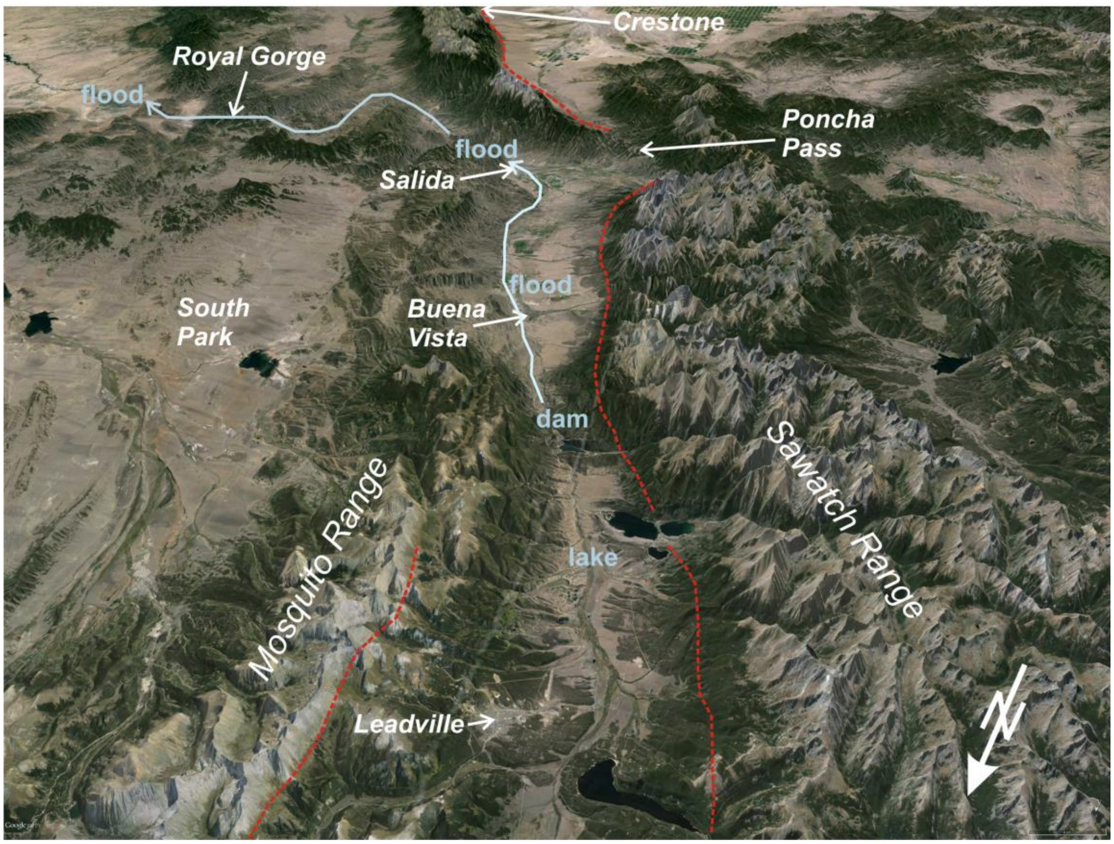
Neotectonics and Quaternary Geology of the Upper Arkansas Valley— Active Faults, Glaciers, Ice Dams, Landslides, Floods

Post-Meeting Field Trip for the
Workshop on Paleoseismology, Active Tectonics, and Archaeoseismology
Focus Group on Paleoseismology and Active Tectonics
INQUA Terrestrial Processes Commission
03-JUNE-2016



Looking south down the axis of the Upper Arkansas Valley; active faults in red.

Edited by J.P. McCalpin
Trip Leaders:
James P. McCalpin, Alan R. Nelson, Dean Ostenaa, Richard P. Smith,
Vince Matthews

Guidebook 11
Crestone Science Center
P.O. Box 837
Crestone, CO 81131 USA
27-MARCH-2016

Neotectonics and Quaternary Geology of the Upper Arkansas Valley— Active Faults, Glaciers, Ice Dams, Landslides, Floods

LEADER: James P. McCalpin, GEO-HAZ Consulting & Crestone Science Center, Box 837, Crestone, CO 81131; phone (719) 256-5227, cell phone (719) 588-4279, mccalpin@geohaz.com

CO-LEADERS: Dean Ostenaa, Ostenaa Geologic LLC, 25 Grays Peak Trail, Dillon, CO 80435; deano3geo@gmail.com

Alan R. Nelson, U.S. Geological Survey, 1711 Illinois St., Golden, CO 80401; phone (303) 273-8592; anelson@usgs.gov

Richard P. Smith, Smith Geologic and Photographic Services LLC, 13786 Schroger Rd. Nathrop, CO 81236; phone (719) xxx-xxxx; rps3@ridgeviewtel.us

Vincent Matthews, Leadville Geology, Leadville, CO 8, phone (303) 798-7698, leadvillegeology@gmail.com

Trip Sponsor:

Crestone Science Center, Inc.

Education and Research in the Earth Sciences

TABLE OF CONTENTS

PATA POST-MEETING FIELD TRIP ITINERARY (Friday, June 3, 2016)

CRESTONE-PONCHA PASS-EDDY CREEK-MT. PRINCETON HOT SPRINGS-COGAN HORST-BUENA VISTA-TWIN LAKES-LEADVILLE-CLIMAX-COPPER MOUNTAIN-SILVERTHORNE-EISENHOWER TUNNEL-DENVER

The Post-Meeting Field Trip (all day Friday, June 3) travels from Crestone to the Best Western Plus-DIA hotel near the Denver International Airport, a 230-mile (370 km) route. The trip provides transport back to Denver for those Registrants who traveled to Crestone on the bus of the Pre-Meeting Field Trip, or anyone else who wants to return to Denver. The Field Trip bus will leave from the Desert Sage Restaurant in Crestone after breakfast on Friday, at 8 am. Estimated arrival time in Denver is 7 pm.

Unlike the Pre-Meeting Field Trip, this field trip will have multiple geologic stops where we will examine Quaternary landforms and deposits such as fault scarps and landslides. Some short walking will be required, on gentle terrain.

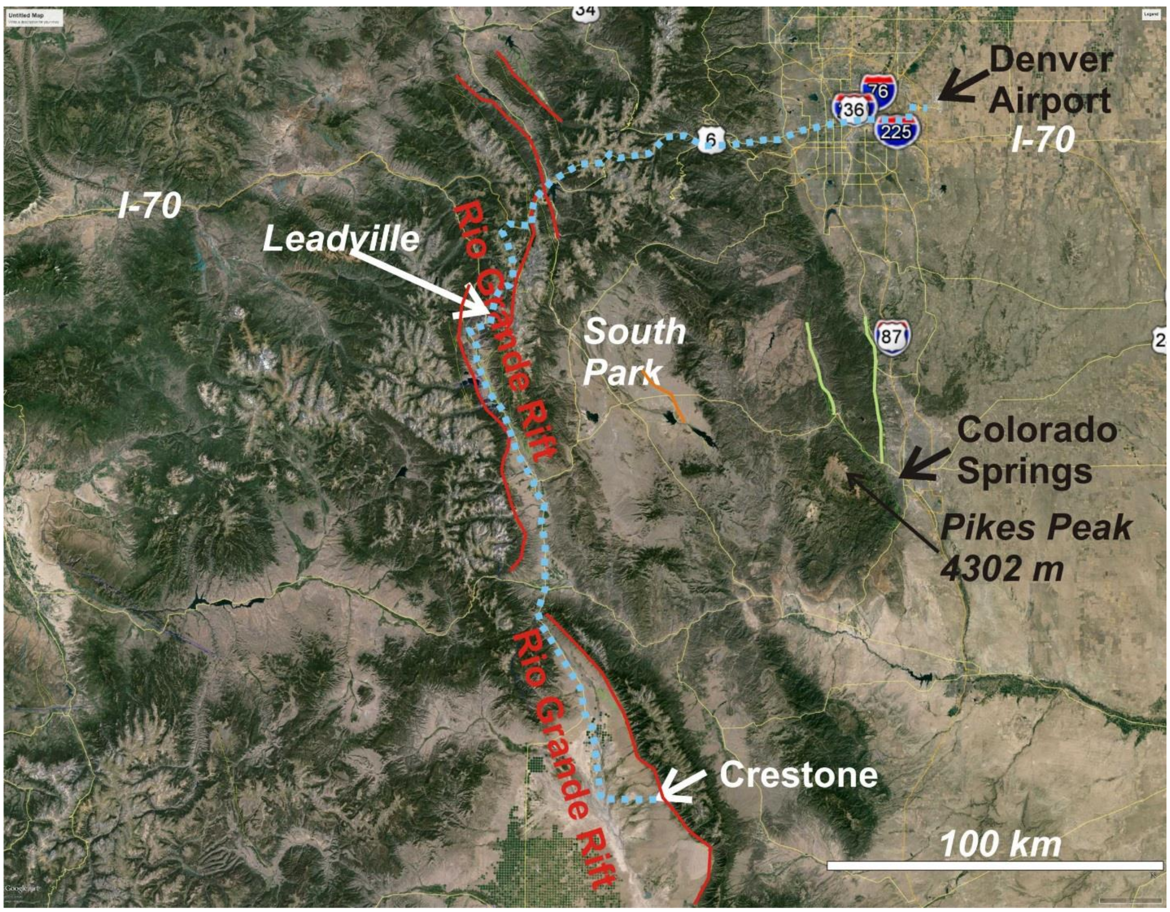


Fig. 1. Route of field trip (blue dotted line) superimposed on a Google Earth image of Colorado. The route goes north from Crestone on Colorado Highway 17, then merges with US Highway 285 and continues to Buena Vista. From Buena Vista we travel north on US Highway 24 through Leadville, then onto Colorado Highway 91 and over Fremont Pass to Copper Mountain. At Copper we intersect Interstate Highway 70 and drive east over the Continental Divide to Denver.

INTRODUCTION and Acknowledgements

This field trip will have multiple geologic stops where we will examine Quaternary landforms and deposits such as fault scarps and landslides. Some short walking will be required, on gentle terrain.The morning part of the trip concentrates on active rift-margin and intra-rift faults in the southern part of the Upper Arkansas Valley. Lunch will be on the banks of the Arkansas River at Riverside Park in Buena Vista. The afternoon stops will show evidence of the glacial damming of the Arkansas River, the lake behind the dam, and the catastrophic outburst floods. Depending on time, there may be an opportunity to visit the drinking establishments of Leadville, a rough mining town. The final afternoon stop will be at the Fremont Pass (elevation 3450 m) and Climax Mine, the world's largest molybdenum mine. From there, we will travel east on Interstate Highway 70 through the Front Range and back to Denver.

ROAD LOG

Mile

0.0 *DEPART 8 am from Desert Sage Restaurant, Crestone, CO; drive NE on Townhouse Entrance Road for 0.2 mi*
0.2 *Turn L (N) onto Camino Baca Grande; drive for N for 0.15 mi*
0.35 *turn L (W) onto County Road T; drive 12.0 mi to Moffatt*
12.4 *turn R (N) onto Colorado Highway 17 and proceed N*
26.1 *Highway 17 merges with US Highway 285; continue N*
36.2 *town of Villa Grove*
44.7 *Poncha Pass (elevation 2746 m; the divide between the Upper Arkansas Valley and the San Luis Valley)*

OPTIONAL STOP 0 at Poncha Creek roadcuts?

Email from Scott Minor, USGS, 04-JAN-2016; "*Although Jonathan has spent the most time looking at the geology in lower Poncha Canyon, the two of us have examined some features exposed in one of the large road cuts on the west side that* ***appear to be low-angle slide surfaces bounding intensely shattered (but not disaggregated) basement rock****. Clearly oxidizing fluids have flowed through these highly fractured rocks, depositing reddish Fe oxides. We have* ***tentatively interpreted there features as the basal slip planes of a paleo landslide complex that slid into a more youthful (less deep) Poncha Canyon****.* ***There is little/no geomorphic expression of the landslide, suggesting that it is relatively old.*** *Indeed, there are also numerous rooted (tectonic) brittle shear/fault zones cutting the Proterozoic rocks in the canyon, so it can be quite tricky distinguishing such structures from landslide structures and related deformation*".

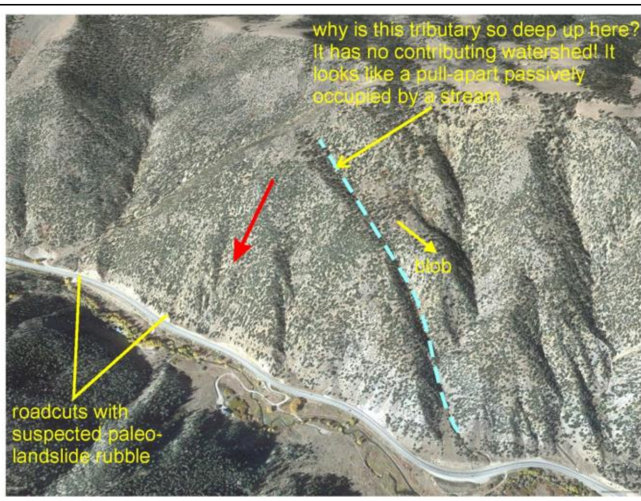


Fig. 0-2. Google Earth oblique image of the west valley wall of Poncha Creek, at the site of the roadcuts exposing low-angle shear zones and pervasive fracturing (lower left). The distinct shear planes at the base of the roadcut dip out of the slope at a relatively shallow angle, raising the possibility they are landslide shear planes, not tectonic faults. The entire rock mass here is shattered over a broad area, which does not show the core vs damage zone pattern typical of tectonic faults. Instead, the rock mass appears to have been shattered by a uniformly-applied external force. The ridge above the roadcuts has some anomalous tributaries that cut into the slope at an angle oblique to the fall line, which appear to be structurally controlled.

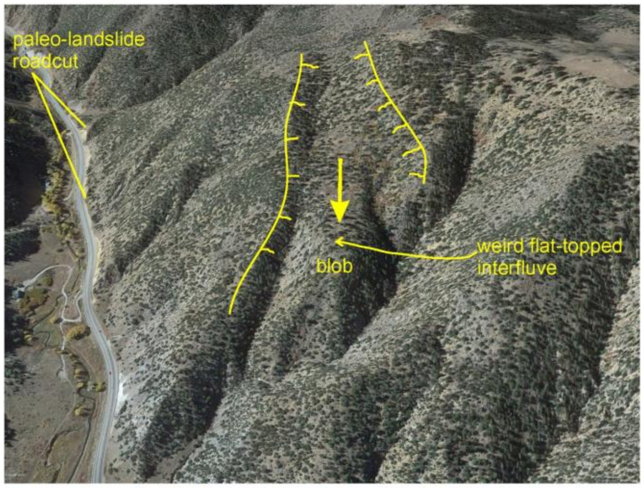


Fig. 0-3. The slope above the landslide contains anomalous sidehill gullies and scarps (yellow) that are more parallel than perpendicular to contours. One interpretation of these odd gullies and the flat blob between them, is that they represent a downdropped gravity block above a slope that has failed outwards downslope. This would be like the headscarp graben or pull-apart zone in a landslide. However, the fact that the graben is still preserved on the steep slope means that the rock mass did not slide very far downslope. This accords with the deformation observed in the roadcut.

Mile

52.2 Town of Poncha Springs and junction with US Highway 50; continue straight north through stoplight
52.7 Junction with US 285 N; turn R (N) and proceed N on US 285
59.7 junction with Colorado Highway 291 to right; mouth of Brown's Canyon 1.3 miles to the East; continue N on US
64.8 junction with County Road 272; turn W and drive 2.3 mi
67.1 Forest Boundary; road turns to Forest Road 272; continue W 1.1 mi
68.2 Forest Road 272 turns to South; continue straight on Forest Road 274 for 0.3 mi
68.5 Forest Road 273 goes off to L (W); continue on FR 274 for 0.6 mi
69.1 fork in road; FR 274 goes to L, FR 274A goes to R; take 274
70.1 FR 274A rejoins route from E; continue on FR 274
70.3 road begins curving to N; fault scarp in Pinedale outwash (Trench ET-2) lies 70 m to W

STOP 1- EDDY CREEK TRENCHES ON THE SAWATCH FAULT (9:30 am; MI 70.5; 45 min stop); Stop Leaders-Dean Ostenaa, Alan Nelson

INTRODUCTION

In 1978 –1981, we participated in an extensive seismic hazard investigation for Bureau of Reclamation facilities in the upper Arkansas valley. As part of this investigation, geologic reconnaissance mapping was conducted throughout the upper Arkansas Valley to identify evidence of potential late Quaternary fault activity and to extend existing mapping of Quaternary deposits as a basis for assessing fault activity. Fault scarps along the southern awatch fault from the area of Buena Vista to west of Salida were mapped in detail, profiled, and trenched in two locations near Cottonwood and Eddy Creeks (Fig. 1).The results of the seismic hazard investigation were compiled into a draft report in 1981and used in internal Reclamation engineering analyses, but were never finalized or widely circulated. Parts of the study have appeared in publications, including a short summary of slip rate and recurrence data (Ostenaa et al., 1981), fault scarp maps and scarp profile data for the Sawatch fault (Colman et al., 1985), and a discussion of Quaternary mapping and soil relative-age data for the area near Twin Lakes and Leadville (Nelson and Shroba, 1998).

At this stop, we will walk along the fault scarp near Eddy Creek where it cuts Bull Lake and Pinedale glacial deposits (Figs. 1 and 2). Two trenches were excavated at this site in 1978-1979 on private property located within the National Forest boundaries.

SETTING

The upper Arkansas Valley between Salida and Leadville is the northernmost of themajor rift basins, defined by thick sections of Neogene fill, that define the Rio Grande Rift (Tweto, 1978, 1979; Kellogg, 1999). Structurally and topographically, the upper Arkansas Valley can be viewed as two distinct but coeval grabens, bounded on the west by a major fault at the base of the Sawatch Range (Fig. 1). Both grabens contain thick sections of Neogene fill and are likely broken by numerous intra-graben and secondary aults along their eastern margins. The southern graben extends from near Salida to north of Buena Vista. The northern graben extends from near Twin Lakes to just north of Turquoise Lake. South of Twin Lakes, a narrow extension with some Neogene fill extends to Clear Creek, where the Arkansas River flows from the north graben to the south graben through a narrow canyon over a bedrock high.

Recurrent late Quaternary displacement in the south graben is demonstrated by sharply truncated east-trending spurs, faceted at the west valley edge along a north-trending lineament coinciding with the trace of the southern Sawatch fault. From the North Fork of the South Arkansas River to about North Cottonwood Creek, mid-Quaternary alluvial deposits (Nebraskan of Scott, 1975) appear to be in fault contact with pre-Quaternary bedrock between the major drainages. Along the range front in this area, the fault contact is evidenced by a steep, linear, slightly to moderately dissected bedrock escarpment rising at least several tens of meters above the alluvium (Fig. 1). This relationship is exposed above a trail crossing the fault in the SW1/4 section 13, north of Chalk Creek. At this location an approximately 1-m-wide shear zone in alluvium separates mid-Quaternary alluvium from hydrothermally altered Tertiary intrusive rock.

Shear fabric in the alluvium and the rock contact dip 55° east (Fig. 9). Geothermal exploration drilling 1 km northeast indicates the presence of at least 600 m of Quaternary and Tertiary alluvium (D. Pilkington, Amax G.P., pers. comm., 1980).

Late Quaternary glacial deposits in the Rocky Mountain region are commonly assigned tothe informal allostratigraphic units “Bull Lake,” and “Pinedale.” We have no numerical ages for deposits in the upper Arkansas Valley, but on the basis of our soil relative-agedata (Table 1; Fig. 3) we suggest that the major deposits are broadly correlative with deposits of the Pinedale and Bull Lake glaciations (see discussion and references in Nelson and Shroba, 1998; reprint to be handed out on trip). Studies of the past two decades employing radiocarbon, obsidian hydration, and Uranium-series dating indicate ages of about 14 to 47 ka for deposits of the Pinedale glaciation, 130 to 160 ka for deposits of the Bull Lake glaciation, and 300 to 700 ka for deposits of one or more pre-Bull Lake glaciations. Recent cosmogenic-isotope dating of the surfaces of boulders on moraines in the Wind River Range of Wyoming yields ages of 16-23 ka for Pinedale moraines (Grosse et al., 1995), 95-130 ka for two groups of Bull Lake moraines of differing relative age, and >130 ka for moraines from two older glaciations that were previously mapped as Bull Lake (Phillips et al., 1997; Chadwick et al., 1997).

