PRE-TRIP HIKING LOG: MOLAS LAKE TO THE ANIMAS RIVER AND TRAIN RIDE ON THE DURANGO-SILVERTON RAILROAD TO SILVERTON

KARL E. KARLSTROM[1] AND DAVID A. GONZALES[2]

[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, kek1@unm.edu;
[2]Department of Geosciences, Fort Lewis College, Durango, CO 81301, GONZALES_D@fortlewis.edu

Important times and locations:

7:30 AM — Leave Ouray (if you are staying there)
8:15 AM — Assemble in Silverton where the train unloads near the corner of Cement and 12th street. We will leave most of the cars here and carpool all hikers in the rest of the vehicles to the Colorado Trailhead near Molas Pass (37.747670, -107.688059).
9:00 AM — Begin hike on Molas Creek Trail.
2:30 PM — Arrive at Animas River
3:00 PM — Load train to Silverton
3:30 PM — Carpool to retrieve vehicles left at Trailhead
4:30 PM — Arrive in Ouray by 4:30-5:00 PM for ice breaker at the Elks Club

Logistics:

From Silverton, drive south on Highway 550 for 5.0 mi (~8 km), past the dirt road marked Big Molas Lake and Molas Park, and then turn left into the parking lot for the Colorado Trail. Our hike starts from the south side of the Colorado Trail parking lot. We will hike on a segment of the Colorado Trail (#665) for a distance of ~4 mi (~6.4 km) to the Animas River (Fig. 0.1), with a descent of about 1700 ft (518 m). The well-marked and maintained trail crosses open meadows, passes aspen groves, and involves a series of not-too-steep switchbacks to reach the bottom of Animas Canyon. We will board the Durango-Silverton train for a lift to Silverton (a ride of about 20 minutes).

What to bring: You will be walking for about 5 hours at over 10,000-ft (3048-m) elevation in alpine vegetation near tree line; vistas and hiking are both "breath taking". You need sturdy shoes, a day pack, adequate water, lunch, sunscreen, hat, wind breaker or sweater, and raincoat. Walking poles might be useful also. Trip leaders will bring a first-aid kit, but you may want to consider bringing a personal kit as well.

DESCRIPTION OF DAY ZERO HIKE FROM MOLAS PASS TRAILHEAD TO THE ANIMAS RIVER

Stop 1 (37.74761, -107.68805). Park and start hike. As shown in Figure 0.1, the trail starts from the south part of the parking lot for the Colorado Trail. The trail leads south from the parking lot and then turns more easterly.

Stop 2 (37.74474, -107.68782). Views south and north.

The view to the south (Fig. 0.2) shows the >13,000-ft (>4000-m) summits of Kendall Mountain and the peaks of Kendall, Whitehead, and Arrow. Fifty miles (81 km) of the Continental Divide lie within the Weminuche Wilderness, including the skyline in this view. The headwaters to the Rio Grande are just east of (behind) the skyline peaks, whereas Elk Creek is flowing toward us into the Animas River drainage that is concealed in the foreground. Rio Grande and Animas River ultimately flow into the Atlantic and Pacific oceans, respectively.

The view to the north (Fig. 0.3) is dominated by the Grand Turk at 13,160 ft (4011 m). One can clearly see an angular unconformity atop reddish strata of the Permian Cutler Formation. This unconformity is regional in importance and has been called the "Eocene erosion surface" (Epis and Chapin, 1975) or "Rocky Mountain Erosion surface" (Evanoff and Chapin, 1994; Chapin and Kelley, 1997). It is interpreted to mark post-Laramide beveling of the Rocky Mountains. At this location, the unconformity is overlain by ~100 ft (31 m) of Oligocene Telluride Conglomerate. This conglomerate records an unroofing sequence of the rocks we are standing on that were exposed in the fault-bounded Snowdon block to the south. Telluride basal conglomerates contain up to car-size blocks dominated by Paleozoic clasts at the base, with Precambrian clasts including Uncompahgre Group increasing in abundance up-section. This conglomerate is dominantly "pre-volcanic", but it does contain sparse clasts of volcanic rock in its upper part that are 65-69 Ma (Mudge and Gonzales, 2016). Detrital zircon studies (Donahue, 2016) show a young population that yields an age of

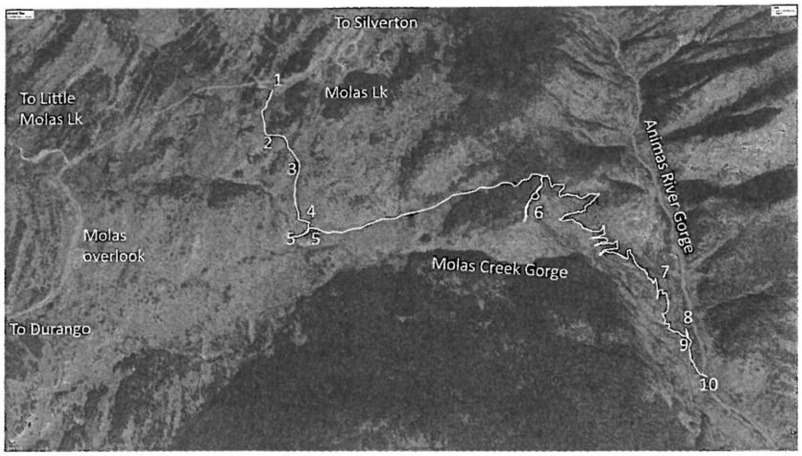


FIGURE 0.1. Google Earth image showing oblique view looking north at the Molas Creek hike and stops 1-10. For a color version, see Color Plate 2A.

