Seismic Sources and Neogene Faulting in the Northern Front Range, Colorado, Source Area of the 1882 (M6.6) Earthquake; Collaborative Research with the Colorado Geological Survey

Program Element II: Evaluate Urban Hazard and Risk.

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1. ABSTRACT

This reconnaissance investigation did not locate a historic surface rupture that could be attributed to the Nov. 7, 1882 M6.6 earthquake. Normal-faulting earthquakes of that magnitude typically produce a small surface rupture, but in 1/3 of historic cases, such an earthquake produced only sparse ground cracking that would be quickly obscured by erosion. Notably, earthquakes of M6.5 and lower typically do not result in surface rupture (Pezzopane and Dawson, 1996). Therefore, if there is any chance that the M6.6 magnitude estimate is actually an overestimate, then there is a good chance that the 1882 earthquake did not produce a surface rupture, certainly not one that could be located over 120 years later.

This study did document that the Lyons-Estes Park toll road had to be cleared of rocks in the spring of 1883, implying that an anomalously large number of rocks rolled onto the road during the winter of 1882. However, we could not locate any historic documents that mentioned the cause of the anomalous rockfalls, nor could we locate any written accounts of the earthquake from people living in Estes Park in November of 1882, despite an extensive search in local library collections and museums.

We did locate several landslides and sackungs in the epicentral area, which appear to have a higher spatial density than is normal in the Precambrian rocks of the northern Front Range. However, none of these slope failures appear to be historic, so even if they are related to strong earthquake shaking, it would be from prehistoric events.

Two of the faults studied have indirect evidence suggestive of, but not conclusive of, Quaternary fault movement. On the “Estes Park” fault (informal name used herein), the oldest set of Quaternary terraces in Dry Gulch are truncated at a downward step in the top of bedrock, very close to the mapped location of the fault. This truncation could also be explained by erosion, as could some anomalous deformation features in a small gully on the western side of Dry Gulch. The only way to rule out Quaternary faulting in any formal manner would be to trench one or both locations.

A large quarry into the Thompson Canyon fault near Glen Haven exposes the western boundary fault, and the overlying Quaternary colluvium has some peculiar relationships across the fault, both in the quarry and in the adjacent roadcut of County Road 43. Due to the reconnaissance nature of this study, neither exposure could be cleaned off well enough to confirm that the steep contacts in the colluvium were depositional rather than tectonic. We located at least two viable trench sites on the Thompson Canyon fault where early- to middle Pleistocene deposits overlay Precambrian bedrock, and would potentially record any fault movements in the Quaternary. These sites could be trenched if funding were made available.

2. INTRODUCTION

2.1 Purpose and Scope of Study

The overall goal of this collaborative study was to look for field evidence of neotectonic faulting in the Colorado Front Range north of the latitude of Boulder, Colorado (40° N latitude). The "Quaternary Fault and Fold Map and Database of Colorado" (Widmann et al., 1998) shows no Quaternary faults in the entire northern Front Range. However, prior to this study the northern Front Range had never been subjected to a focused seismotectonic study (Fig. 2-1).