Moderate to large drainages have cut embayments into the range front, which are now floored with late Quaternary alluvial deposits. In many locations scarps present in the deposits trend directly into the bedrock/alluvial escarpment . Elsewhere, due to the en-echelon character of the scarps, scarps may occur up to 1 km from the range front. Heights of the scarps are up to 3.5 m on Pinedale surfaces and up to 11 m on Bull Lake surfaces. The scarps occur in groups several kilometers in length and are separated by several hundred meters to a kilometer from adjacent groups in right en echelon arrangement. The ends of the range front-bounding scarp groups comprising the Sawatch fault generally do not overlap significantly (a exception to this observation is seen at the Cottonwood Creek trench site, Fig. 1), but numerous linear features in the basin paralleling the range front have been noted on airphotos to overlap one another (Scott,1975). Along major streams, such as Cottonwood Creek, Holocene alluvial deposits cover the scarp, but along minor drainages streams are usually incised to the base of the scarp. Alluvial fans are nearly always present on the downthrown surface immediately adjacent to the scarp, and the minor drainages are often incised into the fans. Maximum scarp slope angles average 24°, with a range of 11° to 33° (e.g., Colman et al., 1985).The scarps, particularly those on Bull Lake surfaces, are frequently characterized by multiple slope breaks suggesting that the scarp was produced by at least two earthquakes.

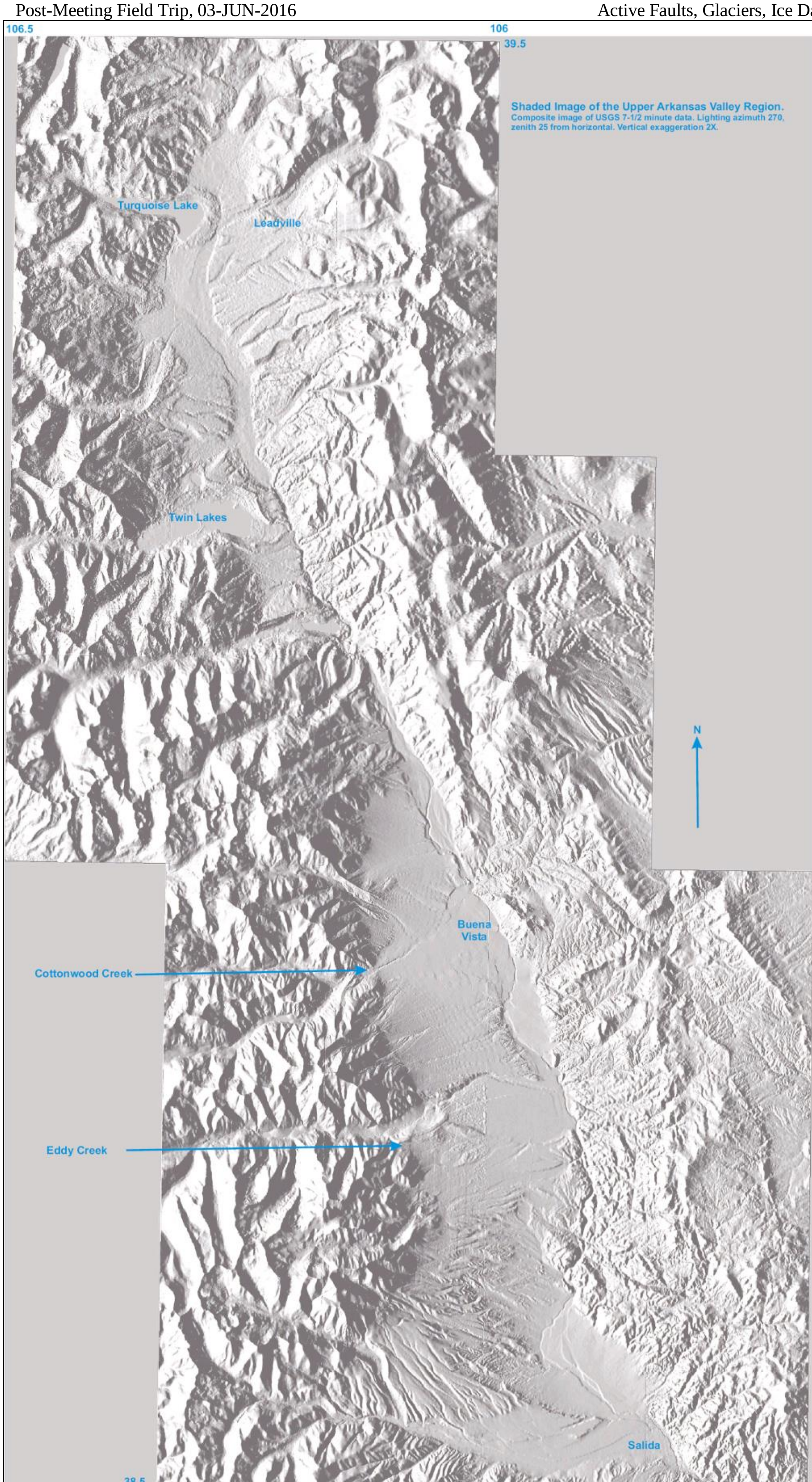


Fig.1-1. Shaded relief image of the upper Arkansas valley produced from USGS 7.5 min DEM data. Field trip Stop 1 is at Eddy Creek in the lower half of the image. The fieldtrip route is up the center of the valley along the Arkansas River from Poncha Springs to Leadville.

Inset A shows location of the upper Arkansas Valley (lightly shaded area between the Sawatch and Mosquito ranges) in central Colorado. Light dashed line shows the boundary of the informal designation of the northern and southern parts of the upper Arkansas Valley. Darkly shaded area locates map A within the state of Colorado (inset in A). Triangles mark major mountain peaks.

Eddy Creek Trench Site

The Eddy Creek Trench Site is located in the SE1/4 NE1/4 of sec. 36, T. 15 S., R. 76 W.,16 km southwest of Buena Vista (Fig. 1). Two trenches were excavated across scarps in deposits mapped by Scott et al. (1975) as younger Bull Lake outwash and by us as Bull Lake and Pinedale.

In the vicinity of the trenches, patches of Bull Lake outwash are separated from one another by drainages and are bounded on the south and west by colluvium mantling Tertiary quartz monzonite porphyry of the Mt. Princeton batholith (Ti) and on the north and east by Pinedale outwash (Fig. 2, 4 and 5). North of the trenches, younger Eddy Creek alluvium overlaps and grades into the Pinedale outwash. A 50-m high Bull Lake lateral moraine bounds the Pinedale channel on the north. Further north, nested within this moraine, are hummocky Pinedale lateral moraines of lesser height.

The Sawatch fault is expressed by a single scarp near the Eddy Creek trenches. South of the trench site, the scarp trends north-northwesterly at the base of the range front, separating bedrock from colluvium and alluvial fan materials (Fig. 1 and 5). It abruptly urns northward about one-half km south of the trenches, and trends through glacial deposits for 1 km, ending at the Pinedale lateral moraine north of the trench site. North of Chalk Creek, the range-front, which is bounded by a normal fault dipping 55° east, steps eastward by about 1 km.

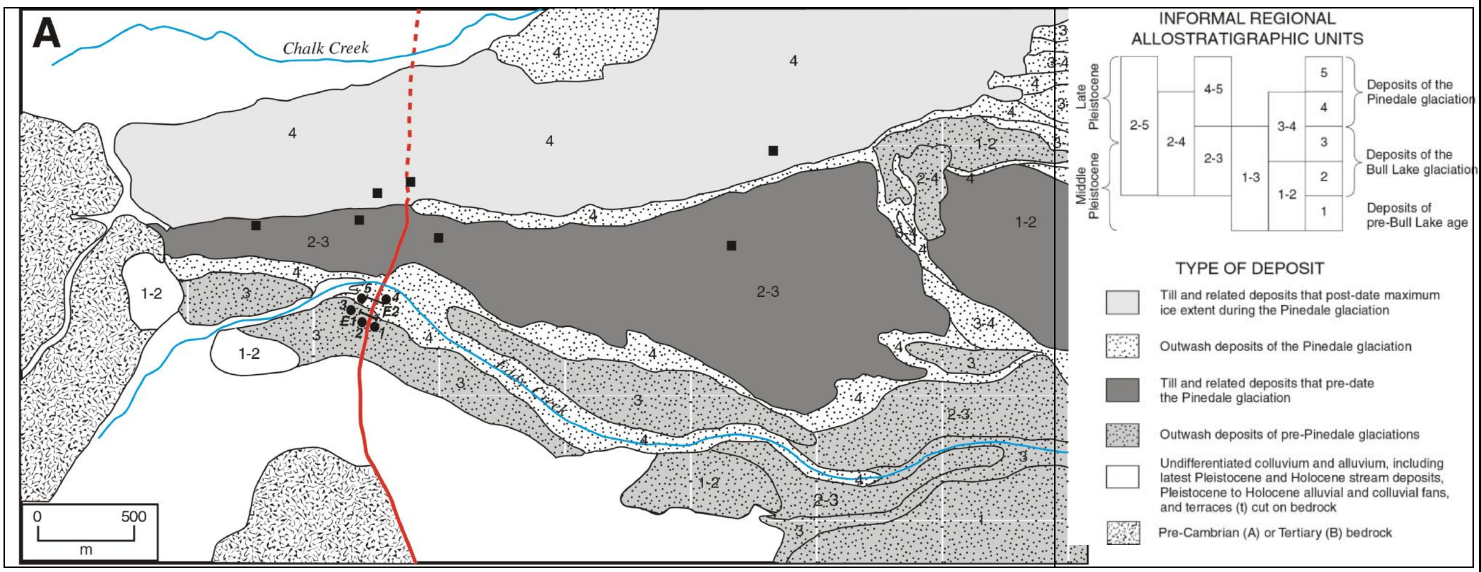


Figure 1-2. Map of glacial deposits (primarily till and outwash) of the Pinedale and Bull Lake glaciations at the Eddy Creek trench site. Late Pleistocene to Holocene colluvium and alluvium, including small colluvial fans overlying till and outwash, and postglacial to Holocene stream alluvium are not mapped. Soil index data for profiles (labelled dots) is shown in Figure 3 and Table 1. Data from boulder weathering sites are discussed by Nelson et al. (1984, Part I). Mapped units are informal allostratigraphic units of the North American Commission on Stratigraphic Nomenclature (1983). The terms Pinedale and Bull Lake glaciations are used in the sense of diachronic events, as proposed by Johnson et al. (1997). Numbers show relative-age groups based on correlations with the sequence of outwash and alluvial terraces northwest of Leadville (Fig. 1) discussed by Nelson and Shroba (1998).

Surface offset is 8 to 9 m in Bull Lake outwash and the scarp is moderately to deeply dissected by streams that have cut to or below the base of the scarp (Fig. 4 through 7).Surface offset in the Pinedale outwash is about 3.7 m and the scarp is slightly dissected. On the surface, the fault scarp at the trenches is bouldery on its upper portion and relatively free of boulders on its lower portion. This difference in surface boulder frequency indicates deposition of a wedge of relatively fine-grained colluvium subsequent to faulting events. A decrease in scarp height northward in the Pinedale alluvium probably resulted from deposition of late Pinedale and Holocene alluvium by Eddy Creek. Adjacent to Eddy Creek the scarp is not present.

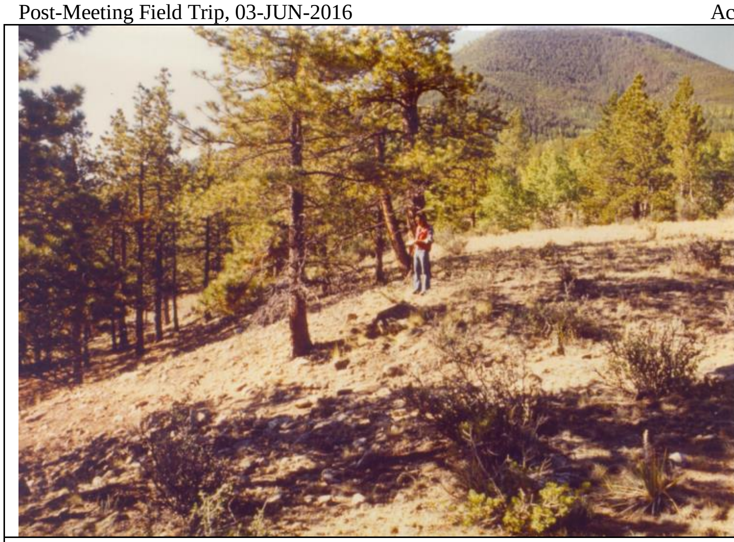


Fig. 1-3, LEFT: Fault scarp in Bull lake outwash near Eddy Creek trench 1, looking South. Scarp is about 8 m high.

RIGHT: Same scarp looking North. Tree-covered ridge in background is Bull Lake moraine (south lateral moraine of Chalk Creek). Scarp in moraine is about 48 m high.

On the north side of Eddy Creek, the scarp trends north through the Bull Lake moraine and is marked by a 48-m step in the moraine crest (Fig. 4 Right). This step is of far greater height than the scarp in the approximately correlative Bull Lake outwash at the trench site, suggesting that not all of the step in the moraine crest is directly attributable to faulting. In addition, marked differences in morainal morphology across the step suggest a nontectonic influence on scarp development. Kirkham and Rogers (1978) reported an 8-m scarp in the Pinedale moraine south of Chalk Creek, but our field mapping could not confirm unequivocal evidence of a fault scarp in this moraine. Numerous irregular ridge crests with both east and west-facing scarps are present; most have an ice-contact origin but some are probably part of the fault scarp. As with the scarp in the Bull Lake moraine, the apparent scarp height in the Pinedale moraine is significantly greater than in the correlative outwash. Part (but not all) of this height discrepancy might be explained by earthquakes postdating the deposition of the Bull Lake moraines and predating the end of fluvial activity on the Bull Lake outwash surface.

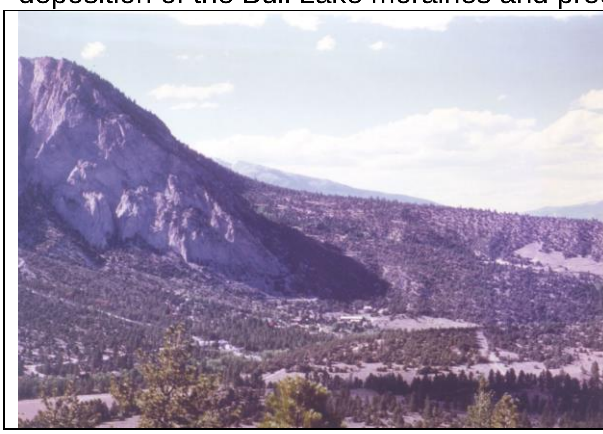


Fig. 1-5. View north across Chalk Creek at Sawatch fault. Fault plane dips 55° east at contact between altered Tertiary intrusive rocks and early Quaternary alluvium.

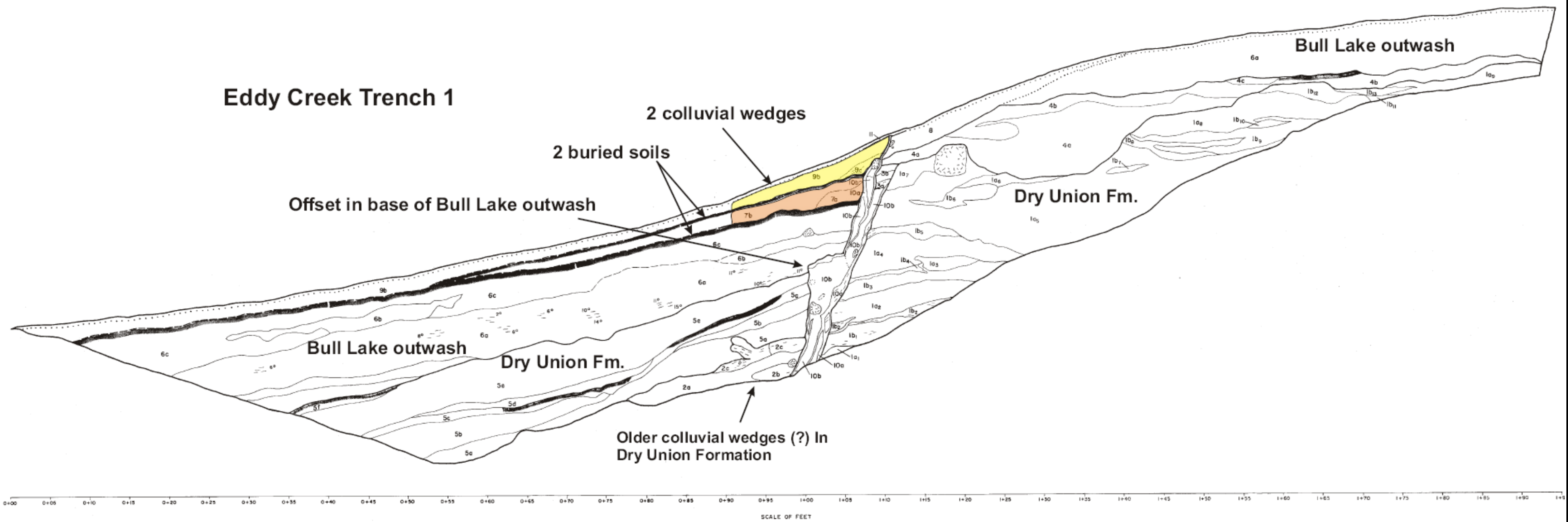


Figure 1-6. Trench ET-1 exposed two major units: 1) Dry Union Formation alluvial-fan and colluvial materials (units 1-5 on trench log), overlain by 2) Bull Lake outwash (unit 6 on trench log). The fault (unit 10) is an anastomozing shear zone up to a meter wide, dipping 70° east. Multiple faulting episodes in the Dry Union Formation are shown by (1) a truncated fault zone within the Dry Union (between units 1 and 3), and (2) stone lines and buried soils in colluvial unit 5 of Dry Union age on the downdropped side of the fault. These displacements do not contribute to the present scarp height. One mapped fault splay is truncated by the Bull Lake outwash, suggesting an event during Bull Lake outwash deposition.

The main fault zone extends through the outwash, but is truncated by Holocene colluvium (unit 11). At least two episodes of post-Bull Lake surface rupture are recorded by scarp-derived colluvial wedges (units 7a and 9a on log) overlying the outwash. The upper 20 to 25 cm (8 to 10 in) of unit 6 consists of the B21tb horizons which have soil properties matching those of the soils on Bull Lake outwash elsewhere in the upper Arkansas Valley. B-horizon development in unit 7b, as shown by clay content, argillan morphology, color, and percent of grussified clasts indicate that the soil developed in this unit is much older than that developed in the overlying unit (unit 9), but it is probably somewhat younger than the most strongly developed soils on Bull Lake outwash in the north Arkansas graben. Near the east end of ET-1, unit 7 is covered by less than 1 m (3 ft) of younger colluvium, suggesting that it is still being affected by pedogenic processes. We suggest that this soil developed over a time interval somewhat shorter than that generally attributed to Bull Lake soils, but longer than that for Pinedale soils. However, the B2t horizon developed on the Bull Lake outwash (unit 6c) beneath unit 7 is just as well developed adjacent to the main fault (station 1+05) as it is near the east end of the trench. This suggests enough time elapsed for this horizon to develop before it was buried near the fault by scarp-derived colluvium.

In contrast, the degree of soil development in unit 9 is relatively weak, similar to that in profiles developed on Pinedale outwash and colluvium. A few thin argillans are the only evidence for clay accumulation and no clasts are grussified. The stratigraphic position of unit 9 immediately above colluvial unit 7, which has post-Bull Lake soil development characteristics, also suggests a Pinedale age for unit 9.

In ET-1, dip separation of the base of the Bull Lake outwash is 5.1 m (17 ft) at the fault, whereas the subsurface displacement of the correlative Bull Lake surface is 8.6 m (28.5 ft). This difference in displacement can be explained by the gradual increase in the dip of bedding in sandy units, from 6° to 8° at 0+25 ft in the trench, to about 11° adjacent to the fault. Tectonic deformation resulting from surface faulting at this site is a combination of discrete surface rupture forming fault scarps and near-fault folding.