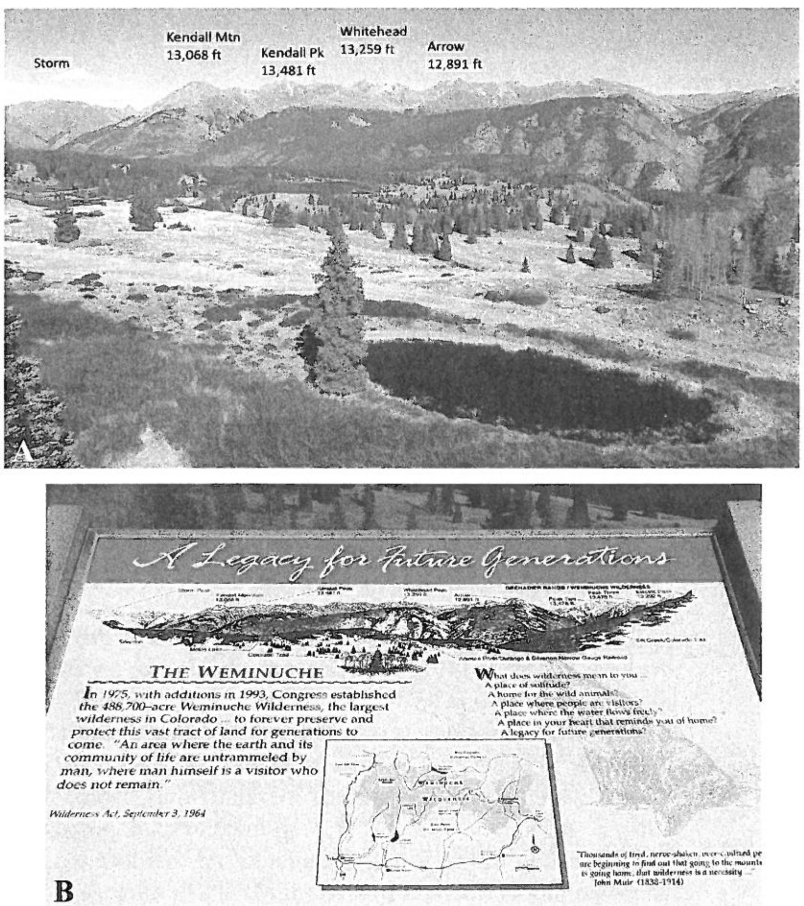


FIGURE 0.2. Molas Pass overlook and view to the east from Stop 1. **A.** The Weminuche Wilderness area was designated in 1975. It is the largest designated Wilderness Area in Colorado. Its average elevation is 10,000 ft (~3000 m) and many peaks are 13,000 to over 14,000 ft (>4000 m) such as Eolus, Sunlight, and Windom Peaks. In the view to the northwest, peaks >13,000 ft (~4000 m) are Kendell Mountain, Kendell Peak, Whitehead, and Arrow (See Color Palte 2B). **B.** Fifty miles (~81 km) of the Continental Divide lie within the wilderness. The Rio Grande headwaters are just east of these peaks. Elk Creek is flowing towards us into the Animas River (concealed from sight). Rio Grande and Animas rivers ultimately flow into the Atlantic and Pacific oceans, respectively.

31.3±2.0 Ma which provides a maximum depositional age of ~31 Ma for this unit. Thus, rather than recording Eocene erosional "beveling" of Laramide uplifts, this unit records Oligocene doming and early tectonism related to the San Juan volcanic field (Donahue, 2016). The overlying volcanogenic San Juan Formation makes up the dark top of Grand Turk. This unit is dated at 27.6–28.3 Ma (Lipman, 2007), exceeds 3281 ft (1 km) in thickness, and is overlain by the 164-ft (50-m)-thick 27.6 Ma Crystal Lake tuff (Lipman et al., 1973; Bove et al., 2001) that erupted from the Silverton caldera. Thus, the Rocky Mountain "erosion surface" in this area records a tectonic event of early Oligocene doming and conglomerate deposition into developing accommodation space to the north and west just prior to the massive ~28 Ma caldera eruptions of the southwestern San Juan Mountains. This uplift likely involved fault reactivation of the Molas Creek and Snowdon faults that helped in the unroofing of the Snowdon sub-block of the Grenadier block (Fig. 0.3) and caused northerly and westerly transport of, first, Lower Paleozoic strata, then material from Uncompahgre Group (+ Proterozoic granites and gneiss) in debris flows, alluvial fans and braided rivers (arrows in Fig. 0.4).

Stop 3 (37.74362, -107.68637). Molas Formation and view to Pennsylvanian Hermosa Group.

This part of the hike traverses across the contact between Lower Paleozoic Devonian Ouray Limestone and Mississippian Leadville Limestone, and the basal Pennsylvanian units of the Molas Formation (Fig. 0.5). The Molas Formation was deposited on a Pennsylvanian karst surface developed on the Leadville carbonates; it consists of red beds (dominantly mudstone and siltstone) that have highly variable thickness and that filled the karst topography (Baars and See, 1968). As summarized by Thomas (2007), the Molas Formation grades up into a succession of gray shale, sandstone, and limestone of the Pennsylvanian Hermosa Group. The Pennsylvanian Hermosa Group is ~2854 ft (~870 m) thick and contains successions of shallow-marine limestone, mudstone, and deltaic sandstone units with shallowing-upward cycles up to 40 ft (12 m) thick that are interpreted to be prodelta, distal-bar to delta-front, distributary-channel, and delta-plain deposits (Thomas, 2007). The Leadville Limestone in this area is extensively silicified and dolomitized, likely from post-70 Ma magmatism and mineralization.

Stop 4 (37.73999, -107.68561). Lower Paleozoic strata — Devonian Ignacio and McCracken Sandstone, Elbert Formation, Ouray Limestone, and Mississippian Leadville Limestone.

