaging 114 ft to 139 ft at Beaver Lakes, and 314 ft in the deep wells sunk into the Pinedale lateral moraines of Iowa Gulch. The Iowa Gulch wells indicate how depth to groundwater generally increases towards the eastern margin of the quadrangle, as the depth of stream incision into the high terraces increases.

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