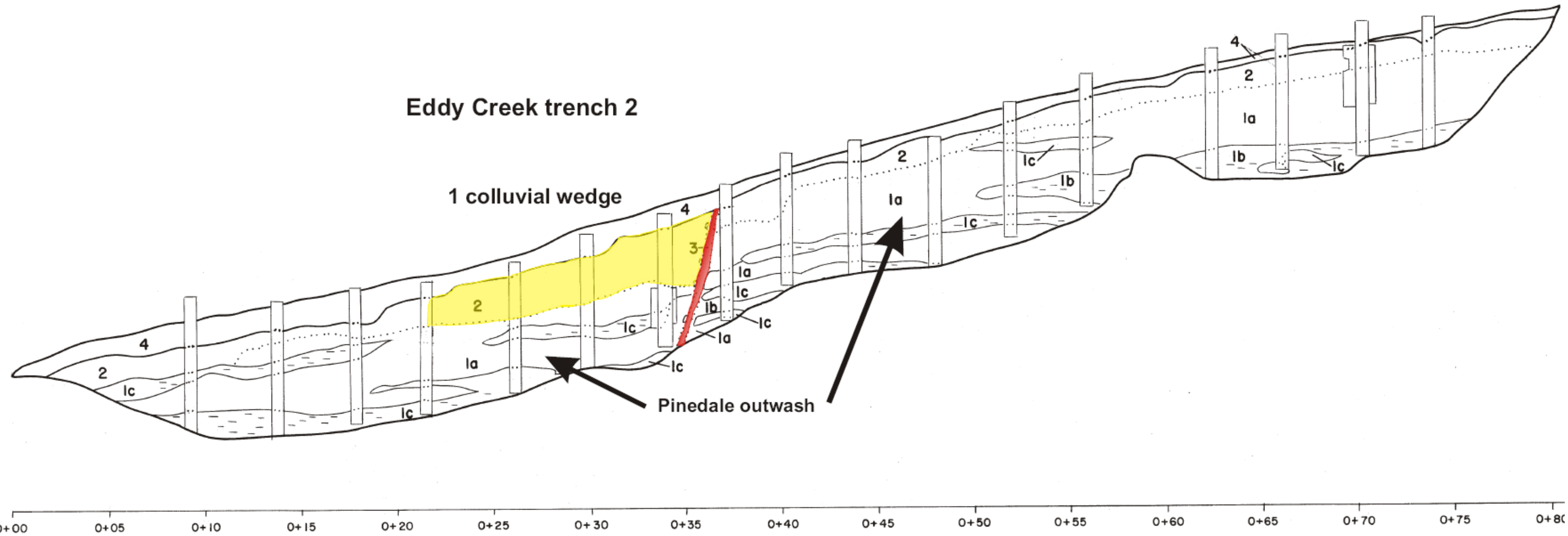


Figure 1-7. Trench ET-2 exposed Pinedale glaciofluvial gravels (unit 1) overlain by two colluvial units (units 2 and 4). A single fault (unit 3-RED), dipping 70° east, displaces the outwash and the base of colluvium unit 2. No discrete scarp-derived colluvial wedges were recognized in the trench, but colluvial units thicken across the fault trace. The base of colluvial unit 2 (YELLOW) is displaced a minimum of 1.2 m (4 ft), as measured at the fault. On the hanging wall of the fault, this contact appears to be parallel to weakly stratified units (1c) in the Pinedale outwash. On the footwall, the basal contact of unit 2 is subparallel to the ground surface, has abrupt steps, and appears to truncate stratification projected from units 1b and 1c on the outwash. These relations suggest that significant erosion of the scarp has taken place during the deposition of unit 2, perhaps to such an extent that most or all of the scarp from youngest event was removed.

PALEOSEISMIC DATA FOR THE SOUTHERN SAWATCH FAULT (from Ostenna, Nelson and Losh, 2002)
Fault scarps are limited to a section of the Sawatch fault in the southern graben, west and southwest of Buena Vista, that is approximately 28 km in length. North of North Cottonwood Creek, similar-aged deposits are clearly not faulted along the northern extension of the fault. Late Quaternary slip rates based on these scarps range between 0.05 to 0.1 mm/yr depending on the assumed age of Bull Lake deposits and assumptions
regarding fault dip. Slightly higher rates can be derived from scarps in Pinedale deposits, but the paleoseismic data indicates these rates are likely high because the average interval between faulting events is likely greater than the age of the Pinedale deposits.

The trench data support 2, and possibly 3 surface-faulting events along the southern Sawatch fault in the past 130-160 ka (Fig. 10 and 11). Based on the fault scarps, maximum surface displacements for these events were likely in the range of 3-4 m. We now see as equivocal the evidence for additional small displacement events suggested by Ostenaa et al. (1981), including an event with 0.15 m displacement about 4 ka.

All ages estimates for paleoseismic events along the southern Sawatch fault are based on indirect and regional correlations. Geomorphic mapping of the fault scarps indicates that only the youngest Pinedale deposits are not faulted. This suggests an approximate age for the most recent faulting event in the range of about 15-25 ka, which appears consistent with soil development on the youngest colluvial wedges in the trenches and ages inferred from fault scarp profiles. Buried soils that underlie the most recent colluvial wedge have greater soil development than Pinedale deposits which indicates that the interval that preceded the most recent faulting event was greater than about 15-25 kyr. Buried soils that underlie the oldest colluvial wedges on Bull Lake deposits are also more developed than Pinedale soils suggesting a similar period of without faulting prior to deposition of the older colluvial wedges that lie atop Bull Lake deposits. These older colluvial wedges also have greater soil development than the Pinedale deposits indicating that intervals between faulting events are greater than about 15-25 kyr. Based on the number of events in the trenches and the most likely regional ages for the Bull Lake deposits it appears that inter-event intervals must be in the range of 25-50 kyr along the southern Sawatch fault.

-10:15 am; retrace route back E to County Road 270 (4.0 mi)

Mile
74.5 turn L (N) onto County Road 270 and drive N 4.0 mi to County Road 162
78.5 turn L (W), drive downhill and cross Chalk Creek, then continue to Mt. Princeton Hot Springs

STOP 2- MOUNT PRINCETON HOT SPRINGS (10:45 am; mi 79.2; 15 min stop for bathrooms and snacks; Fred Henderson speaks about geothermal, and possibly Dick Smith about the inherttance of rift faults from caldera rim faults; seeSmith's 2013 GSA presentation

11:00 am; Exit Hot Springs and turn N onto County Road 321; drive N 2.5 mi to County Road 323 (Mt. Princeton Road) on L (W)

Mile
81.7 continue N 3.6 mi to County Road 326
85.3 turn L (W) onto County Road 326; drive 0.5 mi to low, W-facing fault scarp

STOP 3- WESTERN BOUNDARY OF THE COGAN HORST (11:15 am; 85.3 MI; 15 min stop)

Tell story of discovery of Cogan Horst in 2003 while mapping the Buena Vista East quad for STATEMAP; prior evidence for horst from USGS, 1971; compare 2003-2004 scarp mapping with that from LiDAR

The structural geology of the interior of the Upper Arkansas graben is less well known, due to a relative lack of detailed subsurface studies in the valley. Zohdy and others (1971) measured a 6 mile-long, east-west electrical resistivity profile across the valley floor about 3 miles south of Buena Vista (Maxwell Park area). Their cross-section (fig. 38) shows that the valley floor is underlain by a series of three thin, tabular, high-resistivity layers; the series thins from about 800 feet thick near the range front to 100 feet thick at the Arkansas River. The upper layer in this series corresponds to the older Bull Lake outwash fan (Qboo) deposited from Maxwell Creek. The other two high-resistivity layers probably represent older coarse-grained Quaternary outwash gravels derived from a similar source. The series thins to a negligible thickness just east of Maxwell Park and then thickens again near the eastern boundary of the Buena Vista West quadrangle.

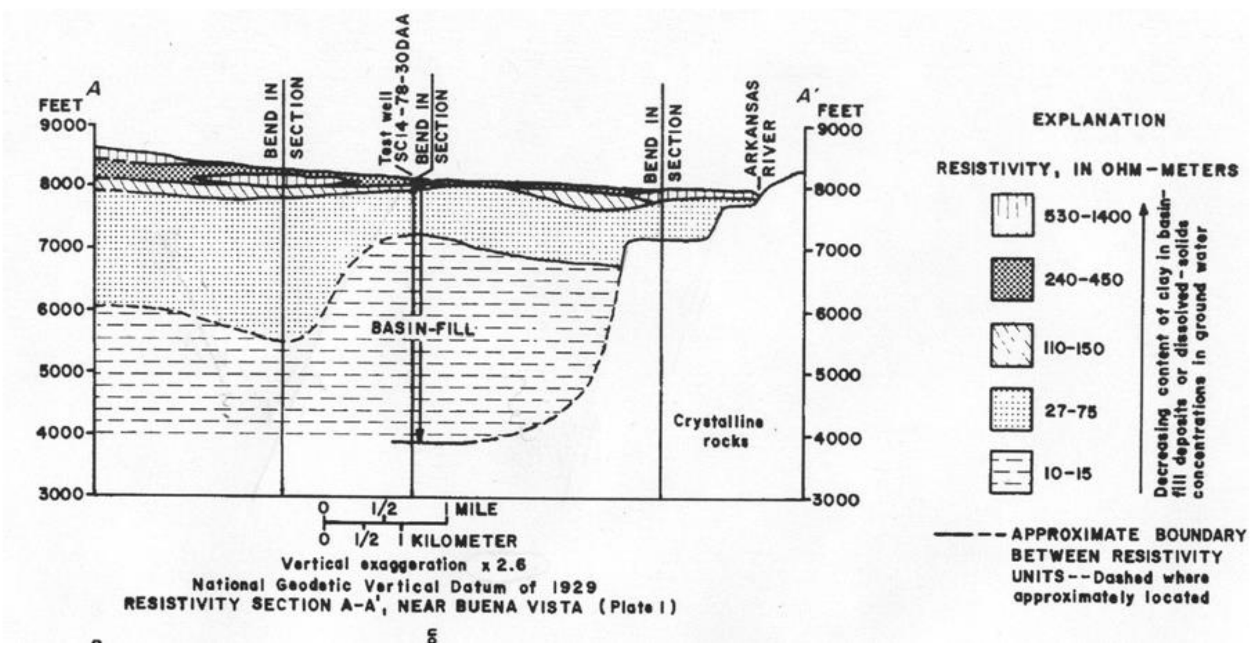


Figure 3-1. East-west electrical resistivity cross-section across the Upper Arkansas Valley about 3 miles south of Buena Vista. From Crouch and others, 1984, after Zohdy and others, 1971.

The high-resistivity wedge overlies two much thicker (4,000 ft-thick) lower-resistivity units that probably represent the Tertiary Dry Union Formation. A 1,000 foot-deep well on the line of section (eastern margin of Sec. 30, T14S, R78W) penetrated only 20 feet of Quaternary alluvium (Qk) before entering the Dry Union Formation (Crouch and others, 1984). The contact between the two low-resistivity units within the older basin fill drops 1,600 feet down-to-the-west to the west of the deep well and then slowly rises toward the range-front fans. This drop coincides with a west-facing fault scarp on the valley floor, described below. To the east of the well, this same contact declines gently to the east. The structural high in the low-resistivity basin fill strata, and the drastic thinning of the high-resistivity wedge of Quaternary deposits, indicate the deep well in Sec. 30 is located in an intragraben horst block.

On the eastern side of the Upper Arkansas Valley (mainly in the Buena Vista East quadrangle) the resistivity profile indicates crystalline basement rocks at shallow depth. Basement is downdropped to the west along a series of step faults, the largest of which lies about 1 mile west of the Arkansas River.

Partly on the basis of this resistivity data, Tweto (1979) estimated up to 3,800 feet of graben fill near Buena Vista and 4,800 feet of graben fill near Salida. Scott (1975) and Scott and others (1975) suggested that the valley fill was the deepest (greater than 4,800 feet) along the western side of the graben. Keller and others (2004) estimated about 2,000 feet of valley fill on the east side of the rift (in SW corner of the Buena Vista East quadrangle), and postulated that it thickens westward toward the Sawatch Range.

Southwest-facing fault scarps exist on the valley floor 4 miles from the range front (Maxwell Park area) and displace Nebraskan, Kansan, and Bull Lake piedmont alluvium as much as 8.0-10.0 feet (fig. 39). These scarps are continuations of similar west-facing scarps mapped in the Buena Vista East quadrangle (Keller and others, 2004) and are interpreted as overlying a down-to-the-southwest normal fault that is responsible for the anomalies shown on the resistivity profile. This fault comprises the western margin of an intragraben horst, the eastern margin of which is a down-to-the-east normal fault mapped in the adjacent Buena Vista East quadrangle by Keller and others (2004). This horst explains why the oldest valley fill (Dry Union Formation) crops out only near the valley center, where normally the oldest valley fill would be found at the greatest depth.

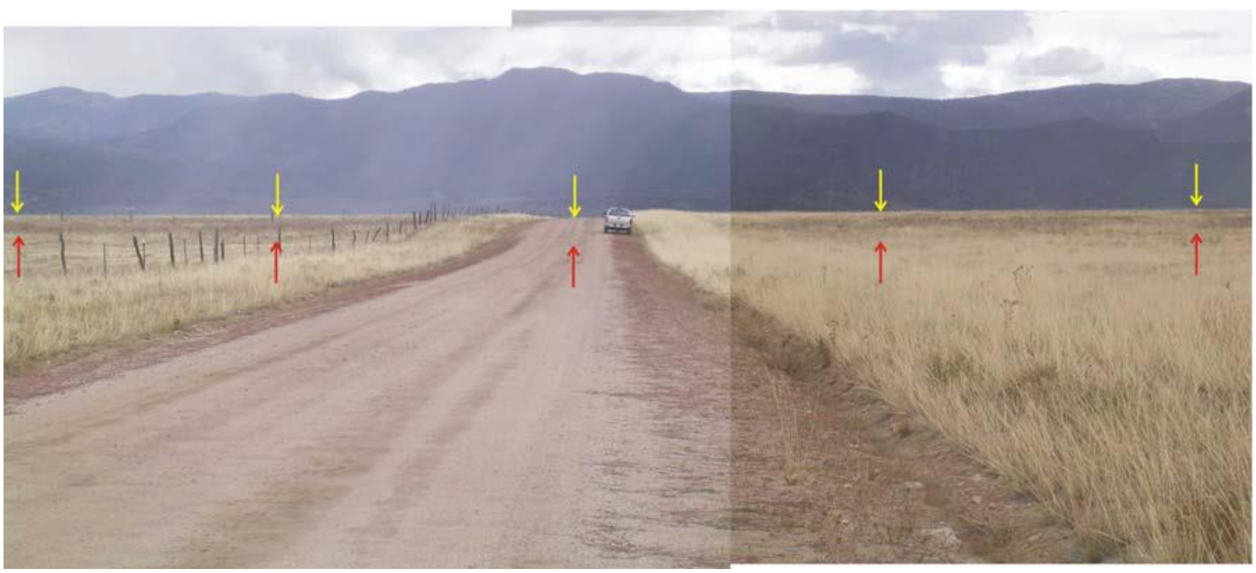


Figure 3-2. View of antithetic fault scarp (between arrows) offsetting Kansan alluvium (Qk) by 2.5-3 m in Maxwell Park. View to east along County Road 328. Pickup truck on scarp is 2.2 m high.

West of the intragraben horst surface, gently sloping Maxwell Park is bounded by opposing fault scarps at the surface and coincides with the lowest deflection of valley fill contacts on the resistivity cross-section. These data suggest that Maxwell Park is underlain by an intragraben graben, which may contain the deepest valley fill in the rift at this latitude.

Overall, the resistivity cross-section and the pattern of surface fault scarps indicates that the Upper Arkansas graben in the Buena Vista West and East quadrangles is composed of a deep western sub-graben beneath Maxwell Park, a central horst (mainly buried), and a shallower eastern sub-graben (in the Buena Vista East quadrangle) that contains the modern Arkansas River. This internal structure is strikingly similar to that of the next major rift basin to the south, the San Luis Basin (Chapin and Cather, 1994).

11:30am; Turn vehicles around and return to County Road 321
85.8 turn L (N) onto County Road 321 and drive 1.9 mi N to County Road 306 (road to Cottonwood Pass)
87.7 turn R (E) onto County Road 306 and drive 0.75 mi to US Highway 50 in Buena Vista
88.5 continue across US 24 and drive 0.5 mi to Riverside Park;

STOP 4- LUNCH AT RIVER PARK (11:45 am; mi 89; 45 min stop); The Upper Arkansas River is the largest component of Colorado's commercial river-rafting "industry." The river makes abundant white water due to the large boulders in the channel, but the gradient of the river and thus its velocity are not very high, considering the apparent turbulence of the waters. Thus, rafters get the impression that the water is fast and dangerous, when in fact it is much less dangerous than many rivers. The anomalous combination of big white water with only moderate gradient/velocity are due to the presence of thousands of boulders in the channel which are too big for the Holocene Arkansas River to transport. These boulders were all deposited in the river during catastrophic outburst floods when ice-dammed lake upstream failed at the end of the Last Glacial Maximum. Most rafters do not realize that the white water is the result of two geologic "accidents" that occurred at 17 ka and 19 ka.

12:30 pm; drive N along river for 0.5 mi, then curves W and turns into Swick Avenue for 0.3 mi to County Road 371 (North Colorado Avenue); notice large boulders on terrace

89.8 turn L (S) onto North Colorado Ave. and drive 0.35 mi to East Arkansas Street
90.1 turn R (W) onto East Arkansas Street and go 0.2 mi to US 24
90.3 turn R (N) onto US 24 and drive 9.8 mi N on river terraces to County Road xxx

After lunch we concentrate on the glacial ice dams that dammed the upper Arkansas River during various ice advances, the lake that formed upstream from the dam (Three Glaciers Lake), and the flood gravels deposited downstream from the ice dams when they failed catastrophically. The evidence for the flood was first described by Scott (1975, 1984), but he only speculated on the location and height of the ice dams, and he never identified any features associated with the ice-dammed lake. His dating of the floods had to rely mainly on relative-age dating and correlation; neither luminescence dating nor cosmogenic surface-exposure dating had been developed at the time of his studies.

The "new" flood story was outlined in large part by Keenan Lee, working independently of the STATEMAP mappers (McCalpin and crew), the moraine mappers and hydrologic calculators (Eric Leonard and crew), and the cosmogenic daters, (Briner, Young and crew). USGS geologists Cal Ruleman and Ralph Shroba got all the parties together in 2008. We now have some more quantitative answers about the sequence and numerical ages of moraine deposition, river damming, lake formation, dam failure, and outburst flooding. However, there are still unresolved issues, for which we solicit comments, and hopefully, brilliant solutions, from our field trip attendees.