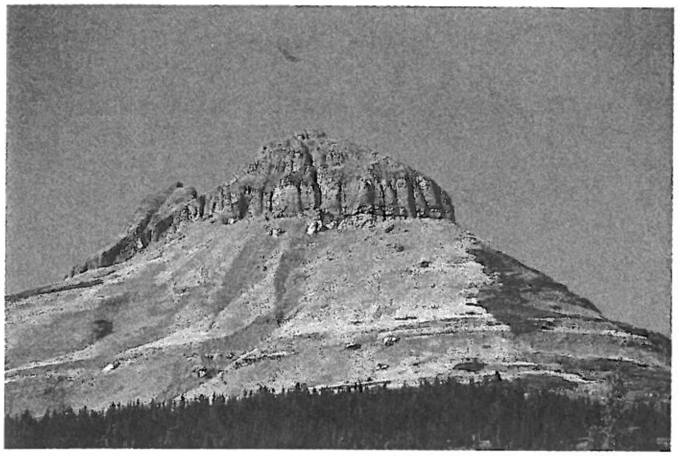


FIGURE 0.3. Stop 1: View north at Grand Turk, elevation 13,160 ft (4011 m). Subhorizontal "steps" above the trees in the lower slopes are carbonates of the Pennsylvanian Hermosa Group which are overlain by red rocks of the Permian Cutler Formation. The Paleozoic rocks are gently tilted and overlain with angular unconformity by the ~30 Ma Telluride Conglomerate, which in turn is overlain by the San Juan Formation of the San Juan volcanic field.

The trail makes several short switchbacks and allows a cross sectional view of Lower Paleozoic strata. As summarized by McBride (2016), Cross and co-workers (Cross et al., 1905a, 1905b; Cross and Hole, 1910; Cross and Larsen, 1935) first mapped the area and named the Paleozoic stratigraphic units. The oldest Paleozoic unit, dominated by sandstone, was named the Ignacio Quartzite. It is overlain by dolostone, shale, and sandstone of the Elbert Formation with rare Late Devonian fish fossils. McBride (2016) summarized a large literature devoted to discussion of the age of the Ignacio Quartzite and whether there is a regional disconformity between the Ignacio Quartzite (possible late Cambrian?) and McCracken Member of the Ouray Formation (Late Devonian). McBride (2016) concluded that the Ignacio and McCracken units are both Late Devonian based on the presence of one Ordovician detrital zircon in the Ignacio in a sample that also has oboloid brachiopods of questionable late Cambrian age, but that occurs with well-dated Late Devonian placoderm fish plates. The compositional differences between the feldspar-rich Ignacio and the "billiard-ball" quartz grains of the McCracken may be due to two different coeval river systems, where the northern (McCracken) river had a supply of eolian quartz grains in contrast with the southern (Ignacio) river that was dominated by granite-derived K-feldspar (McBride, 2016).

Baars (1965) proposed a NW–SE-trending fault block of Precambrian rock that he called the Grenadier Horst or Highland (Fig. 0.4). Several workers considered this highland to have affected Devonian sedimentation as part of the Transcontinental Arch, with Ignacio and McCracken sediments recording the earliest stages of transgression across Precambrian rocks of the Transcontinental Arch in southern Colorado. The apparently conflicting NE and NW trends of the Transcontinental Arch and Grenadier uplift respectively suggests a complex geometry for early Paleozoic sedimentation and preservation as discussed by Myrow et al. (2003). These Devonian sandstone units are possibly equivalent to hydrocarbon exploration targets in the Paradox Basin to the west. The Grenadier uplifted block appears to have affected deposition at multiple times: during the Proterozoic (?), Devonian, Pennsylvanian Ancestral Rocky Mountains orogeny (Thomas, 2007), and during mid-Tertiary uplift and deposition of the Telluride Conglomerate.

Stop 5 (37.73948, -107.68519). Weasel Skin Conglomerate, waterfall area, and Molas Creek fault (37.73921, -107.68603).

Campbell (1994) introduced the name Weasel Skin Member for the basal conglomerate of the Ignacio Quartzite that is up to 76 ft (23 m) thick (Fig. 0.6). This unit remains poorly dated and has been proposed to be a basal member of the