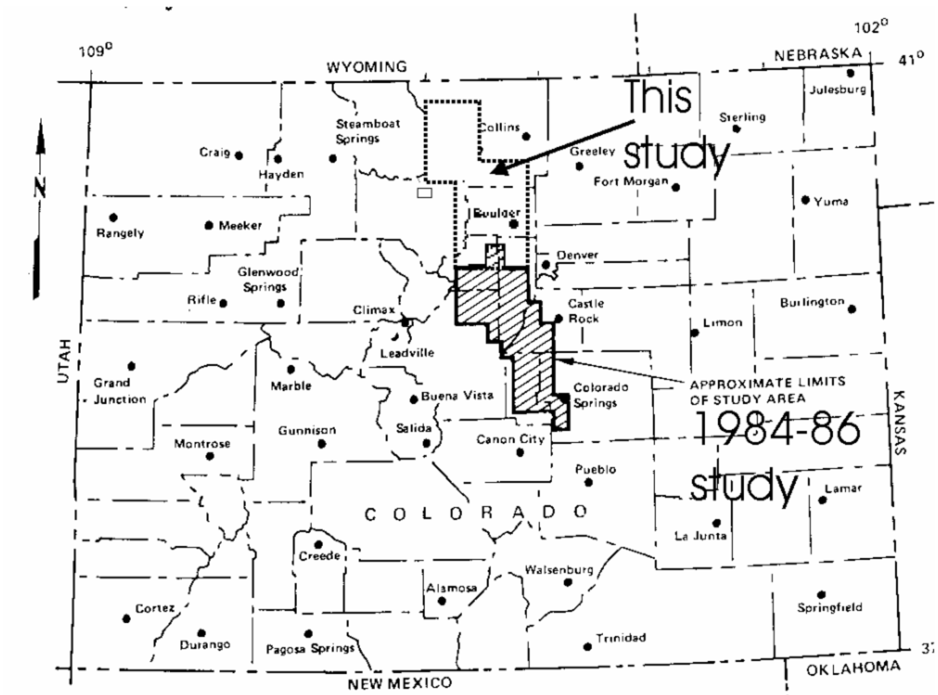


Fig. 2-1. Extent of this study (dotted line) compared to the extent of the 1984-86 neotectonics study of the central Front Range for the proposed Two Forks Dam (diagonal pattern).

In contrast, the central part of the Front Range was subjected to a comprehensive series of seismotectonic studies in the early to mid-1980s (summarized in Geotechnical Advisory Committee, 1984, 1985a, 1985b, 1986), as part of the Two Forks Dam project of the Denver Water Board. This large multi-year project involved lineament mapping (Steele, 1984, 1985, 1986), fault mapping (Dickson et al., 1986; Harza Engineering Company, 1985a; Hornback, 1984, 1986; Shlemon, 1985a;), geologic mapping (Hornback, 1985b), Quaternary stratigraphic and soil stratigraphic studies (Shlemon, 1985b, c; 1986; Wallace and Friedman, 1985), fault trenching (Cochran, 1984; Dickson, 1986; Dickson and Paige, 1986; ESA, 1985; Harza Engineering Company, 1985b, c; Hornback, 1985a; Shlemon, 1984; Yadon, 1986), and geochronology. As a result, several Quaternary faults were discovered (Geotechnical Advisory Committee, 1986).

When we first proposed this present study to NEHRP, GEO-HAZ and the CGS envisioned a 2-year program (FY2002 and FY2003) that would topically mimic the studies done for the Two Forks Dam, but at a much lower level of effort due to the budgetary constraints of the NEHRP program. Our FY2002 effort was to be devoted to "regional" fault mapping and geologic reconnaissance of sites of suspected Quaternary faulting. Our FY2003 effort was to be devoted to trenching the suspected sites from FY2002. The FY2002 project was funded by NEHRP (02HQGR0094 to CGS; 02HQGR0095 to GEO-HAZ) and is the subject of this report. The FY2003 project was not funded.

The study was split into two components. The Colorado Geological Survey (02HQGR0094) performed lineament mapping and compilation of all previously-mapped faults (see Appendix 1; also Morgan, 2003) in the northern Front Range. GEO-HAZ Consulting performed field checking in the 1882 epicentral area and mapping of selected field sites where there appeared to be some evidence of Quaternary faulting.

2.2. Overview of the Neotectonics of the Colorado Front Range

The following overview is taken from Leonard et al. (2002).

One of the most striking geologic features of the Denver area is the Rocky Mountain front, a 500–1000m high incline of Precambrian crystalline rocks on the east side of the Front Range. West of this feature surface topography rises gradually to the west, then steepens abruptly again near the high peaks along the Continental Divide. Travel from the plains into the mountains is usually via one of several deep canyons cut into this step of Precambrian rocks. Similar topography exists in other ranges of the southern Rocky Mountains. This topography has fascinated geologists for over 130 years and is still a subject of study. Questions remain concerning its origin and evolution and the timing of its development. This field trip will examine this topography and discuss the various models proposed for its origin.