STOP 5- THE TWO PINEDALE FLOOD TERRACES (17.3 KA, 19.3 KA)

97.5 reach first moraine deposit crossed by road; moraines to W for next 2.6 mi until Pine Creek; to E across river is a large concave erosional scar where floodwaters undermined a bedrock slope (the "whamout" of Lee, 20xx).
100.1 Pine Creek; the southernmost of three glaciers that dammed the Arkansas River in the Latest Glacial Maximum
102.6 Clear Creek Road, with Clear Creek Dam and Reservoir to W; dam consists of a relatively small embankment that fills an erosional gap in an otherwise intact recessional moraine ridge; this is a common way to make reservoirs in glaciated valleys in Colorado
104.3 town of Granite; popular site for gold placer mining

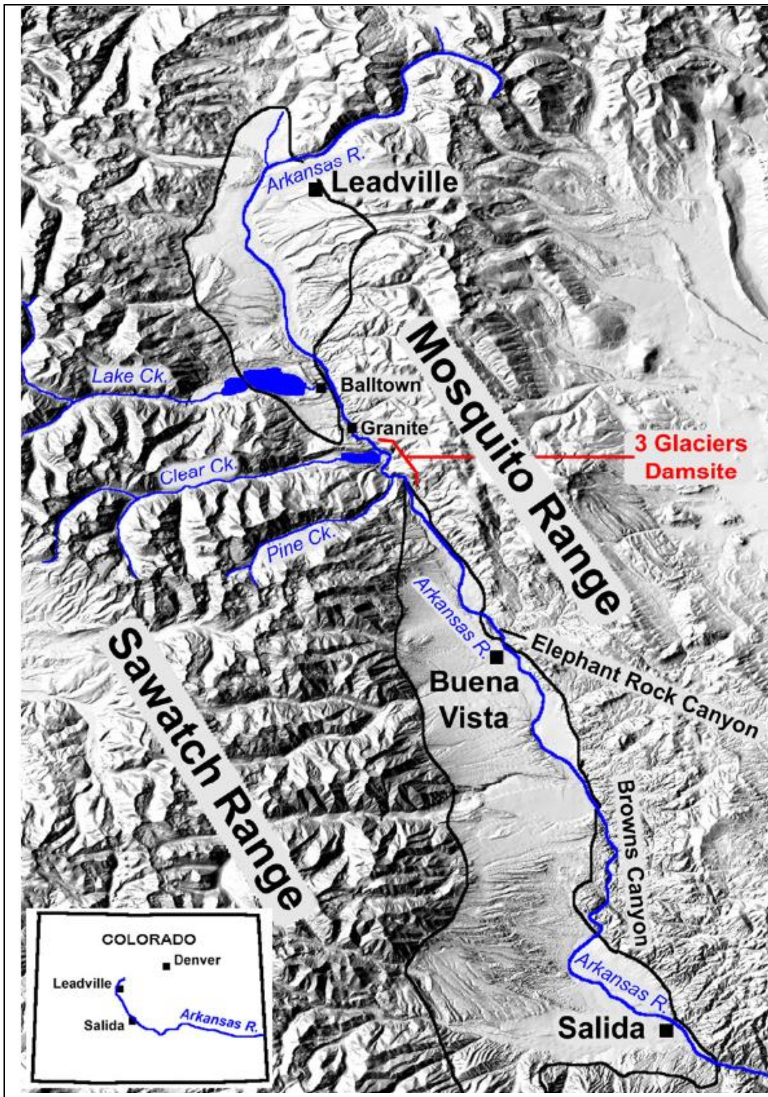
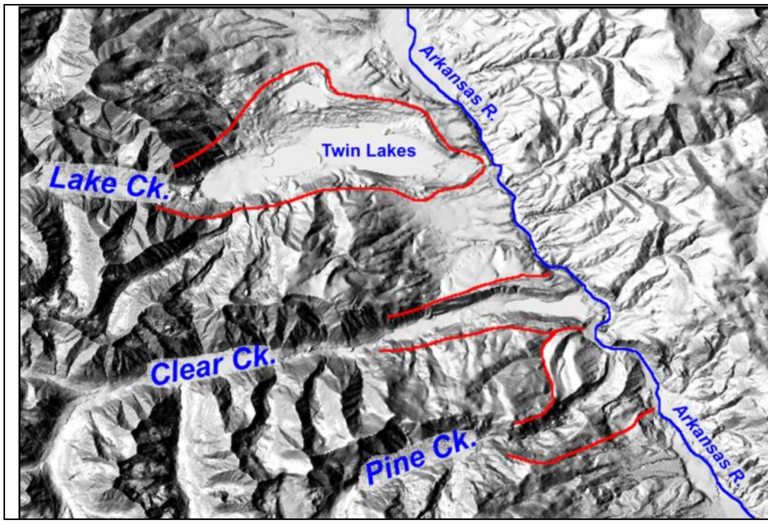


Fig. 5-1. TOP: Upper Arkansas Valley in Colorado. Black line shows the boundary of unconsolidated deposits of valley fill with solid bedrock, which also fairly well defines the valley floor. Glaciers flowed down from 14,000 ft peaks of the Sawatch Range.

BOTTOM: Glaciers advanced down each of three contiguous tributary valleys that drained the east flank of the Sawatch Range - from north to south, these were the Lake Creek glacier, the Clear Creek glacier, and the Pine Creek glacier. Red lines show the boundaries of moraines left by each glacier. From Lee, 20xx.

The glacier flowing down Lake Creek reached the Arkansas River, which at the time was in a gravel channel considerably west of the current channel. The ice advanced quicker than the river could melt it, and the glacier pushed the river to the east, onto granite bedrock, but it did not actually stop the river flow.

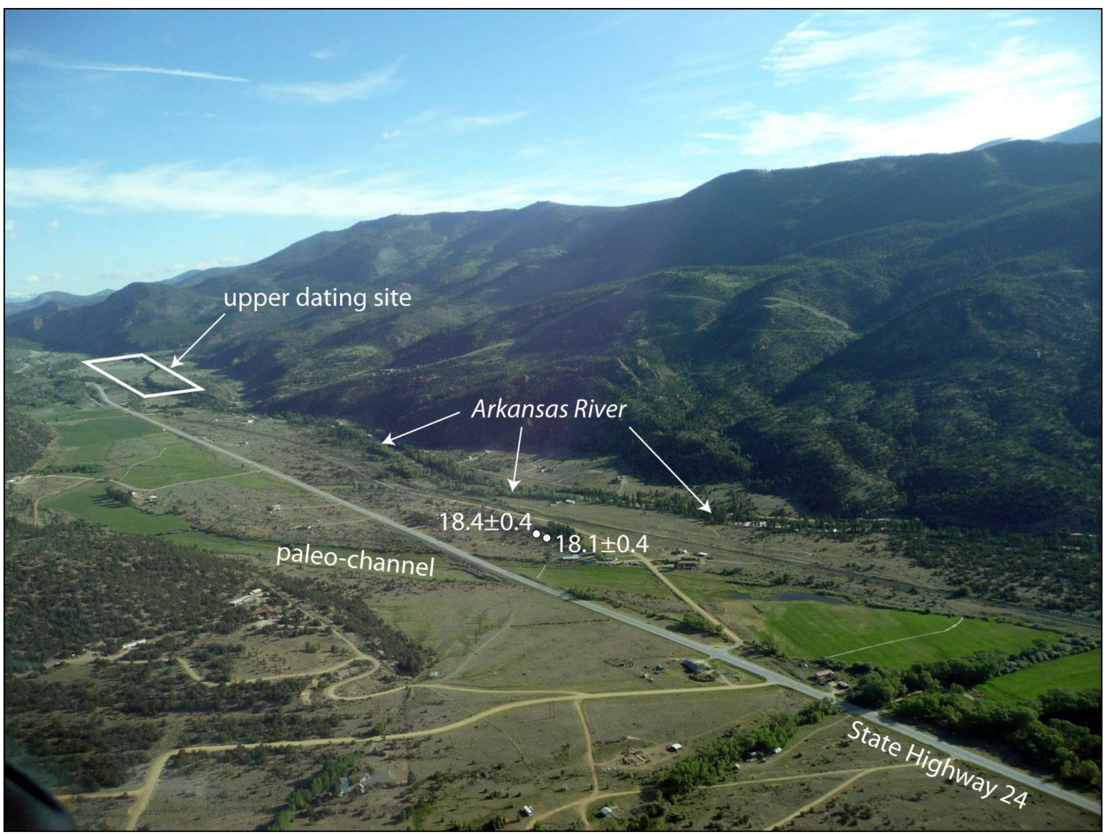
The Clear Creek and Pine Creek glaciers, however, pushed the Arkansas River up against a steep wall of granite and managed to dam the river's flow when the glaciers rammed into the granite wall on the other side of the valley.



Stop 2-6: Lower flood terrace?

Turn around and get back to HWY 24, turn left (south). Drive 3 miles, and turn left onto CO RD 385 (32.5 mi). Drive along the dirt road for 0.25 miles and park or turn into the driveway of the farmhouse on the left (33 mi).

This stop is the second stop at terrace boulders that were sampled for 10Be dating. This stop will serve as the final stop and thus the conclusion of the field trip prior to the drive back to Denver.



At this location, we obtained two ^{10}Be ages of 18.4 ± 0.4 ka and 18.1 ± 0.4 ka from boulders resting on the lower flood terrace (Figure 5). However, these ages raise the possibility that boulders at this location are resting on a terrace that is geomorphically and chronologically separate from the lower terrace viewed at stop #10 (i.e. a terrace intermediate in height and age between the upper and lower terraces). Outburst floods are geologically instantaneous events, and this should be reflected in a ^{10}Be age distribution from a uniform depositional surface. However, ^{10}Be ages from the lower terrace seem to be bimodal across the two sampling locations. Even so,all ^{10}Be ages overlap at 2-sigma confidence and have a mean age of 17.8 ± 0.6 ka. It is interesting that the age of the lower terrace is not expressed in the Clear Creek or Pine Creek moraine records.Nonetheless, deposition of the lower flood terrace requires that glaciers were at or near their Pinedale maxima in order to dam the Arkansas River. Based on theclose correlation between Clear Creek moraine abandonment and upper flood terrace ages (19.3-19.2 ka), wehypothesize that the Clear Creek valley glacier was near its Pinedale maximum and damming the Arkansas River ca. 17.8 ka (Figure 6).

From this stop we will continue downvalley about 10 miles (16 km) through the town of Buena Vista, before turning northeast to return to Denver. Along the way, we will pass by flood boulders on the three higher terrace surfaces. Flood boulders occur on terraces at least as far downstream as Parkdale (Scott, 1984) about 130 km downvalley from this stop.

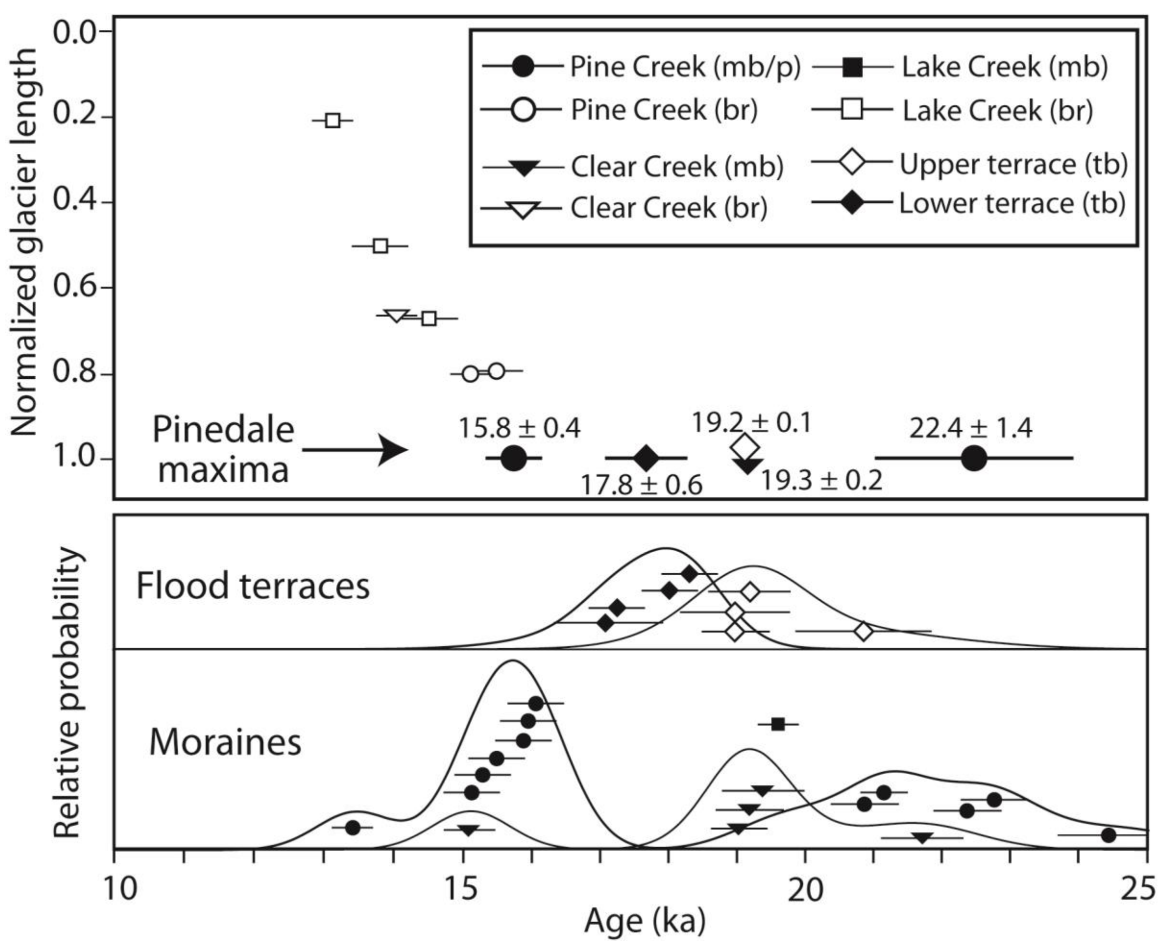
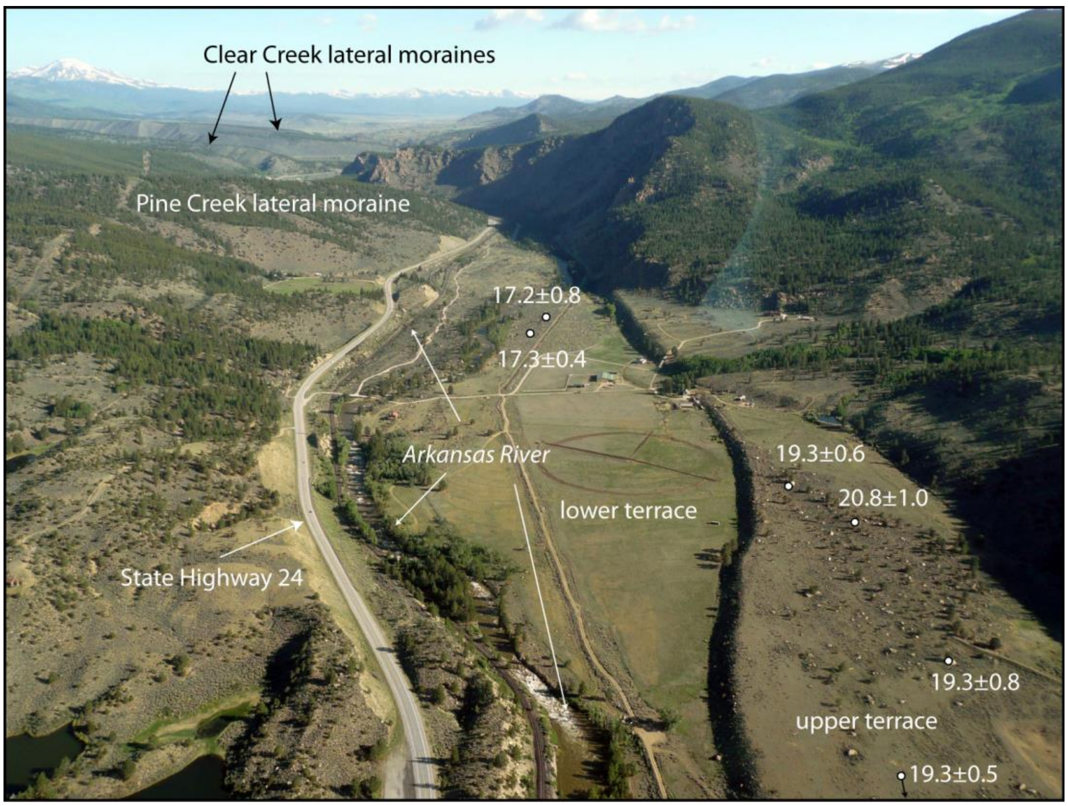


Figure 6. All ^{10}Be ages from the Arkansas River valley. ^{10}Be ages from moraines and flood terraces are plotted individually along with the summed probability distribution of each geomorphic feature (bottom panel). Glacial culminations are shown in the top panel along with the relative location of ^{10}Be ages from glacially polished bedrock within each valley.

Stop 2-5: Upper and lower flood terraces

Drive the 0.75 miles back out to HWY 25 (26.3 mi). Turn right (south) on HWY 24 and proceed 2.2 miles (28.5 mi). Turn left onto the dirt road, cross the Arkansas River, and turn left 0.25 miles from HWY 24 (28.8 mi) on the dirt track; proceed up the dirt track and park after 0.25 mi (29 mi).

This site is host to some of the largest flood boulders found in the Arkansas River valley ranging in size from ~1.5 to 15 m in length (Figure 4). This will be our first stop at terrace flood boulders, and we will visit boulders that were sampled for 10Be dating. Near the mouth of Pine Creek, upper terrace flood gravels are ~18 m thick and thin to ~5 m in thickness about 11 km farther downstream (Lee, 2010). Lower terrace flood gravels range from ~9 m in thickness just below the damsite to at least 6 m farther downstream (Lee, 2010). The upper terrace ranges from 10–20 m above the modern river channel, with a median height of ~15 m, the lower terrace 2.5 m above the channel, with a median height of ~6 m (Lee, 2010). Scott (1975) originally mapped the upper and lower terraces as both being Pinedale in age; however, others (e.g. Lee, 2010) have suggested that the upper terrace is Bull Lake in age.



Based on her lake-volume determinations discussed at stop 8 and different empirical models of the relationship between glacier/moraine-dammed lake volumes and outburst-flood magnitudes (Clague and Mathews, 1973; Costa, 1988; Desloges et al., 1989), Bush (unpublished) estimated that peak discharge from the a 2855 m surface elevation Pinedale lake (Lee, 2010) was in the range of 11,000 to 21,000 m3/sec. Discharge from the higher “middle Pleistocene” lake identified by McCalpin et al. (2010) was in the range of 18,000 to 34,000 m3/sec. We have not yet identified slackwater deposits or other water-surface indicators associated with the outburst floods, so have not been able to model discharges more accurately using step-backwater methods.

At this location, we obtained four 10Be ages from boulders positioned on the upper terrace and two ages from boulders resting on the lower terrace. On the upper terrace, the10Be ages are 20.9 ± 1.0 ka, 19.3 ± 0.5 ka, 19.1 ± 0.8 ka and 19.1 ± 0.6 ka. Lower terrace boulders returned ages of 17.3 ± 0.4 ka and 17.2 ± 0.8 ka. We note that the cluster of 10Be ages on the upper terrace at 19.2 ± 0.1 ka (n = 3) correlates with the mode of 10Be ages at ca. 19.3 ka from the Clear Creek Pinedale moraine, implying that the Clear Creek glacier acted as the main ice dam. Furthermore, all 10Be ages from this sampling location suggest that both the upper and lower terraces were deposited during the Pinedale glaciation.

The tremendous pressure on the granite wall gouged out concave hollows on the far wall, later enhanced by floodwaters pouring through, that Lee (20xx) called "whamout" zones [Fig. 5-x].

Fig. 5-x. The Pine Creek "whamout" (erosion scar) carved out of a granite hill by lateral erosion of the LGM Arkansas River during an outburst flood. View is to the north, up the Arkansas River. The mouth of Pine Creek out of view behind the hill at left, which is the south lateral moraine of Pine Creek. The boulder-laden flood terrace makes up the lower right quadrant of the photo. From Lee, 20xx.

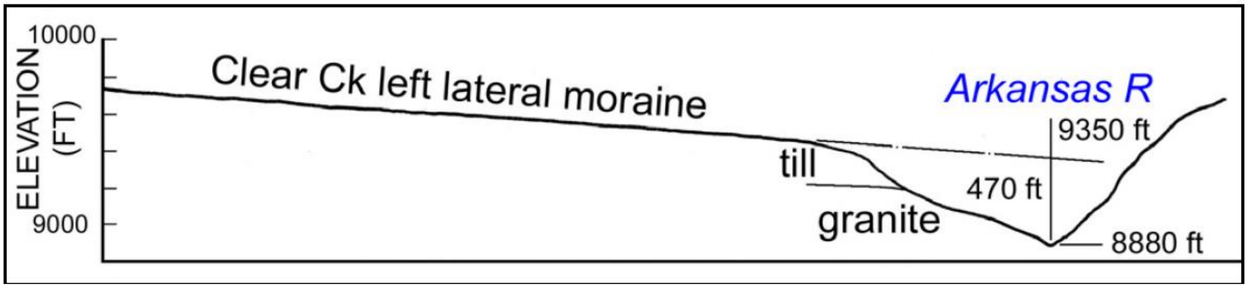


Fig. 5-x. Profile of Clear Creek left lateral moraine [see Fig. 3] and the Arkansas River looking upriver. The end of the moraine was torn away by the flood, but projection of crest shows it reached the Arkansas River at 9350 ft. From Lee, 20xx.