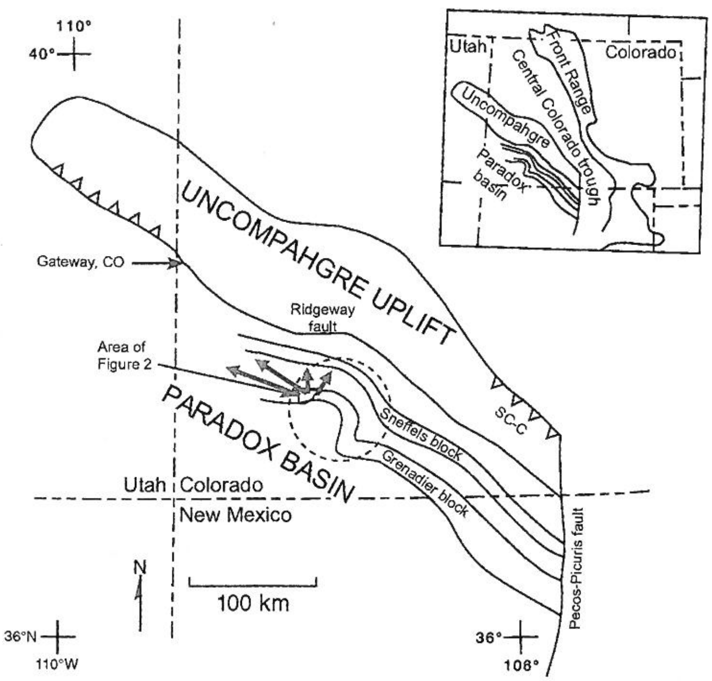
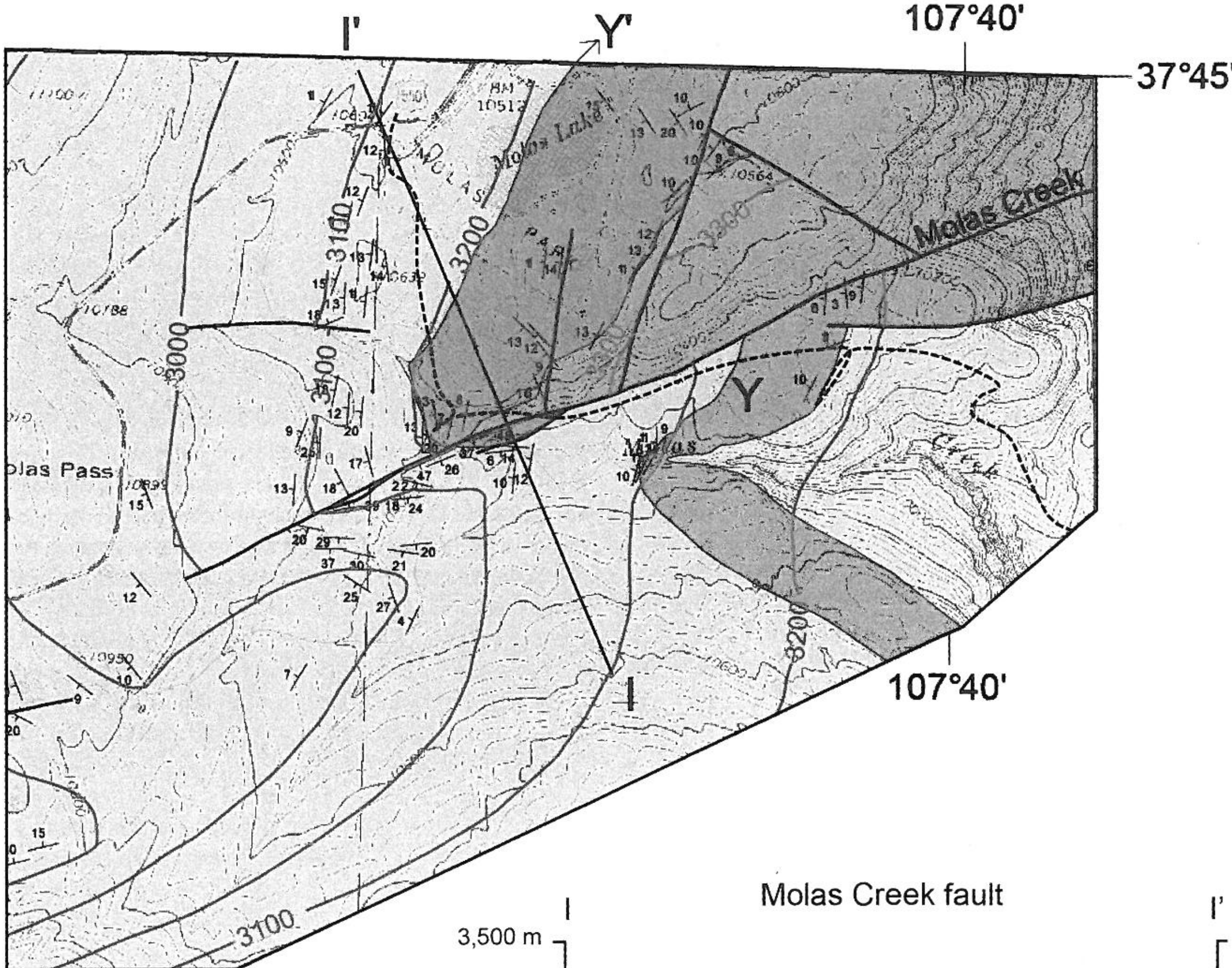


FIGURE 0.4. Index map of the Pennsylvanian Ancestral Rocky Mountains (modified from Thomas, 2007) showing uplifts that influenced early and late Paleozoic sedimentation. Precambrian rocks of the NE-trending Transcontinental Arch (Amato and Mack, 2012) were not covered until Devonian time in the San Juan Mountains such that the SW Colorado region may have been an elevated, non-depositional region from the Cambrian through Devonian (Thomas, 2007), or alternatively it may reflect erosion (non-preservation) of thin Cambrian to Devonian strata, for example by Devonian faulting similar to the Ouray fault (Myrow et al., 2003). NW-trending uplifts and basins of the Pennsylvanian Ancestral Rocky Mountains were dominated by the Uncompahgre thrust uplift and related Paradox Basin. But sub-blocks such as the fault-bounded Grenadier block also influenced Devonian through Pennsylvanian thicknesses (Thomas, 2007). Dashed-line circle shows location of the Laramide San Juan dome. Box shows location of Figure 0.4. Reactivated uplift of the Grenadier block also influenced deposition of the ~30 Ma Telluride Conglomerate (arrows).



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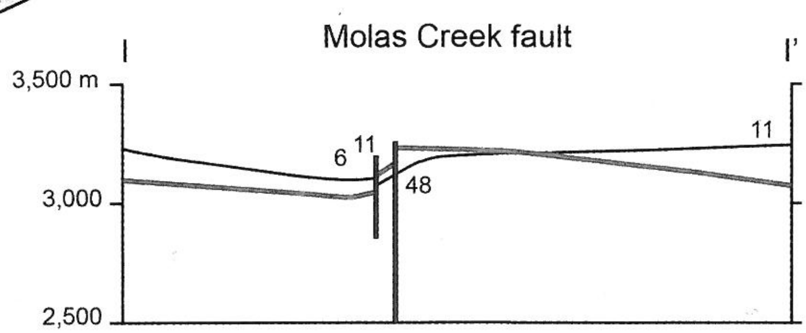

B

EXPLANATION

Pennsylvanian-Permian
Cutler Group
Hermosa Group
Moles Formation

Cambrian-Mississippian
Leadville Limestone
Ouray Limestone
Elbert Formation
Ignacio Formation

Precambrian
Uncompahgre Group

Precambrian
gneiss, schist, granite
(Twilight Gneiss,
Irving Formation,
Tenmile Granite)

FIGURE 0.5. **A.** Geologic map of the Molas Creek fault area (cropped and modified from Thomas, 2007). Path of the hike is shown as black dashed line. Topography (40-ft contours) is from Engineer Mountain and Snowdon Peak 7.5-min quadrangles. The 100-m structure contour lines are from the base of Pennsylvanian strata (base of Molas Formation). **B.** The cross section I-I' shows N-side up and sinistral separations on the Molas Creek fault. This fault is interpreted to be the north bounding fault of the Grenadier block, a synsedimentary Pennsylvanian positive flower structure that formed during Ancestral Rocky Mountain orogeny and is cored by resistant Uncompahgre Group. Pennsylvanian strata thicken by a factor of 3 away from the upthrown Grenadier block (Thomas, 2007). For a color version, see Color Plate 3.

FIGURE 0.6. Weasel Skin conglomerate contains large rounded clasts dominated by quartzite from the Uncompahgre Group.

Ignacio Formation (hence Devonian, Thomas, 2007) or possibly Late Precambrian (Condon, 1995; McBride 2016). Thomas (2007) shows this as a "boulder conglomerate" facies of the Ignacio Formation that was deposited near the Molas Creek fault. It thins rapidly to the north away from the fault. Leadville and Ouray limestones also thicken markedly across this fault indicating syn-depositional Pennsylvanian transpressional (sinistral/south-side-up) slip (Thomas, 2007).

We will take a short jaunt east from the Colorado Trail to view the box canyon and waterfall of upper Molas Creek. Figure 0.7A shows cliffs that are made up of Devonian McCracken and Elbert formations and Mississippian Leadville Limestone. The creek bed contains outcrops of the Weasel Skin conglomerate. At their south side, the cliffs end abruptly against redbeds of the Molas Formation defining the trace of the Molas Creek fault (Fig. 0.7B). The map and cross section of Figure 0.5 indicate 660-985 ft (200-300) m of north-side-up vertical separation and about 3281 ft (1000 m) of sinistral strike separation. Combined, these are interpreted to represent a Pennsylvanian transpressional regime (Thomas, 2007).

Stop 6 (37.73997, -107.67207). Deformational structures in phyllite of the Uncompahgre Group.

This stop is on glacially polished quartzite and phyllite in the Uncompahgre Group at the very brink of the cliffs of Animas River gorge. Basal Paleozoic rocks of the Elbert Formation directly overlie basement as seen in outcrops a short distance to the west both along the Colorado Trail and in the nearby aspen grove. Thus, we are just below the Great Unconformity which represents greater than a billion years of missing time (1.4 to 0.4 Ga) that is not recorded by rocks in the Needle Mountains. Both the outcrops and the views are unparalleled.

Figure 0.8 shows a portion of the map of basement rocks of this area by Gibson and Harris (1992). The location of this stop is within a few hundred meters south of the sheared and subvertical basement-cover contact seen in the cross section (and that we will view from the train window later today). Harris et al. (1987) recognized several deformational events "D" in the basement rocks: $D_b = D_{basement}$ that predated deposition of the Uncompahgre Group. Additional deformational events that affected both basement and Uncompahgre Group cover, are called: $D_{b/c} = D_{basement/cover}$. As shown in Figure 0.9A, basement rocks show intense transposition of foliation due to isoclinal folding of interleaved mafic supracrustal rocks (Irving Formation) and intrusive (Twilight Gneiss) basement rocks. The timing of D_b basement deformation is constrained to between 1.71 and 1.69 Ga and likely took place at amphibolite facies as first noted by Gonzales (1997) based on U-Pb ages of metamorphic sphene and Sm-Nd garnet and whole-rock isochron age. D_b is thus correlated with the 1.75-1.70 Ga Yavapai orogeny. Deposition of the Uncompahgre Group is now known to have taken place after the 1,700 and 1,715 Ma Whitehead and Tenmile granites (Gonzales, 1997; Gonzales and Van Schmus, 2007), and before a newly dated granitic dike that intrudes the Uncompahgre Group near Coalbank Pass that yielded an $^{40}Ar/^{39}Ar$ muscovite age of 1690 to 1700 Ma (Gonzales and Heizler, personal commun., 2017). This shows that the Uncompahgre Group was deposited during or just after emplacement of the 1695 to 1700 Ma Bakers Bridge Granite. The ultra-clean quartz arenites of

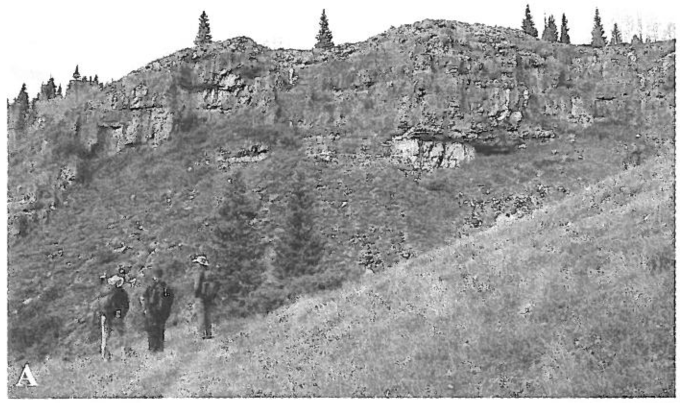

Figure 0.7. **A.** Waterfall area of Little Molas Creek made by resistant cliffs of the Elbert and Leadville carbonates. **B.** South end of the cliffs shows the trace of the Molas Creek fault that juxtaposes basal Paleozoic strata on the north side with red karst breccia of the Molas Formation on the south. This fault has ~660 ft (~200 m) of north-side-up dip separation and ~3281 ft (~1000 m) of sinistral strike separation as shown by the map and cross section in Figure 0.5.