As the flowing ice piled up at the granite wall, it thickened and spread out upriver and downriver, forming a bulbous mass that from above had a tulip shape [see Pine Ck. moraines in Fig. 4]. The Pine Creek glacier spread out so much that it effectively merged with the Clear Creek glacier, and the combined glaciers set up a formidable ice dam.

We don't know exactly how high the dam was, because the end moraines and parts of the lateral moraines were destroyed by the ensuing flood. From the remaining lateral moraines, however, we can estimate the height by projecting the elevation of the moraine crests down to the river [Fig. 6]. This suggests the moraine on the upriver side was 470 ft high, at an elevation of 9350 ft. The glacier was higher than its moraines, of course, but how much higher is uncertain. A dam elevation of about 9400 ft is a reasonable estimate

107.0 junction with Colorado Highway 82, turn L (W) onto 82 and drive 4.0 mi through recessional moraines and past the Twin Lakes Dam and Reservoir
111.0 turn R (N) onto Lake County Road 24 and ascend the lateral moraine 2.2 mi to the Mount Elbert Forebay;

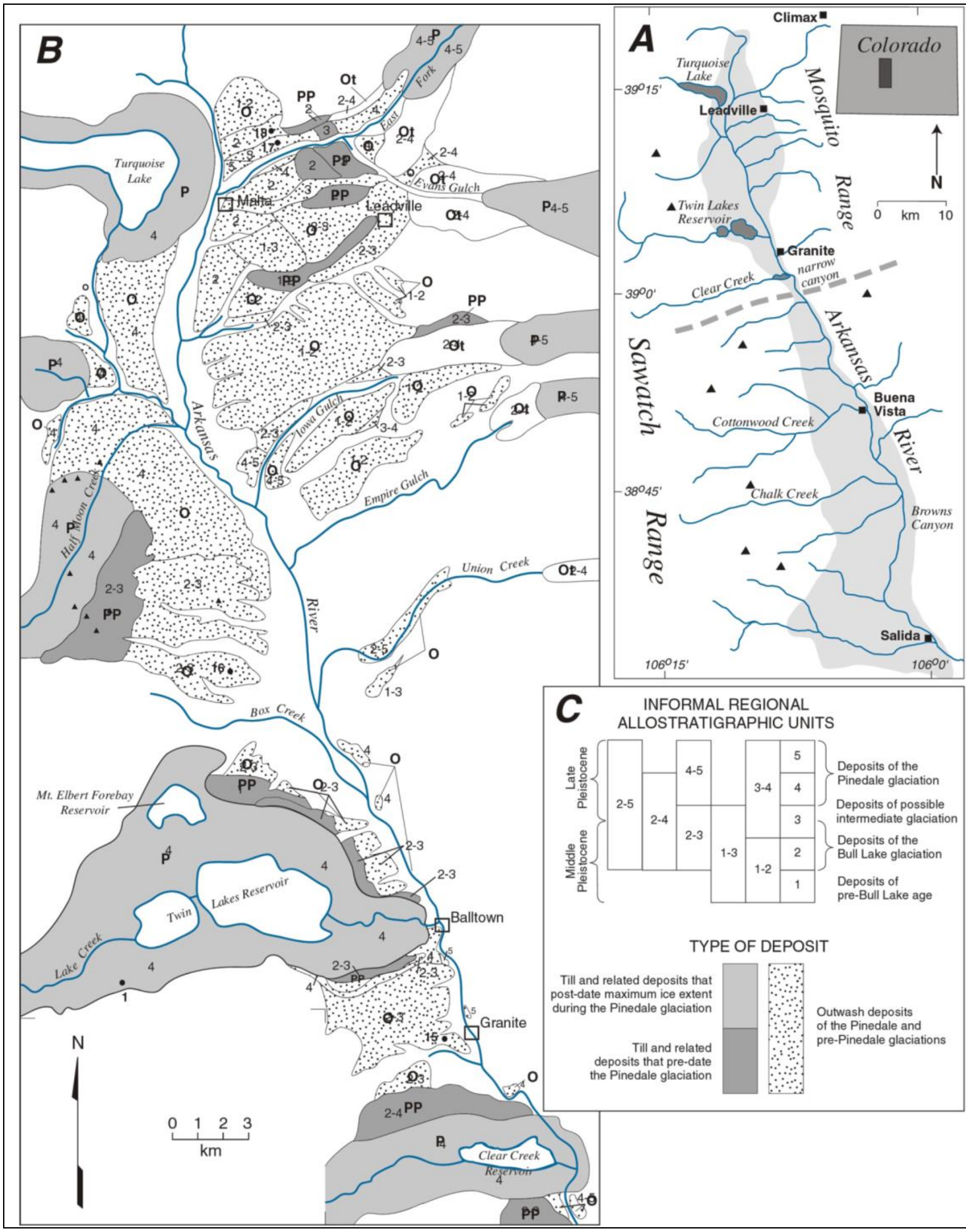


Fig.

STOP 6- TWIN LAKES MORAINES (2:45 pm; 116.0 MI; 15 min stop)

Also View of Mount Massive Lakes landslides, and maybe shorelines carved on it at xxxxft elevation

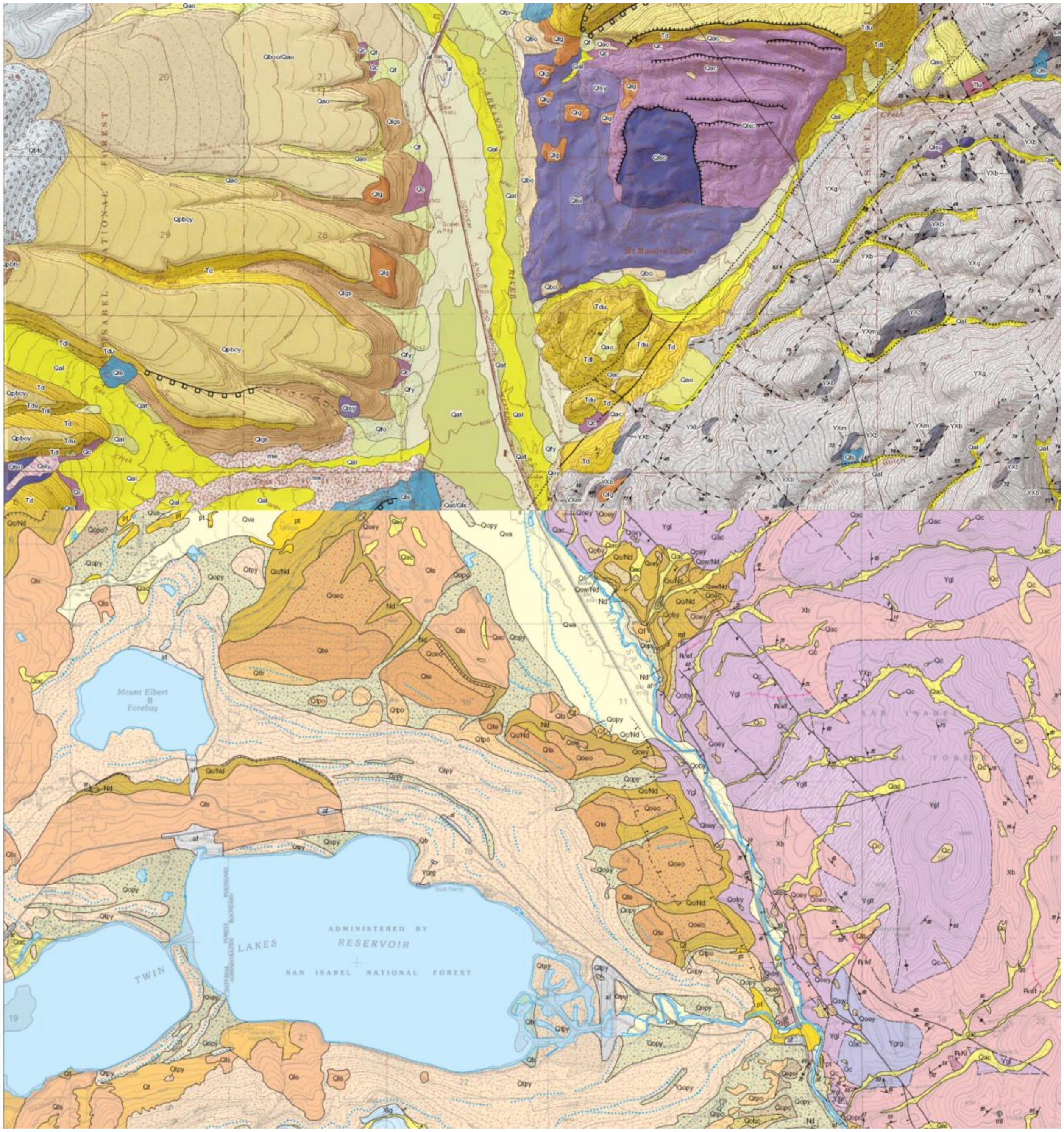


Fig. 6-1. Comparison of recent 1:24,000-scale geologic maps of the Granite quad (Shroba et al., 2014, USGS; lower half) and Leadville South quad (McCalpin et al, 2012, CGS; upper half).

-pass the Forebay and descend the lateral moraine into valley of Box Creek; drive E past dredge tailings to County Road 10 (2.8 mi)
116.0 park at County Road 10 and walk up jeep road 0.5 mi (80 m elevation gain) to top of landslide headscarp

Background to Three Glaciers Lake (K. Lee)

The dammed Arkansas River backed up behind the glacial dam and created Three Glaciers Lake, which was more than 500 ft deep at the dam and extended 14 miles up the Arkansas Valley to the Malta substation, just below Leadville [Fig. 7]. There is, unfortunately, no direct evidence of the lake elevation, such as shorelines, but there are two indirect lines of evidence. The Lake Creek glacier was flowing into Three Glaciers Lake, and like many such glaciers flowing into the sea today, it calved off icebergs. Being normal glacial ice, they carried with them boulders, and when the icebergs melted, the boulders ended up on the lake bottom. These ice-rafted boulders could have dropped out individually as the iceberg melted, or, if the iceberg was blown aground along the shore, they would have formed a cluster of boulders.

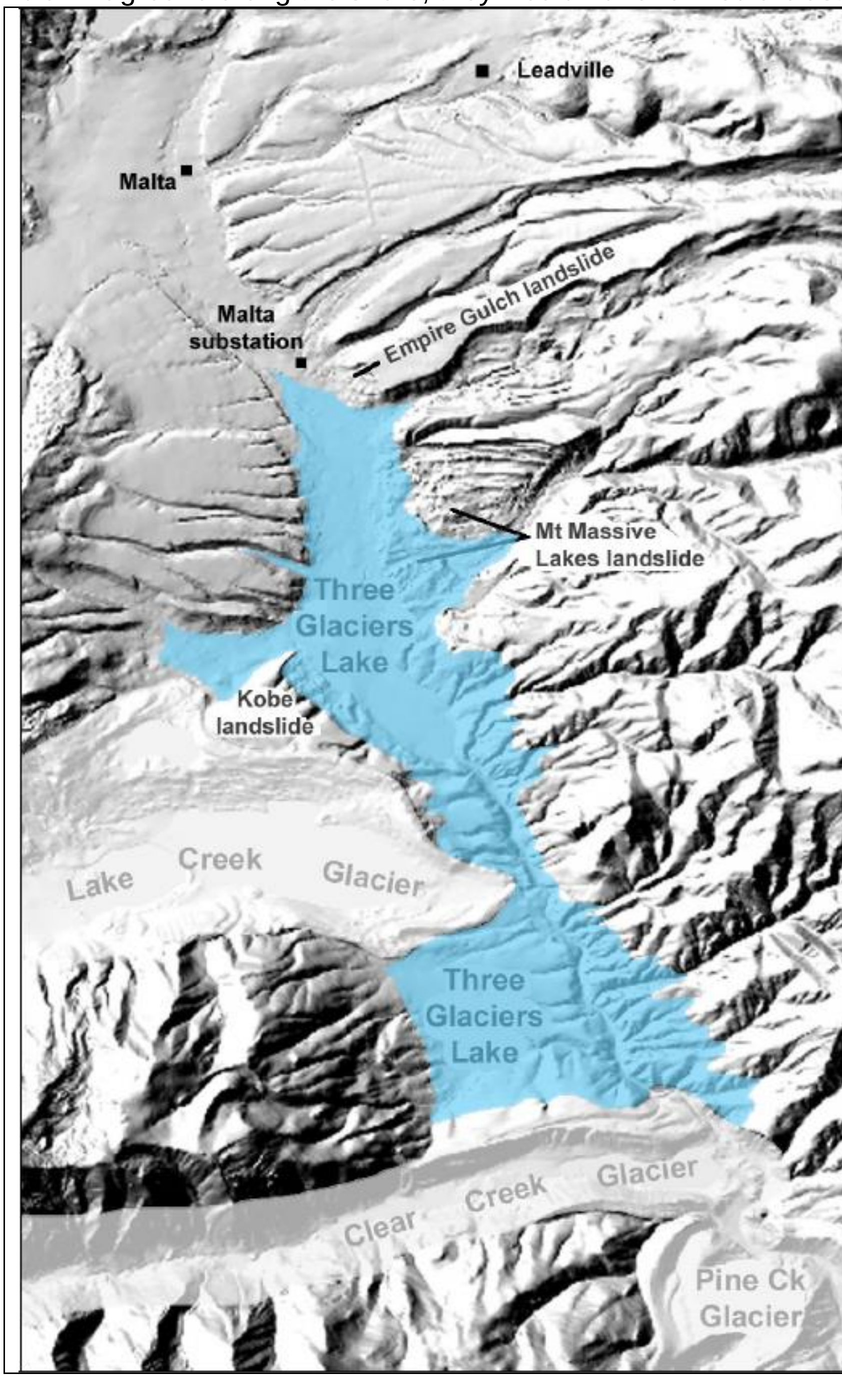


Fig. 6-2. The Leadville South 7.5' quadrangle (mapped in 2008; published in 2012 by Colorado geological Survey) identified landforms and deposits from Three Glaciers Lake. USGS Granite quad (published in 2014) does not recognize any lake-related landforms or deposits. It interprets the gravel-capped benches as alluvial terraces. Test #1: Do gravel-capped benches decline in elevation to the south (terraces), or maintain the same elevation (shorelines).

A second line of evidence is provided by landslides caused by the lake. Three landslides along the shore of Three Glaciers Lake [see Fig. 7] most likely were caused by reversed hydraulic gradients in the saturated sediments when the dam failed and the lake surface dropped catastrophically. The Kobe landslide has a crown scarp at 9400 ft [Fig. 6-x], and the Mt. Massive

Figure 6-3 shows just such a cluster of ice-rafted boulders, sitting on the surface today just north of Lake Creek at an elevation of 9384 ft [2861 m; by GPS]. A second, smaller cluster 1500 ft (450 m) to the north shows a GPS elevation of 9402 ft (2866 m).

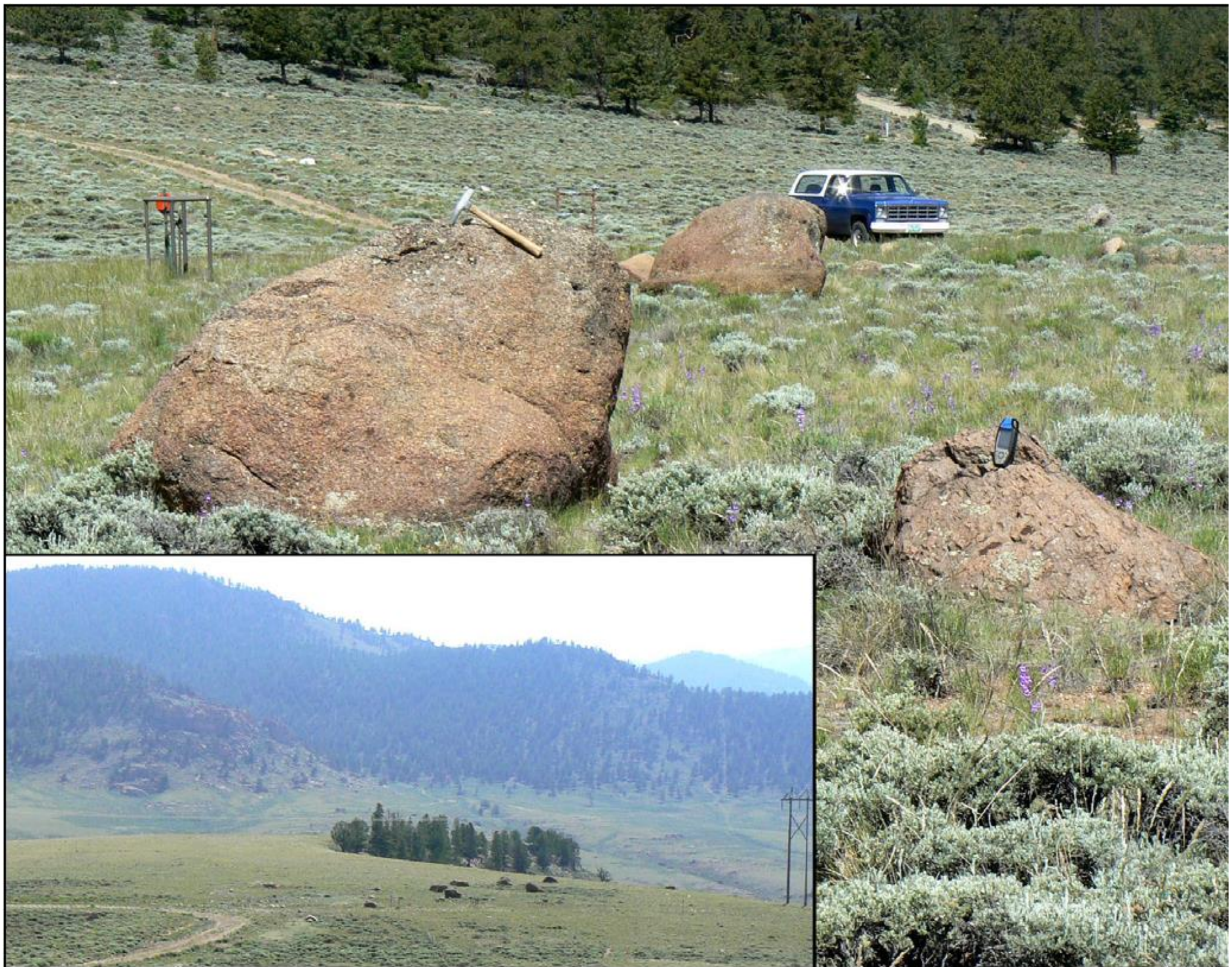


Fig. 6-3. Close-up of ice-rafted boulders that mark the shoreline of Three Glaciers Lake at 9834 ft elevation (2861 m).Inset at lower left shows the geomorphic setting of the boulder cluster, which can be seen in lower right center.