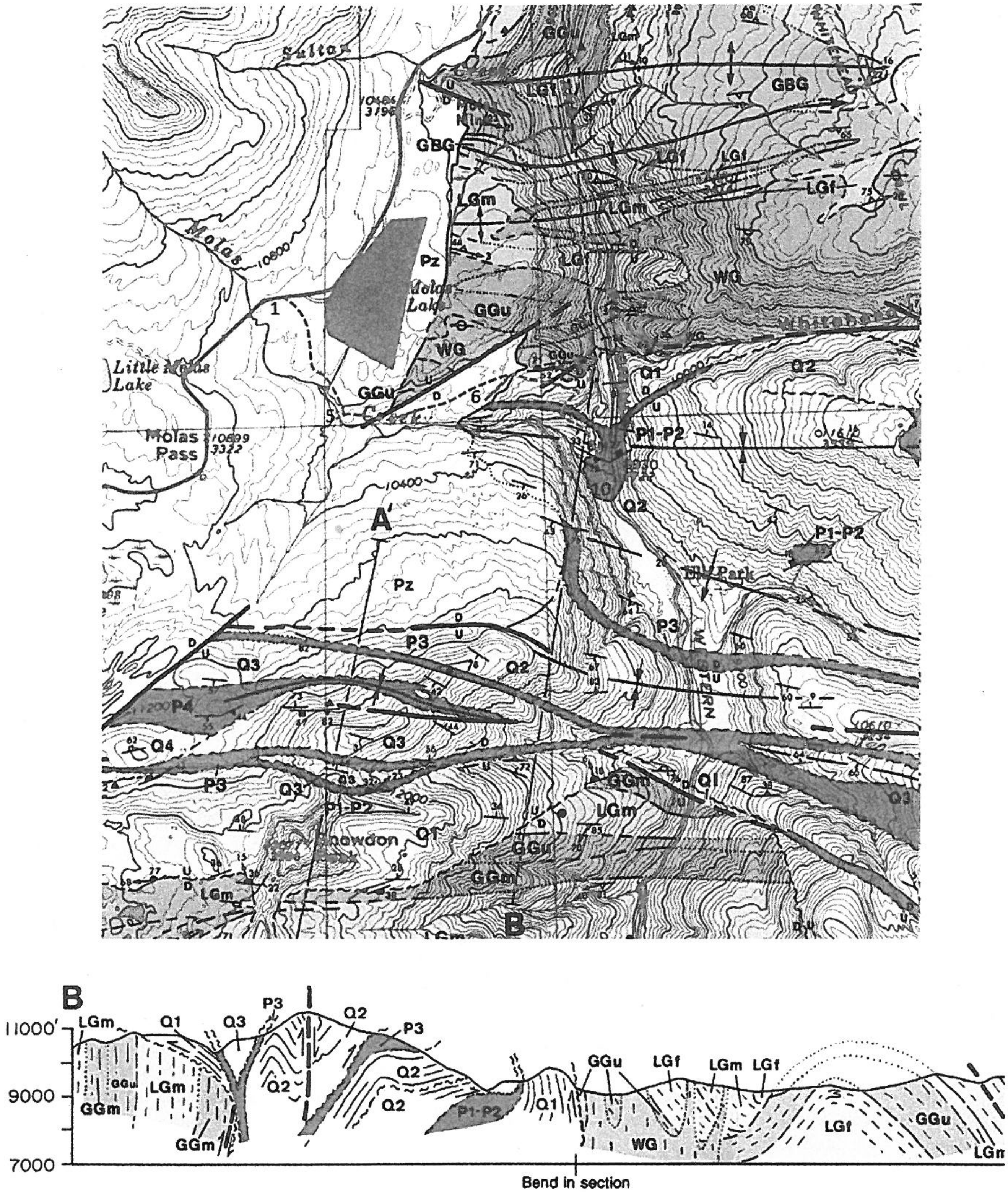

FIGURE 0.8. Geologic map and cross section of Precambrian basement rocks of the Molas Lake area (cropped from Gibson and Harris, 1992). Q1-Q3 and P1-P3 are interbedded quartzite and phyllite units that correlate stratigraphically across Needle Mountains to the Ouray area. The location of our hiking route and numbered stops are shown along the dashed line. East-west upright antiforms and synforms affect both the Uncompahgre Group and its basement that consists of Irving Formation and Twilight Gneiss and intrusive 1715 Ma Tenmile Granite (Gonzales, 1997; Gonzales and Van Schmus, 2007). Harris et al. (1987) and Gibson and Simpson (1988) interpreted the basement to have been penetratively deformed and unroofed before the Uncompahgre Group was deposited. Then several deformations affected both basement and cover, including thrusting to both the north and south as related to continued shortening of a "cuspate-lobate" regional syncline. Tewksbury (1985) and Zinnser (2006) interpreted different thrust directions in terms of different events: S1 involved top-north thrusting and S2 was the main shortening event but also involved localized top-south thrusting. For a color version, see Color Plate 4.

the Uncompahgre Group are interpreted to be the result of intense weathering of arc and back arc basement rocks in a 1.70-1.68 Ga back-arc extensional basin (Jones et al., 2009).

Figure 0.9 shows D_{bc} refolded folds of the basement, and we will be examining refolded D_{bc} in Uncompahgre phyllite #P1/P2 at Stop 5. Overprinting structures of the type shown here document multiple deformation generations but do not of themselves indicate how much time may have elapsed between generations. These structures could be due to progressive deformation involving thrusting and folding during the 1.68-1.60 Ga Mazatzal orogeny and/or as amplified by 1.45 Ga shortening associated with the emplacement of the Eolus granite and the Picuris orogeny. This remains a topic of needed additional research.