Lakes and Empire Gulch landslides, which lack clearly defined scarps, show hummocky landslide topography between 9300 ft and 9500 ft

STOP 6- KOBE LANDSLIDE, A RAPID-DRAWDOWN LANDSLIDE (2:45 pm; 116.0 MI; 30 min stop)

Also View of Mount Massive Lakes landslides, and maybe shorelines carved on it at 9400 ft elevation

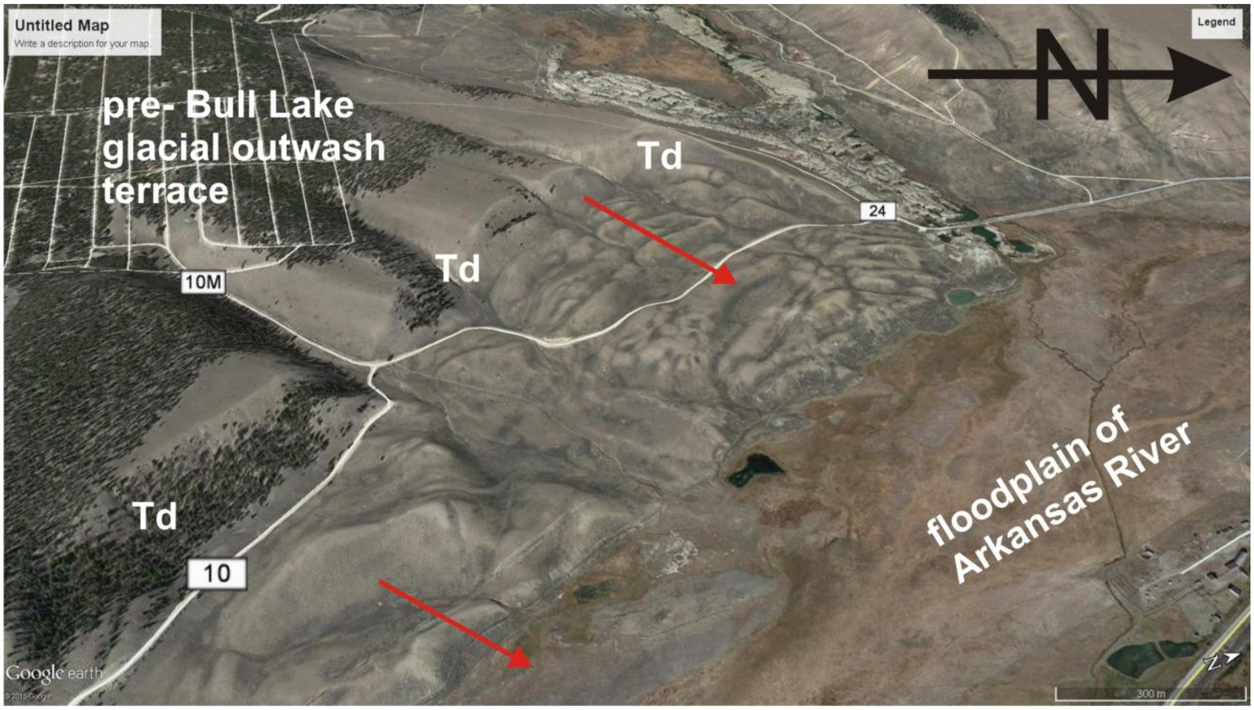


Fig. 6-x. Oblique Google Earth view of the Kobe landslides on the western side of the Arkansas River, between Twin Lakes and Box Creek (dredge tailings at upper right center). The material that failed is interpreted by Shroba et al. (201x) as Tertiary Dry Union Formation (Td).

3:15 pm; return to bus and drive N on County Road 10 2.5 mi to US 24

Mi 8.6: turn left (east) off of US-24 at a large bend onto CR-7. Proceed south. The dirt road on the left (east) goes up Empire Gulch to the Beaver Lakes subdivision, which is built on a huge landslide complex.
Mi 9.2; CR-7 curves to the left and begins ascending onto the Mt. Massive Lakes landslide.
Mi 9.6: turn left off CR-7 onto Forest Road xx; go through gate and continue 0.2 miles on a dirt road.
Mi 9.8: park on left (N) side of road. OPTIONAL STOP:. (Jim McCalpin). Three Glaciers Lake

Optional Stop 2-1: Wave-cut benches and other shorezone features of Three Glaciers Lake; Mt. Massive Lakes landslide and Kobe landslide; type section of the Dry Union Formation.
Shorezone Features of Three Glaciers Lake

Keenan Lee first noticed anomalous shorezone features in the Arkansas valley upstream of Twin Lakes, the most prominent of which is the Kobe landslide (discussed later). During STATEMAP mapping of the Leadville South quad in 2008, more features and deposits were observed at about the same elevation as the top of the Kobe landslide deposit. At Stop 2-1 we will look at two levels of horizontal platforms cut onto the surface of the hummocky topography of the Mt. Massive Lakes landslide (Fig. 2-1a). These platforms lie between about 9400 ft and 9480 ft, and affect the entire surface of the landslide between those elevations, giving it a different morphology than the rest of the landslide. In the geologic map (Fig. 2-1c) this zone of platforms covered with lag gravel was mapped as a different age (Qlsi) than the rest of the slide. Although we now think that the morphology was created after landsliding by wave action, we have kept the original unit designation. These platforms are best developed on the east side of the Arkansas River, where the fetch of waves would have been in the longest in the Lake.

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 2010 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. 13) 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).

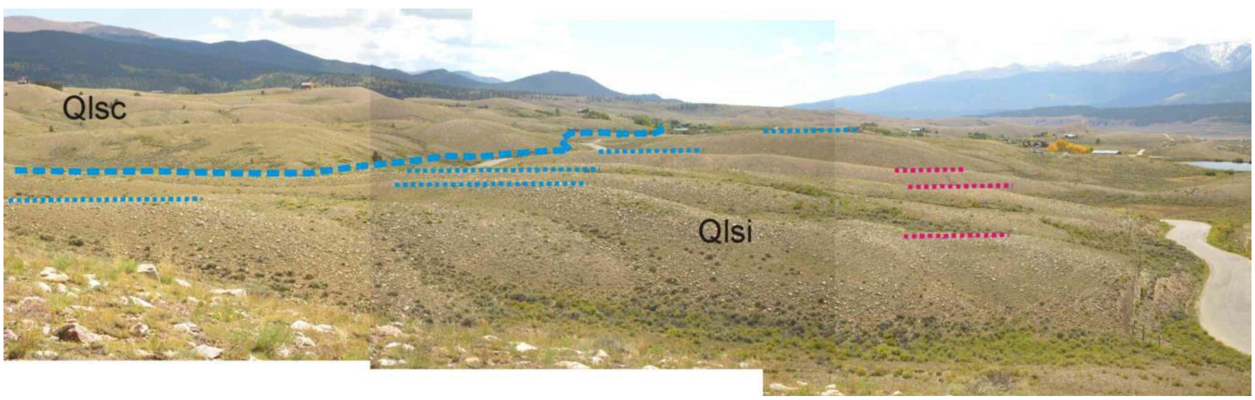


Fig. 2-1a. View of beveled, gravel-capped hilltops on the western flank of the Mt. Massive landslide complex, planed off by wave action of Three Glaciers Lake. View is to south from the northwest corner of the landslide complex (Qlsc, Qlsi); note County Road 7 at far right. Thick blue line shows upper 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].

Farther to the south on both sides of the Arkansas Valley, embayments created by tributary valleys contain fine-grained, well-stratified deposits that we interpret as nearshore lacustrine deposits (Fig. 2-1b). These deposits were placed in map unit Qlgs (see description below). We do not have time to visit those localities today, which is unfortunate, because there is controversy about both their origin and age. Present OSL ages indicate the beds are 65ka to >204 ka (pre-Pinedale), which accords with their elevation well about the ice dam at 9360 ft. So far we have not identified any shoreline features or deposits that would correlate with a Pinedale lake at 9360 ft elevation.

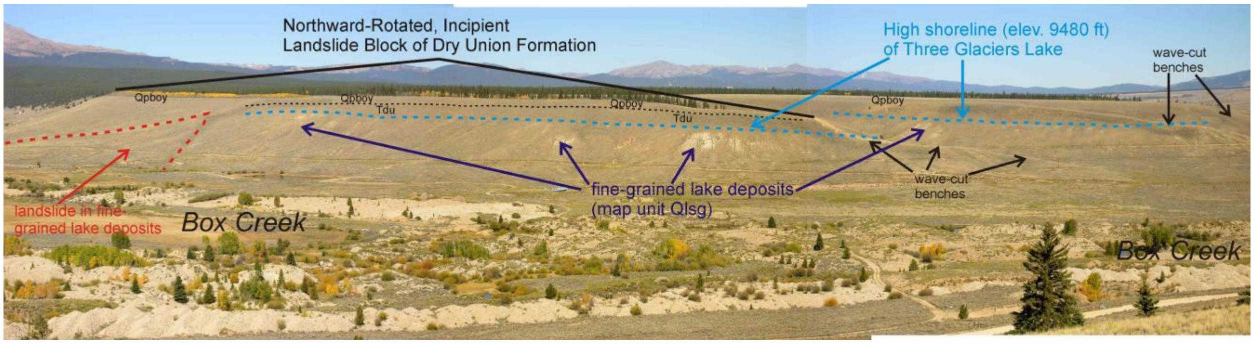


Fig. 2-1b. Annotated photo showing fine-grained lacustrine deposits (our map unit Qlgs) of Three Glaciers Lake mantling mesa sideslopes in the valley of Box Creek. View is to the north. Deposition rates were high in this valley because it formed a shallow reentrant bay in the lake that was fed by large 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

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 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 (Fig. x). 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. 14). 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 (Fig. x). 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.

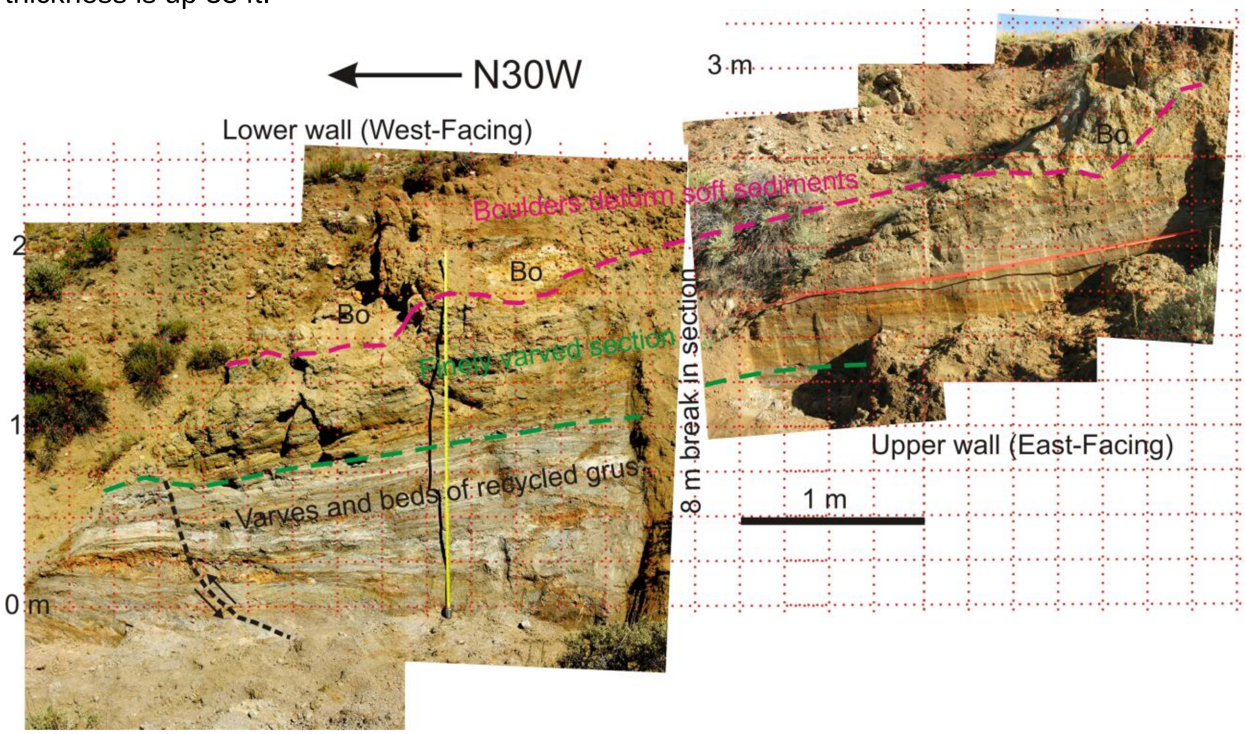


Fig. x. Qlgs deposits east of Arkansas River at xxxx ft elevation. Most of gully wall exposes finely varved, unoxidized to slightly oxidized beds of clay to sand. Granitic boulders at top of wall (Bo) deform the varves beneath them, indicating they were deposited on soft, saturated sediment.

Fig. x. LEFT, fine-grained beds within the Dry Union Formation (Td). Note the pervasive red color and oxidation and the lack of defined stratification. RIGHT, Qlgs deposits west of Arkansas River at xxxx ft elevation, on the north side of Box Creek. Deposits are well sorted and stratified, unoxidized (reduced) to very slightly oxidized. Alternating beds of green-gray clayey sand to sandy clay; cross-bedded coarse sand and granules; and minor small pebble gravel. Dated by optically-stimulated luminescence at 143-146 ka near top (Bull Lake age), and 204 ka near middle.

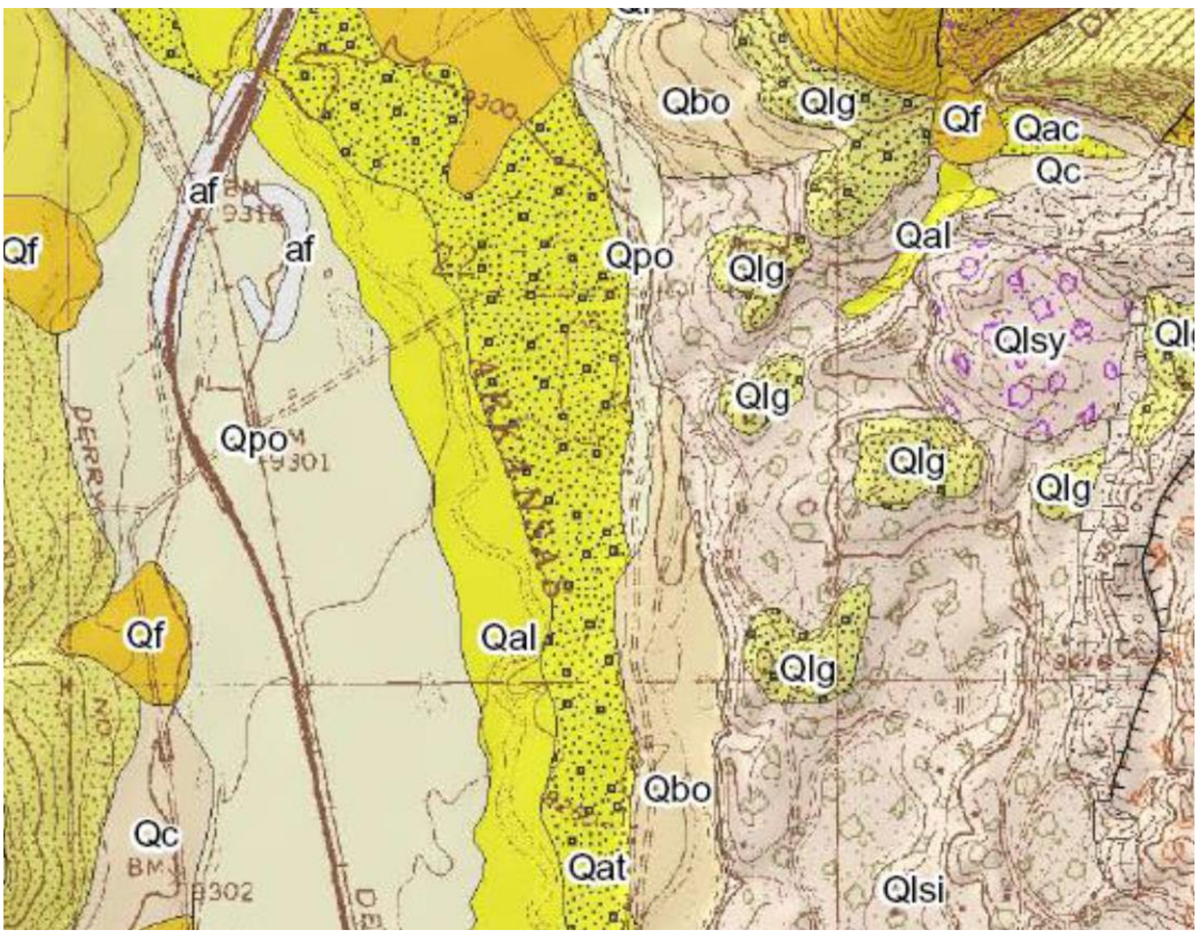


Fig. 2-1c. Geologic map of the area around Optional Stop 2-1.

Landslides around the lake rim are another indirect indicator of Three Glaciers Lake. The Kobe landslide is the best discrete landslide example. Its high width-to-length ratio and low-angle deposit composed of multiple slivers is similar to two types of landslides: (1) landslides in sensitive marine clays (quick clays), and (2) landslides caused by rapid drawdown of reservoirs. Lee (2008) surmised that the Kobe landslide formed when Three Glaciers Lake suddenly drained. To date, there have been no attempts to date the landslide.
In addition, the slopes leading down from the pediment surfaces to the Arkansas Valley floor are all composed of hummocky topography, quite unlike the usual slopes below pediments. Although there are no obvious arcuate headscarps or definable landslide lobes in most of this terrain, it all looks "funny."

Finally, a section of the Qpboy pediment north of Box Creek appears to have rotated and slid southward (Fig. 2-1d). A similar situation affects the ridge of Dry Union Fm. between Dry Union Gulch and the Mt. Massive Lakes landslide. In both cases, the pediment surface has apparently been rotated down-to-the-north.

SOURCE: 2010 GSA Annual Meeting Quaternary Geology and Geochronology of the Uppermost Arkansas Valley; Field Trip 405, October 29-30, 2010 Glaciers, Ice Dams, Landslides, Floods
Crestone Science Center, Field Guide No. 6 www.geohaz.com

Fig. 2-1d. 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.

118.5 turn L (N) onto US 24 and drive 8.7 mi to downtown Leadville

STOP 8- DOWNTOWN LEADVILLE (3:30 pm; 127.2 mi)

Overview of Quaternary geology of Leadville.

The Quaternary geology of Leadville (Fig. 15) could be called "a dog's breakfast", for three reasons. First, the city lies on a piedmont of old (Tertiary?) basin fill that has been veneered and channeled by glacial outwash coming from Evans Gulch to the east. Second, these deposits have been so modified by mining and urbanization that the original landforms have been obscured. Third, the most detailed geological mapping was performed more than 100 years ago when the mines were still active, but scant attention was paid back then to Quaternary deposits, compared to the economic bedrock units. Emmons divided the Neogene deposits into two units, a younger "Wash" (which probably includes all of the Quaternary), and an older "Lake Beds" (probably includes all the late Tertiary), which were exposed only in mine shafts and tunnels (Fig. 16). Even as late as the 1970s Tweto (1974c) surprisingly ignored the Quaternary cover deposits on the Leadville piedmont and mapped the underlying bedrock units, which are not actually exposed (modifying his contacts from Emmons, 1886 and Emmons et al., 1927). In 1984 Nelson and Shroba prepared a reconnaissance Quaternary map for an AMQUA field trip, but based on little field checking. In 2008 McCalpin et al. mapped the Leadville South quadrangle for Colorado Geological Survey, but did not map the Leadville North quadrangle. This awkward legacy is portrayed in Fig. 15, where the city is shown as lying mainly on older Bull Lake outwash from Evans Gulch (lower panel, unit Qboo), with the southwestern part of town lying on a slightly lower terrace (younger Bull Lake outwash, unit Qboy).

The most enigmatic Quaternary feature is Capitol Ridge, on which Stop 5 is located. This 2.3 mile-long ridge rises about 150 feet above the flanking outwash surfaces, and was been mapped by Capps (1909), Nelson and Shroba (1984), and McCalpin et al. (2010b) as a moraine (the latter as a younger pre-Bull Lake moraine).

However, several uncertainties arise if Capitol Ridge is a moraine. First, if it is the south lateral moraine from Evans Gulch, where is the corresponding north lateral moraine? Could it be the ridge behind the dafeway Store in north Leadville that was mapped by Nelson and Shroba (1984) as older Bull Lake (Qbto)? But those two ridges come so close at their upper ends, that there would not be much room for a glacier terminus between them.

Second, Capitol Ridge does not expose many boulders. This could be partly the result of urbanization, or partly the result of long weathering since pre-Bull lake time. For example, the pre-Bull Lake till mapped on the Airport pediment south of Leadville has very few boulders at the surface, and is deeply weathered.

Third, the ridge is about the same elevation as the pre-Bull Lake pediment surface south of downtown Leadville (the Airport surface). One alternative origin is that capitol Ridge is merely an erosional remnant of the same pre-Bull Lake pediment that exists south of the city. However, the trend and shape of the ridge is discordant with that pediment

Fig. 16. 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).
From McCalpin et al., 2010b.

ROLLING STOP, LEADVILLE TO FREMONT PASS: THE MOSQUITO FAULT AND ANTISLOPE SCARP-LANDSLIDE BLOCK

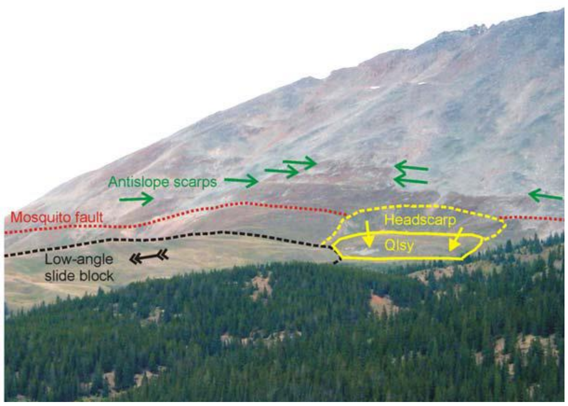


Fig. 8-1. Unannotated and annotated telephoto views of antislope scarps above the Mosquito fault trace between French and English Gulches.

According to the Quaternary Fault & Fold Database of Colorado (Widmann et al., 1998) the Mosquito fault hasexperienced movement as young as late Quaternary (<130 ka), citing Kirkham and Rogers (1981). Kirkham and Rogers, in turn, cite the existence of “several distinctive scarps as much as 12 m high on glacial moraine and landslide deposits”, apparently following remarks of Tweto (1978, p. 18). However, we examined Tweto’s localities and found no evidence for Quaternary faulting of either moraines or landslides. The only young-looking landforms along the Mosquito fault are a series of antislope scarps at the base of the Mosquito Range front between French and English Gulches (Fig. 8-1). These antislope scarps all lie upslope of the fault trace, and only exist in one small reach of the fault that lies directly upslope of the French-English Gulch low-angle slide block. Accordingly, we interpret the scarps to represent gravitational spreading due to toe debutressing, and not any tectonic offset. In our opinion, there is no evidence for late Quaternary movement on the Mosquito fault within the Climax quadrangle.

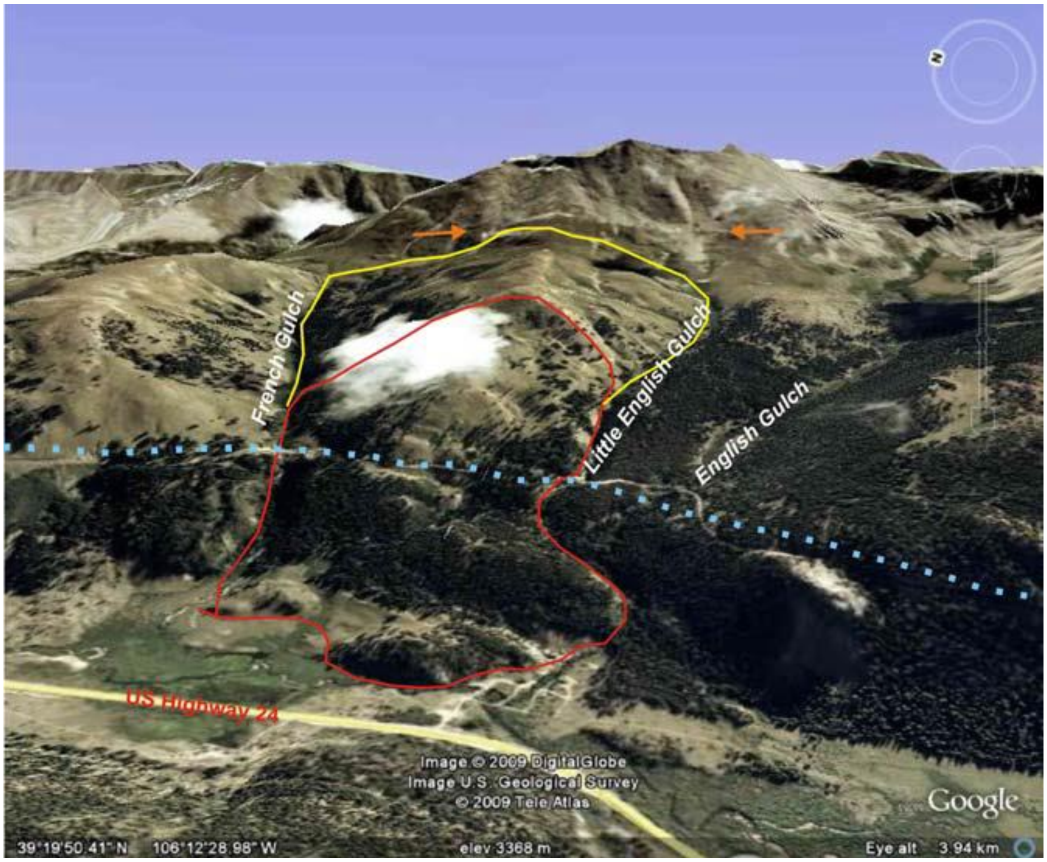


Fig. 8-2. Annotated Google Earth view of the French-English Gulch low-angle landslide block (at center; younger part outlined in red, older part in yellow). View is to the east; the glaciated valley of the East Fork Arkansas River is in foreground. Dotted blue line shows the Pinedale glacial limit. The toe of the younger landslide block is composed of blocks of Tertiary intrusive that were clearly overridden by Pinedale ice, thus this block moved pre-Pinedale. The upper slide block extends all the way to the Mosquito fault, and based on morphology, is older than the lower landslide block. Note that the antislope scarps (orange arrows) along the Mosquito Fault escarpment exist only above the head of the low-angle slide block.

Previous work suggested that the Mosquito fault may have been active in late Quaternary time (see previous section on Structural Geology). For example, the Quaternary Fault and Fold Database maintained by the Colorado Geological Survey (http://geosurveymaps.state.co.us/cgs_faults/) lists the Mosquito fault as a definite Quaternary fault exhibiting latest displacement in late Quaternary time (past 130 ka). This assessment stems mainly from reconnaissance observations by Tweto (1978, p. 18), who stated that “high lateral moraines are faulted” by the fault in a saddle north of the summit of Mount Arkansas. These observations were repeated by Kirkham and Rogers (1981, p. 41), who concluded, however, that “the nature of the anomalous features that occur along the fault trace in the moraine can only be ascertained through detailed studies which would probably have to include trenching.”

According to our mapping and interpretation, all the scarps in the vicinity of the Mosquito fault are related to landsliding or deep-seated gravitational spreading, rather than to coseismic surface faulting in the Quaternary. The largest anomalous landform along the Mosquito fault is the prominent bench and antislope scarp at the toe of the range front escarpment between English and French Gulches (Fig. 8-2).

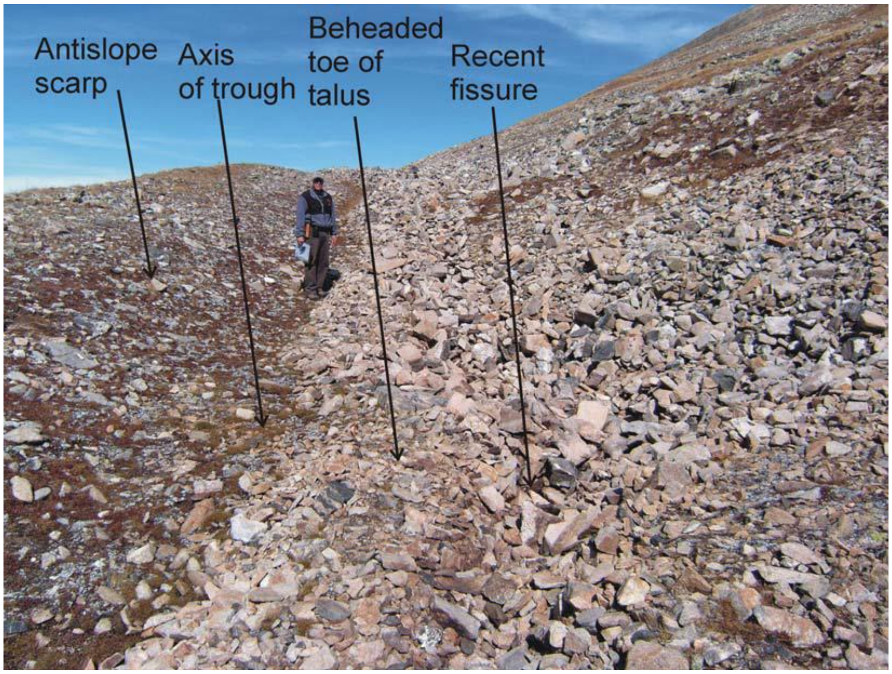


Fig. 8-2. Photograph of the most prominent antislope scarp and trough between English and French Gulches. Active, unvegetated talus at center has been beheaded from its source at right, by the development of a fresh tension fissure. The trace of the Mosquito fault is located about 50 m downslope (to the left). Person for scale is 1.9 tall.

This linear landform lies roughly 50 m upslope from the trace of the Mosquito fault. The most prominent part of this antislope scarp occurs on the upslope end of the ridge that separates French Gulch and Little English Gulch (French-Little English Ridge). The trough behind that scarp exhibits a sharp fissure in active talus that may be as young as historic.

This anomalous series of three antislope scarps on the French-English Ridge is inferred to reflect gravitational spreading and westward toppling of the (altered) fault footwall rocks and overlying range-front colluvium, rather than tectonic faulting, for several reasons: (1) the antislope scarps only exist at the range front, directly upslope of the large French Gulch-English Gulch low-angle slide block, (2) there are no antislope scarps, or valley-facing scarps, elsewhere along the mapped trace of the Mosquito fault in the Climax quadrangle, and (3) the young fissure shown in Fig. 20 cannot be coseismic, because there have been no late Holocene or historic earthquakes on the Mosquito fault.
The driving force for the inferred gravitational toppling is the debuttressing effect from a large, low-angle slide block directly downslope, a slide block which contains all of the French-Little English Ridge. The toe of this ridge-slide block protrudes 500-600 ft into the glaciated valley of the East Fork, but was overridden by Pinedale ice; thus it probably last had major movement between the Pinedale and Bull Lake glaciations. However, the very fresh appearance of the trough fissure implies that stress adjustments may still be continuing.

(1) that previously published bedrock maps of the area (e.g. Tweto, 1974a) severely underestimated the extent of landsliding in the region, and (2) there is a continuum of gravitational deformation between sackung, incipient landsliding, and full landsliding (which creates a rubbilized landslide deposit). Areas subjected to the first two stages appear to be intact bedrock at first glance, and have been mapped as such on almost all published geologic maps. This was done without regard for the rather obvious post-glacial landforms (downslope-facing scarps, upslope-facing scarps, linear closed troughs, closed depressions) indicating extensional spreading/toppling at their heads.

STOP 9- FREMONT PASS (3450 m) AND THE CLIMAX MOLYBDENUM MINE

Pull off highway to right (W) and park in front of interpretive signs. This 20-minute stop will be an overview of the pre-Quaternary geology of the Mosquito Range (Vince Matthews).

1—Fremont Pass was scoured out by glacial ice that overflowed from the East Fork paleoglaciers (to the south) and flowed north into the Tenmile Creek valley. We know this because the lower slopes of the pass are mantled with sporadic till and round erratics of Precambrian gneisses from the south side of the Mosquito fault, which could only have come from the cirque of the East Fork Arkansas River.

2—The Mosquito fault is a major Neogene normal fault associated with Rio Grande Rift extension. The fault has displaced the Tertiary Climax ore body (24-33 Ma) 9000 ft vertically. The fault has created a steep range front held up by the Precambrian granites and gneisses of the upthrown block; the downthrown block is more subdued forested topography underlain by the softer Minturn formation (Pennsylvanian).

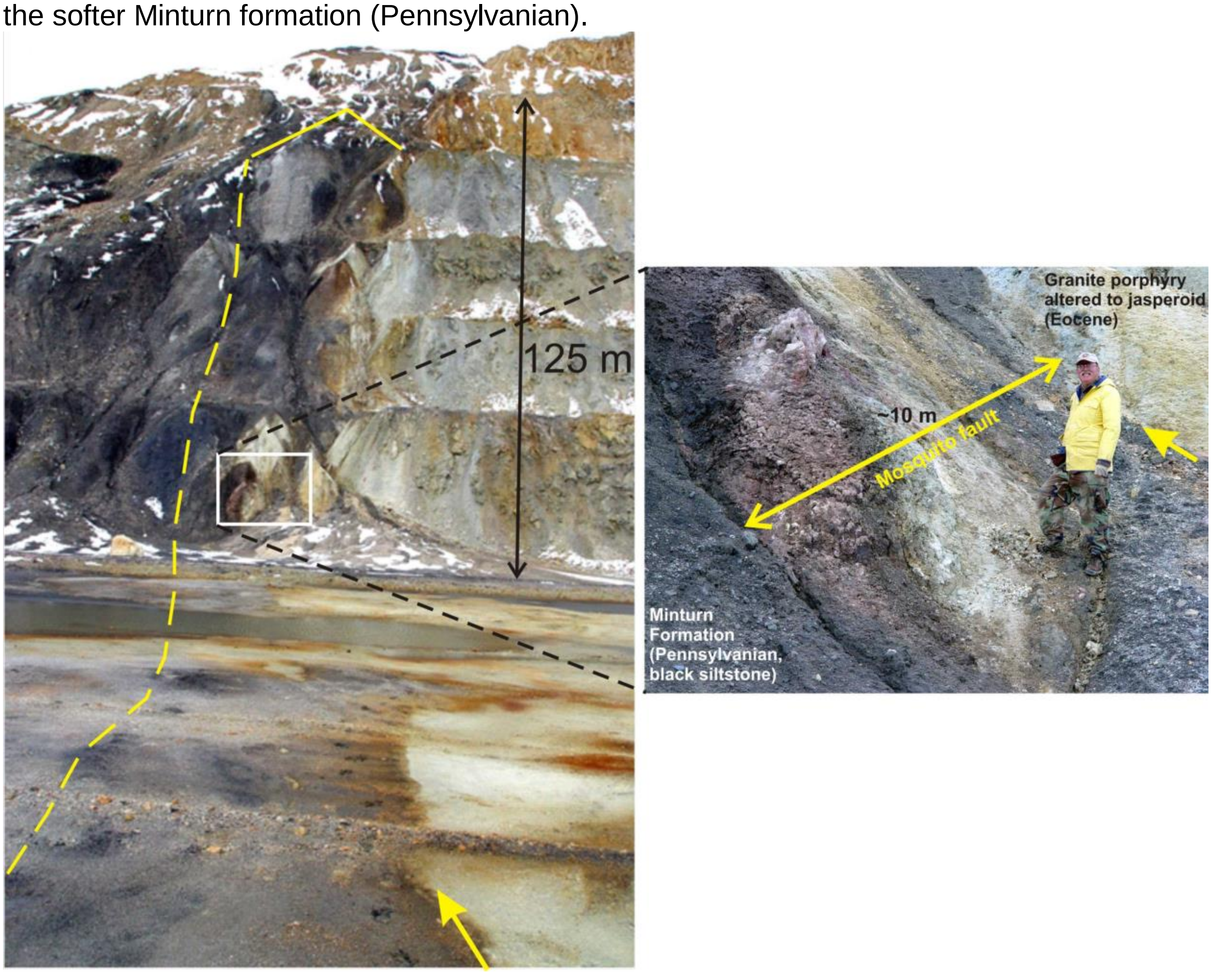


Fig. 9-1. LEFT: The Mosquito fault is well-exposed on the floor and 125 m-high north wall of the Climax Pit (view is to north, along strike). The fault juxtaposes Minturn Formation (to left, black to gray) against lighter Precambrian granite and Tertiary porphyry (to right). The fault zone dips steeply west and is approximately 15 m wide (between yellow dashed line and sharp eastern margin, yellow arrow). W#idmann and others (2004a) describe the eastern margin of the fault zone (yellow arrows) as a 0.3 to 0.5 m-wide zone of light-gray to white, clayey fault gouge, probably derived from crushing and pulverizing of the granitic rock in the footwall. The footwall block has been altered to a jasperoid mass for a distance of at least 15 m from the fault. RIGHT: The wide fault zone is mainly composed of 3-6 foot wide, anastomozing fault slivers of Minturn Formation. The slivers are lens shaped, elongated parallel to the fault zone, and appear to have tapered ends that dovetail into each other.

The Mosquito fault is well exposed in the north wall of the Climax pit (Fig. 9-1). Here it dips steeply to the west and is approximately 50 ft (15 m) wide. Widmann and others, (2004a) describe the eastern margin of the fault zone (fault core) as a 1 to 1.5 foot wide zone of light-gray to white, clayey fault gouge, probably derived from crushing and pulverizing of the Precambrian granite (map unit YXg) in the footwall block. These authors also report that the footwall block has been pervasively altered to a jasperoid mass of rock for a distance of at least 50 ft (15 m) from the fault, but not visibly sheared. The fault damage zone extends about 50 ft (15 m) into the hanging-wall, where it is composed of numerous anastomosing shear zones that bound 3-6 foot (0.9-1.8 m) wide "slivers" of Minturn Formation. The slivers are lens shaped, elongated parallel to the fault zone, and appear to have tapered ends that dovetail into each other. This style of fault architecture has also been noted on normal faults with sedimentary rocks on both sides, and with much less throw (20-30- m; see Fig. 9-2) than the Mosquito fault (2750 m).

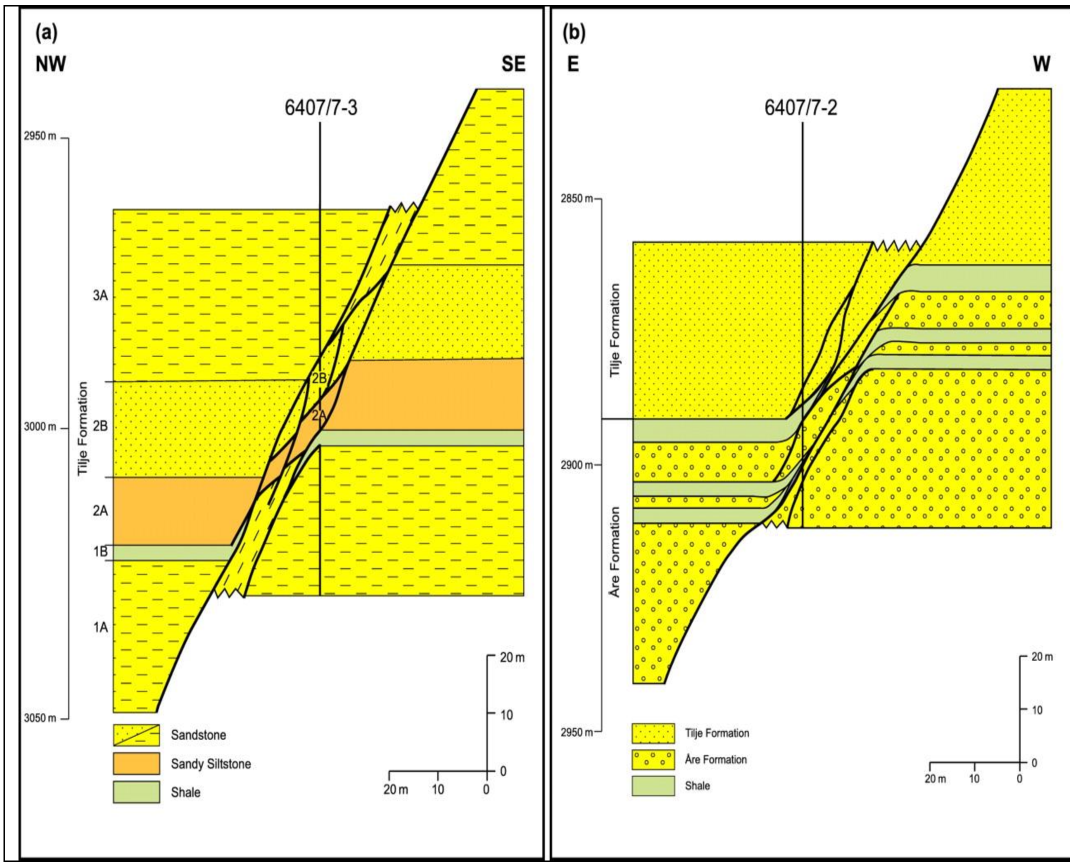


Fig. 9-2.

From the Pit the fault crosses the glaciated valley of the East Fork (Fig. 5, lower photo), and continues along the base of the range front to the SW, below Mt. Arkansas (the high peak). McCalpin et al. (2010) concluded that there was no evidence for late Quaternary movement on this fault.