Stop 7 (37.73997, -107.67207). Cross beds in quartzite of the Uncompahgre Group.

Stratigraphic sections were reconstructed by Harris et al. (1987) based on cross bedding indicators such as the one shown in Figure 0.10. They defined quartzite stratigraphic units Q1-Q4 to be interbedded with phyllite units P1-P5 units and they correlated this stratigraphy across the western Needle Mountains to the Ouray area. Zinnser (2006) expanded this correlation to the eastern Needle Mountains and suggested that the Vallecito Conglomerate stratigraphically underlies the Uncompahgre quartzites further warranting use of the term Uncompahgre Group. The total >9845-ft (>3-km)-thick fluvial and shallow marine rocks in the Uncompahgre Group suggests that tectonic subsidence kept pace with deposition.

Stop 8 (37.73564, -107.66178). Andalusite-bearing phyllite in the Uncompahgre Group.

Andalusite-bearing phyllite occurs in Uncompahgre Group phyllites both in the Animas River location and in the Ouray area. The aureole of the Eolus pluton also contains andalusite in coexistence with sillimanite at distances up to about 2 km from the pluton (Hunter and Andronicos, 2012) that records contact metamorphism at 2–4 kbars (0.2 to 0.4 GPa) with metamorphic temperatures at 1.43 Ga that range from greenschist facies at distances of 6.2 mi (10 km) from the pluton to upper amphibolite facies near the pluton. Regional metamorphic grade in "cold" areas at distance from the 1.43 Ga pluton margin is greenschist grade, but the age of this metamorphism is not well understood. One possibility is that regional andalusite growth occurred during the Mazatzal orogeny at approximately 1.65-1.60 Ga. One $^{40}Ar/^{39}Ar$ hornblende age from the Tenmile Granite in the western Needle Mountains indicates cooling through 500°C at ~1610 Ma (Shaw et al., 2005). The 1715 Ma (Gonzales, 1997; Gonzales and Van Schmust, 2007) Tenmile Granite was exhumed to the surface prior to deposition of the cover sequence (Gibson and Simpson, 1988; Tewksbury, 1989), suggesting that the unit was reheated to temperatures greater than 450° between 1710 and 1610 Ma, conditions within the andalusite stability field. Similarly, an $^{40}Ar/^{39}Ar$ hornblende age of 1650 Ma from amphibolitic (Irving Formation) basement rocks just below the depositional contact with the Uncompahgre Group near Molas Lake of 1650 Ma suggests cooling through ~500°C at that time. These data suggest that the Uncompahgre Group was metamophosed at greenschist facies during the 1.65-1.60 Ga Mazatzal orogeny. However, additional andalusite growth may have taken place regionally at ~1.43 Ga (Hunter and Andronicos, 2012). The majority of hornblende and mica cooling ages from the Needle Mountains indicate cooling through 350°C between 1450 and 1390 Ma (Shaw et al., 2005), indicating that heating during the 1.43 Ga thermal event was a regional event, rather than restricted to the

FIGURE 0.9. Harris et al. (1987) and Gibson and Simpson (1988) proposed several deformational events in the basement rocks (Yavapai orogeny) that predated several deformational events that affected both basement and Uncompahgre Group cover (Mazatzal and/or Picuris orogenies). Deformational features of the basement rocks resulted in intense transposition of foliation due to isoclinal folding of interleaved mafic supracrustal rocks (Irving Formation) and intrusive (Twilight Gneiss) basement rocks. Timing of basement deformation is constrained to 1.71-1.69 Ga and has been correlated with the 1.75-1.70 Ga Yavapai orogeny. Deposition of the Uncompahgre Group took place between 1.70 and 1.68 Ga in a back-arc upper plate extensional basin (Jones et al., 2009, 2012).

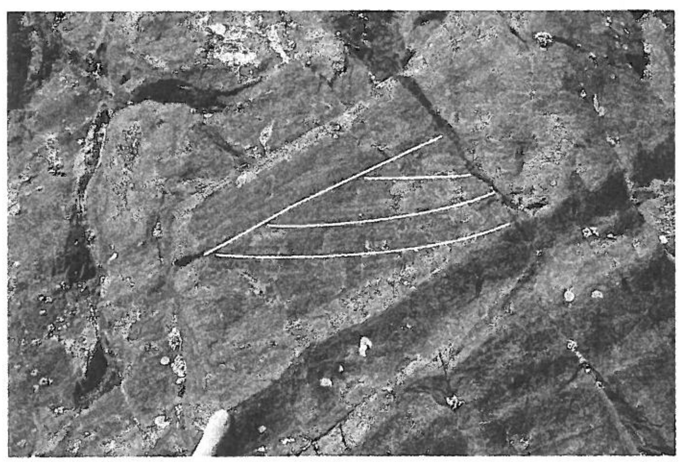

FIGURE 0.10. Crossbedding in the quartzites in unit Q1 of the Uncompahgre Group along the Colorado Trail shows upright bedding that dips and youngs stratigraphically to the south, away from a depositional contact with the underlying basement.