3—The north pit wall has cut away much of Bartlett Mountain. Due to the block-caving method of mining used at Climax before the open-pit phase, the base of the north wall was undermined, leading to an incipient mountain flank collapse (Fig. 5, upper photo). The headscarp of this collapse is over 100 feet high and resembles natural "sackung" landforms created by deep-seated gravitational spreading.

4—The Climax Mine (Fig. 5) was once the largest producer of molybdenum in the world. It has been in a temporary shut-down mode for the past 10 years, but will be reopened once molybdenum reserves of the nearby Henderson Mine are exhausted. This was supposed to have occurred in 2008, but has been postponed. When it was operating, the Mine was the largest employer in Lake County and provided high-wage union jobs.

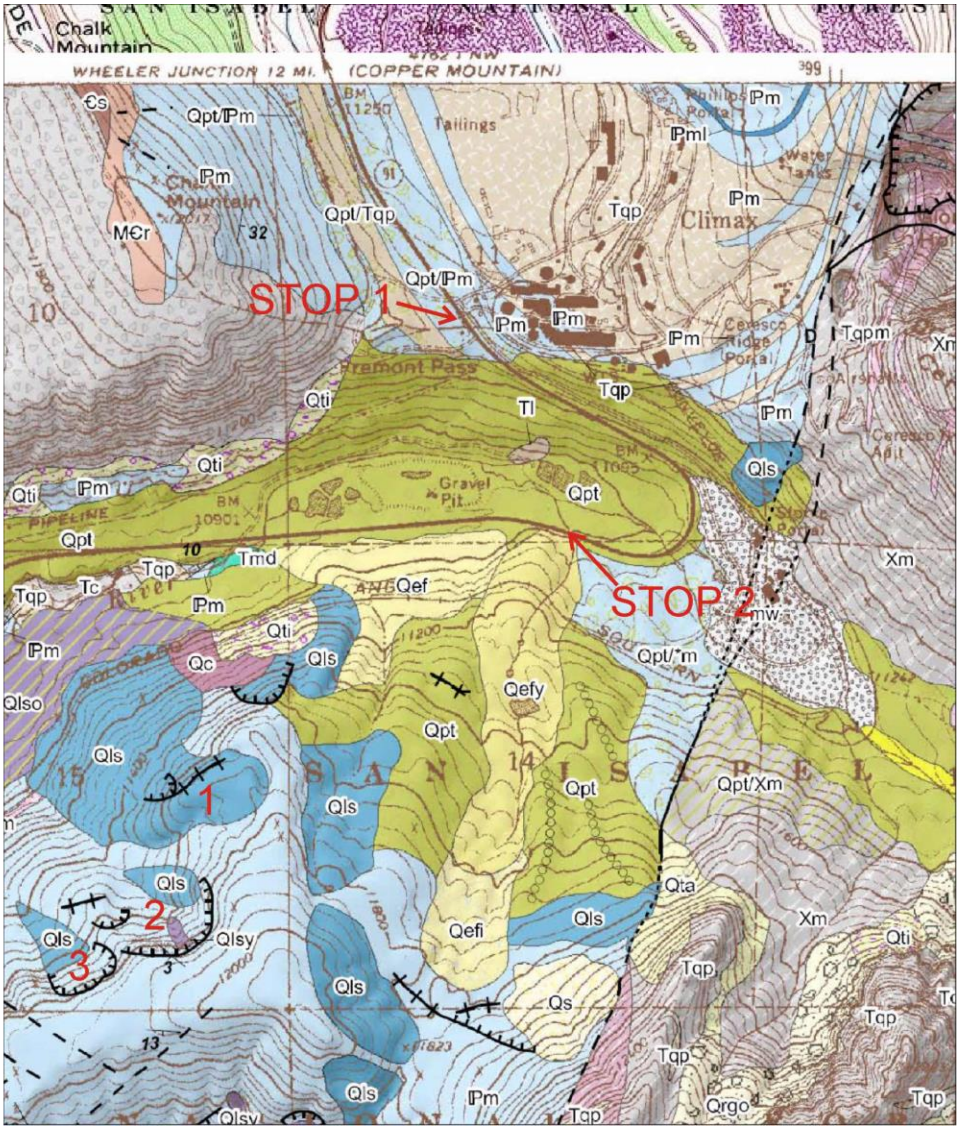


Fig. 9-3. Map of landslides in the Minturn Fm., south of Fremont Pass. Earthflows (young, Qefy; intermediate, Qefi; undivided, Qef) and slumps (Qls).

5— The Minturn Formation (middle Pennsylvanian) underlies the hanging wall of the Mosquito fault here, and is prone to landsliding due to its lithology. According to McCalpin et al. (2010), the Minturn is:

Predominantly white, tan, greenish-gray, or dark purplish-gray arkosic, micaceous pebble- and cobble-conglomerate, sandstone, and shale, interbedded with dark-gray, limestone beds typically less than 30 ft thick. Black shale is most prevalent near the base of the sequence and is interlayered with thinly bedded (platy) dark-purple, gray, or buff micaceous sandstone…. Total *thickness of the Minturn Formation in the quadrangle is estimated to be over 5,000 ft however, the upper part of the section and contact with the Maroon Formation is not observed.*

South of Fremont Pass there are two types of landslides. The landslides below the glacial limit are dominantly earthflows, and are composed of remobilized till which has a matrix of clayey, ground-up Minturn shale. The long Qefi/Qefy earthflow is fed by springs arising downslope of the Mosquito fault, possibly coming out of an unmapped parallel fault in the hanging wall.

However, the more common landslides in the Minturn are slumps and slump-earthflows. These landslides dominate above the glacial limit, where there is no blanket of till to soak up infiltration and become saturated. Some of the slumps in the Minturn east of the East Fork are dipslope failures, caused when the LGM glaciers oversteepened the valley walls. When the ice retreated there was no restraining force to hold in place weak beds that dipped outward into the steep valley wall. However, slumps also occur in the Minturn where slopes are not dipslopes.

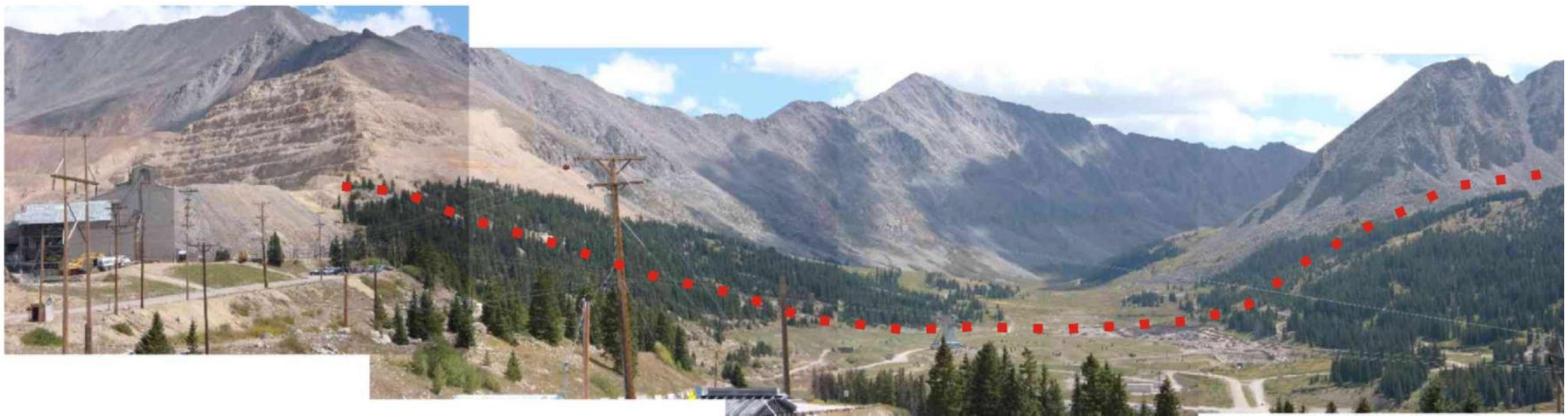
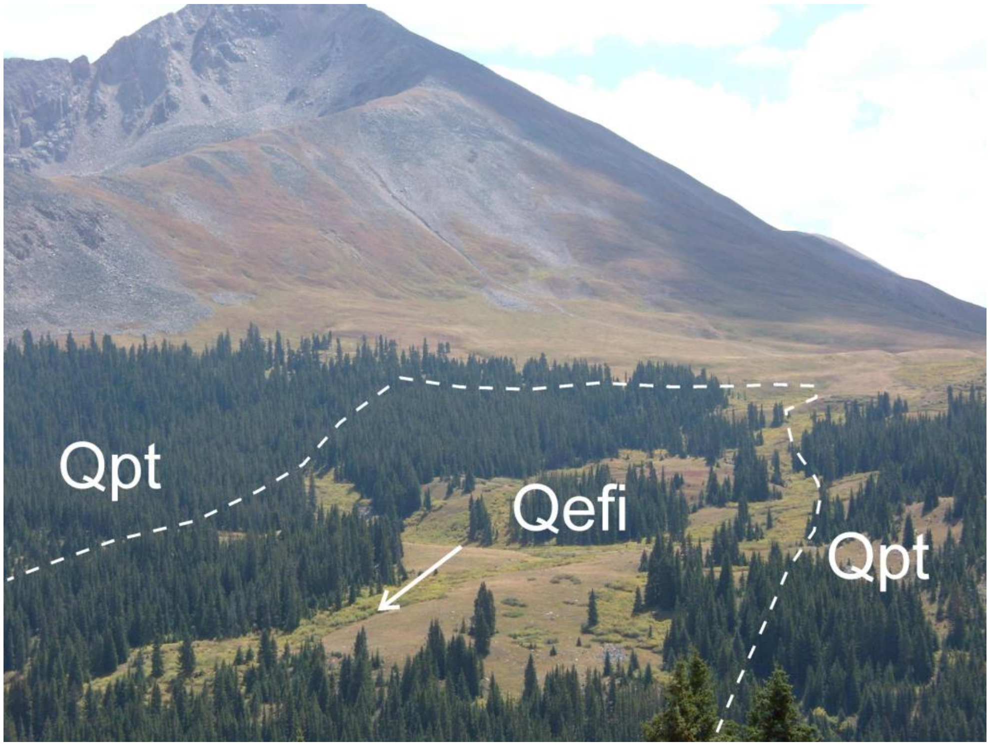


Fig. 9-4. Panoramic photographs of the Climax Mine from Fremont Pass. UPPER PHOTO: the Climax Mine, looking east. The Mosquito fault is exposed between the red arrows at far left. The red dashed line is at the top of the gravitational collapse scarp on Bartlett Mountain. LOWER PHOTO: a continuation of the upper photo, looking to the south. The Mosquito fault (red dotted line) crosses the glaciated valley of the East Fork Arkansas River, and then continues SW at the base of the steep Precambrian range front.



(a).

(b).

Fig. 9-5. (a) Telephoto of the head of earthflow Qefi. This earthflow is composed of remobilized till (Qpt) overlying Minturn Fm.; (b) photomosaic of slumps in Minturn Fm. above the glacial limit.

ROLLING STOP: FREMONT PASS TO I-70

CO-91 descends through the Bull Lake and then Pinedale lateral moraines

to right, failing roadcuts are in Pleistocene till with a matrix of ground-up red Minturn Formation. To right, good views of the Climax tailings piles.

highway cuts through Minturn Formation (red Pennsylvanian sandstones) intruded by Tertiary dikes and sills (light tan porphyry). These Tertiary intrusives are part of the Colorado Mineral Belt and become more common toward Leadville, where they are responsible for the mineralization.

to right, view up Clinton Creek, a glaciated tributary in the Tenmile Range.

For the next mile all roadcuts on right have slope stability problems, some involving major regrading during highway construction, at end of zone to right, roadcut is failing in a large landslide.

to right, view up Mayflower Creek, a glaciated tributary in the Tenmile Range.

Descend long grade section built in the early 1970s.To the rleft old CO-91 goes west on the valley floor toward the old town of Kokomo, now buried under the tailings piles from the Climax Mine. At bottom of grade CO-91 crosses Tenmile Creek.

Pinedale till is exposed in roadcuts to left.

Pinedale lateral moraine of the Tenmile Creek paleoglacier can be seen on valley wall to right, about 400 ft (120 m) above the valley floor.

Valley opens up at Wheeler Flats; Copper Mountain ski area to left; Exit CO-91 onto I-70 eastbound (toward Denver).

ROLLING STOP: I-70 TO EISENHOWER TUNNEL
-cross the Blue River Valley, one of the northernmost expressions of the Rio Grande Rift

-Dillon Reservoir, a component of the Denver Water Board's trans-mountain diversions

-the Williams Fork Mountains (north of I-70), where sackungen have formed where Precambrian crystalline rocks are in overthrust contact with the ductile Pierre Shale, which is extruding out from beneath the heavy granite

ROLLING STOP: EISENHOWER TUNNEL TO DENVER
-difficulties in drilling the tunnels, due to poor rock conditions created by faulting (and perhaps sackungen)

-Silver Plume, a gold mining town

-Georgetown, a bigger gold-mining town

-terminal moraine complex of Clear Creek

-Idaho Falls, a gold mining town (with hot springs!)

-pass through the I-70 roadcut in the Dakota-Morrison Formations, and re-enter the Denver Basin

END OF FIELD TRIP

References:

Briner, J.P., 2009, Moraine pebbles and boulders yield indistinguishable ^{10}Be ages: A case study from Colorado, USA: Quaternary Geochronology, v. 4, 299-305.

Bush, M., unpublished, The Arkansas River Jökulhlaups: modeling volume and discharge of the Pinedale-era Three Glaciers Lake. Unpublished course paper, Colorado College Geology Department.

Capps, S.R., 1909, Pleistocene geology of the Leadville quadrangle, Colorado: U.S. Geological Survey Bulletin, v. 386, 99 p.

Clague, J.J. and Mathews, W.H., 1973. The magnitude of jökulhlaups: Journal of Glaciology 12, 501-504.

Colman, S.M., Pierce, K.L., 1986. Glacial sequences near McCall, Idaho – weathering rinds, soil development, morphology, and other relative-age criteria. QuaternaryResearch 25, 25–42.

Costa J.E. 1988. Floods from dam failures. In Baker VR, Kochel RC, Patton PC (Eds).Flood Geomorphology: John Wiley and Sons: New York; 439–463.

Desloges, J.R., Jones, D.P .andRicker, K.E. 1989: Estimates of peak discharge from the drainageof ice-dammed Ape Lake, British Columbia,Canada:Journal of Glaciology35, 349–54.

Emmons, S.F., 1886, Geology and mining industry of Leadville: U.S. Geological Survey Monograph no. 12, 770 p. plus atlas of maps.

Emmons, S.F., Irving, J.D., and Loughlin, G.F., 1927, Geology and ore deposits of the Leadville mining district, Colorado: U.S. Geological Survey Professional Paper 148, 368 p.

Gosse, J.C., and Phillips, F.M., 2001, Terrestrial in situ cosmogenic nuclides: theory and application: Quaternary Science Reviews, v. 20, 1475-1560.

Hayden, F.V., 1874, Annual report of the U.S. Geographical and Geological Survey of the territories, embracing Colorado, 1873: Washington, D.C., Government Printing Office, 718 p.

Keller, J.W., J.P. McCalpin, and B.W. Lowry, 2004, Geologic map of the Buena Vista East quadrangle, Chaffee County, Colorado:Colorado Geological Survey Open-File Report 04-04,1:24,000 scale.

Lee, K., 2010, Catastrophic outburst floods on the Arkansas River, Colorado: The Mountain Geologist, v. 47, p. 35-47.

Licciardi, J.M., Pierce, K.L., 2008. Cosmogenic exposure-age chronologies of Pinedale and Bull Lake glaciations in greater Yellowstone and the Teton Range, USA. Quaternary Science Reviews 27, 814–831.

McCalpin, J.P., and J.R. Shannon, 2005, Geologic map of the Buena Vista West quadrangle, Chaffee County, Colorado: ColoradoGeological Survey Open-File Report 05-08, 1:24,000scale.

McCalpin, J.P., Temple, J., Sicard, K., Mendel, D. and Ahmad, B., in press (2010a), Climax quadrangle geologic map, Lake and Park Counties, Colorado: Colorado Geological Survey, scale 1:24,000.

McCalpin, J.P., Funk, J. and Mendel, D., in press (2010b), Leadville South quadrangle geologic map, Lake County, Colorado: Colorado Geological Survey, scale 1:24,000.

Nelson, A. R., Shroba,R.R, and Scott, G. R, *Quaternary Deposits of the UpperArkansas River Valley, Colorado.* Boulder, Colorado: AmericanQuaternary Association, 8th Biennial Meeting, August 16-17, 1984, unpublished guide for Field Trip No.7, 51-57.

Nelson, A.R., and Shroba, R.R., 1998, Soil relative dating of moraine and outwash-terrace sequences in the northern part of the Upper Arkansas River valley, central Colorado, U.S.A.: Arctic and Alpine Research, v. 30, p. 349-361.

Pierce, K.L., 2004. Pleistocene glaciations of the Rocky Mountains. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States: Developments in Quaternary Science, vol. 1. Elsevier, Amsterdam, pp. 63–76.

Sarna-Wojcicki, A.M., Pringle, M.S.,Wijbrans, J., 2000, New 40Ar/39Ar age of the Bishop Tuff from multiple sites and sedimentation rate calibration of the Matuyama-Brunhes boundary: Journal of Geophysical Research, v. 105, p. 21 431-21 443.

Scott, G. R, 1975, Reconnaissance geologic map of the Buena Vista quadrangle, Chaffee and Park Counties, Colorado: U.S. Geological Survey Map MF- 657, 1:62,500 scale.

Scott, G. R, 1984, Part III- Pleistocene floods along the Arkansas River, Chaffee County, Colorado. *In* Nelson, A. R., Shroba, R.R, and Scott, G. R, *Quaternary Deposits of theUpper Arkansas River Valley, Colorado.* Boulder, Colorado: American Quaternary Association, 8th Biennial Meeting, August 16- 17, 1984, unpublished guide for Field Trip No.7, 51- 57.

Scott, G.R, Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic map of the Pueblo l° x 2° Quadrangle, south-central Colorado: U.S. Geological Survey Map MI-1022, 1:250,000 scale.

Shroba, R.R., 1977, Soil development in Quaternary tills, rockglacierdeposits, and taluses, southern and central RockyMountains: Ph.D. dissertation, University of Colorado, Boulder,Colorado, 424 p.

Tweto, O., 1961, Late Cenozoic events of the Leadville District and Upper Arkansas Valley, Colorado: USGS ProfessionalPaper 424-B, p. B133-B135.

Tweto, O., 1979, Geologic map of Colorado: USGS, 1:500,000 scale.

Tweto, O., and J.E. Case, 1972, Gravity and magnetic features asrelated to geology in the Leadville 30-minute quadrangle, Colorado:USGS Professional Paper 726-C, p. C1-C31.

Tweto, O., and J.C. Reed, Jr., 1973, Reconnaissance geologic map of the Mount Elbert 15-minute quadrangle, Lake, Chaffee, andPitkin counties, Colorado: USGS Open-File Report 73-287,1:62,500 scale.

Tweto, O., 1974a, Geology of the Mount Lincoln 15-minute quadrangle, Eagle, Lake, Park, and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-556, scale 1:62,500.

Tweto, O., T.A. Steven, W.J. Hail, and R.H. Moench, 1976, Preliminary geologic map of the Montrose 1° x 2° quadrangle, southwestern Colorado: USGS Map MF-761, 1:250,000 scale.

Tweto, O., R.H. Moench, and J.C. Reed, Jr., 1978, Geologic map of the Leadville 1° x 2° quadrangle, northeastern Colorado:USGS Map 1-999, 1:250,000 scale.

Tweto, O., 1978, Northern rift guide 1, Denver-Alamosa, Colorado, in Hawley, J.W. (comp.), Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 13-27.

Westgate, L.G., 1905, The Twin Lakes glaciated area, Colorado: Journal of Geology, v. 13, p. 285-312.

Young, N.E., Briner, J.P., Leonard, E.M., Licciardi, J.M., adnd Lee, K., In press, Assessing climatic and nonclimatic forcing of Pinedale glaciation and deglaciation in the western United States: Geology, doi:10.1130/G31527.1.