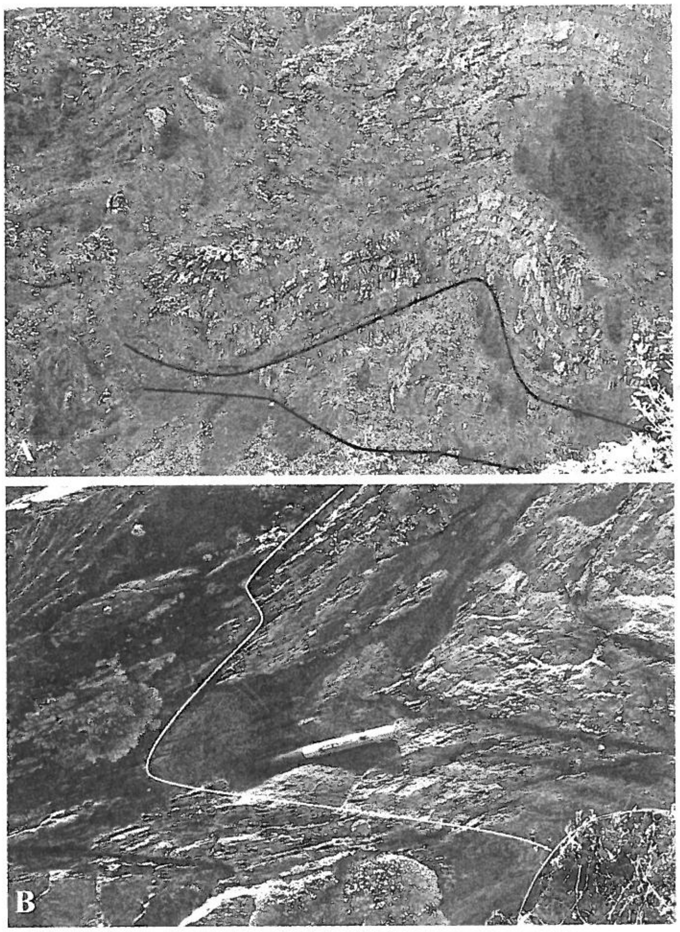

FIGURE 0.11. **A.** Decollement folds in cliff wall indicates bedding-parallel slip during thrusting. **B.** Subhorizontal axial plane cleavage in phyllite in the F2 synforms is interpreted to be related to D1 thrusting of Uncompahgre Group.

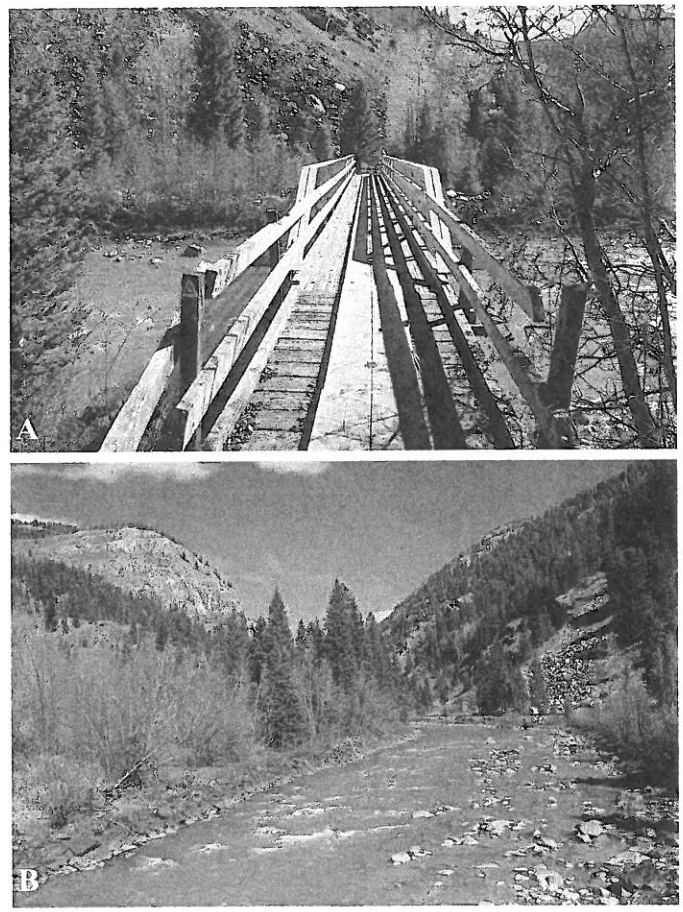

FIGURE 0.12. **A.** Bridge across the Animas River at the end of our hike. We will board the train on the far side. **B.** Views from the bridge show iron stained river cobbles and bounders that reflect long-term cumulative effects of acid drainage from the Silverton area.

immediate aureole of 1.43 Ga plutons. Zinnser (2006) noted that andalusite porphyroblasts across the Needle Mountains overgrow two fabrics (S1 and S2) and are sometimes folded and/or rotated by a later fabric/deformation. Thus, our present interpretation is that there were multiple times of andalusite growth during both Mazatzal and Picuris orogenies and that rocks remained in the middle crust at depths of about 10 km from 1.60 to ~1.45 Ga, when they began to be unroofed.

Stop 9 (37.73524, -107.66145). View of decollement fold and thrust tectonics in Uncompahgre Group.

Decollement folds are folds where shortening is taken up in some layers but not in adjacent overlying or underlying layers, requiring that slip occurred along bedding-parallel decollements. Such slip surfaces are usually localized in weak units like shale. Figure 0.11A shows decollement folds in the N-facing cliff wall across Molas Creek from us. Figure 0.11B shows subhorizontal axial plane cleavage that also suggests thrust-style deformation with the shallow fabric correlated with S1 from Stop 6. Upright axial plane cleavage of the upright decollement folds and other regional synforms and antiforms are interpreted as S2, which records the dominant D_{bc} shortening in the Uncompahgre Group. The ages of S1 (thrusting) and S2 (shortening) fabrics in the phyllites are not well constrained but both are bracketed between 1.7 and 1.45 Ga.

Stop 10 (37.73358, -107.66129). Foot bridge across the Animas River.

The footbridge across the Animas (Fig. 0.12) marks the completion of the hike. We will board the train for Silverton just across (east of) the bridge. Figure 0.12B shows orange staining of Animas River gravels that reflects the cumulative effects (over centuries and millions of years?) of acid mine drainage from the Silverton area, including the Iron King Mine spill that will be discussed in Roadlog 3B.

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