The traditional interpretation of the topography is that following cessation of mountain uplift at the end of the Laramide Orogeny (in the middle Eocene, approximately 45 Ma), a long episode of erosion ensued. The flanks of the mountains were eroded into low surfaces and debris eroded from the mountains accumulated in the adjoining basins and on the Great Plains. The basin fill created stable local base levels that allowed mountain streams to cut extensive pediments onto the Precambrian crystalline rocks on the range flanks. Toward the end of this erosion interval, sediments derived from adjacent mountain ranges and regional volcanoes covered the range flanks and relatively low-lying Laramide structures. The erosional interval extended from the Eocene until the end of the Miocene and was followed by regional uplift in the Pliocene and Quaternary. As a result of this uplift, the basins and Great Plains were stripped of their sediments, and deep, narrow canyons were cut into the flanks of the mountain ranges. In some cases, rivers and streams that had flowed on deposits that buried older Laramide structures were superimposed onto these structures and cut narrow canyons across them, commonly at high angle to the earlier structures. Corollaries to this traditional interpretation are that (1) the mountains and plains were lower at the end of the Laramide Orogeny than they are at present, (2) most, if not all, of post 5 ma erosion has been due to regional tectonic uplift, not climatic change, and (3) major drainages may have shifted throughout the Cenozoic as a result of variable tectonic uplift. Proponents of this model included Blackwelder (1909), Davis (1911), Mackin (1947), Knight (1953, 1974), Steven et al. (2004), and the model was an underlying principle of the volume edited by Curtis (1975).

During the past two decades, a new model for the development of the topography in the southern Rocky Mountains has been proposed. Paleoclimatic analyses of fossil floras, including the Florissant, Pitch Pinnacle, and Creede floras, have yielded paleoelevation estimates for the late Eocene and Oligocene that are equal to or higher than present elevations (Meyer, 1986 , 1992 ; Wolfe, 1992 ; Gregory and Chase, 1992 ; Gregory, 1994 ; Gregory and McIntosh, 1996). Proponents of the new model argue that late Cenozoic canyon cutting occurred due to climate change rather than tectonic uplift. According to this model, increased storminess resulting in increased peak discharges and competence and capacity of mountain and plains river systems (Gregory and Chase, 1994). Any rock uplift of the mountains and plains that occurred during this interval may have occurred as an isostatic response to erosion, rather than a response to tectonic forcing. Canyon cutting and resulting isostatic response could increase local relief and uplift the crests of the mountains, without changing the average elevations of the region (England and Molnar, 1990). This model suggests that (1) post-Laramide elevations in the southern Rockies have remained fairly consistent over most of the Cenozoic, (2) climatic change led to the stripping away of the sedimentary aprons along the frontal ranges, dropping local base level, and triggering the late Cenozoic increase in canyon cutting without regional uplift, (3) major drainages should have been relatively constant in position through late Cenozoic time, and (4) any late Cenozoic rock uplift occurred as an isostatic response to erosion, and therefore its distribution should be broadly related to erosion patterns.

Steven et al. (2004) propose a third hypothesis, that uplift of "broad composite domes" occurred in Pliocene and Pleistocene (post-Ogallala) time. They state: *"DEEPLY entrenched meanders occur at one place or another along every major and moderate-sized stream that drains the Front Range. Judged from modern streams such as the South Platte River, these meanders originally formed at gradients of 5 to 10 feet per mile, yet the streams with incised meanders have clearly anomalous gradients of tens to hundreds of feet per mile. We infer that the intrenchment and steepening gradients indicate penecontemporaneous differential uplift and related erosion.*

Meanders were initiated along low-gradient streams during rejuvenated erosion resulting from irregular uplift of the Front Range beginning in the middle Miocene. This rejuvenation followed development of a hilly to low-relief paleotopography when most of the irregular cover of Oligocene volcanic rocks was being removed. Early stages of rejuvenation were relatively slow, and broad valleys with hilly interfluves formed; meanders developed along the larger streams in these valleys. The broad valley-hilly interfluve stage aggregated into an irregular bench all along the east flank of the Front Range that Lee in 1923 called the Rocky Mountain peneplain. The meanders developed at the same time as middle-upper Miocene Ogallala Formation of the Great Plains was deposited to the east, and gravel deposited in some broad mountain valleys and now surviving in scattered patches may be correlative with the Ogallala. Later phases of incised erosion progressively developed flaring-walled canyons that pass downstream into steepwalled canyons toward the mountain front. Early into canyon development, uplift expanded east into the plains, terminating deposition of the Ogallala, causing excavation along the main streams and entrenchment of the inherited meanders within the mountains.

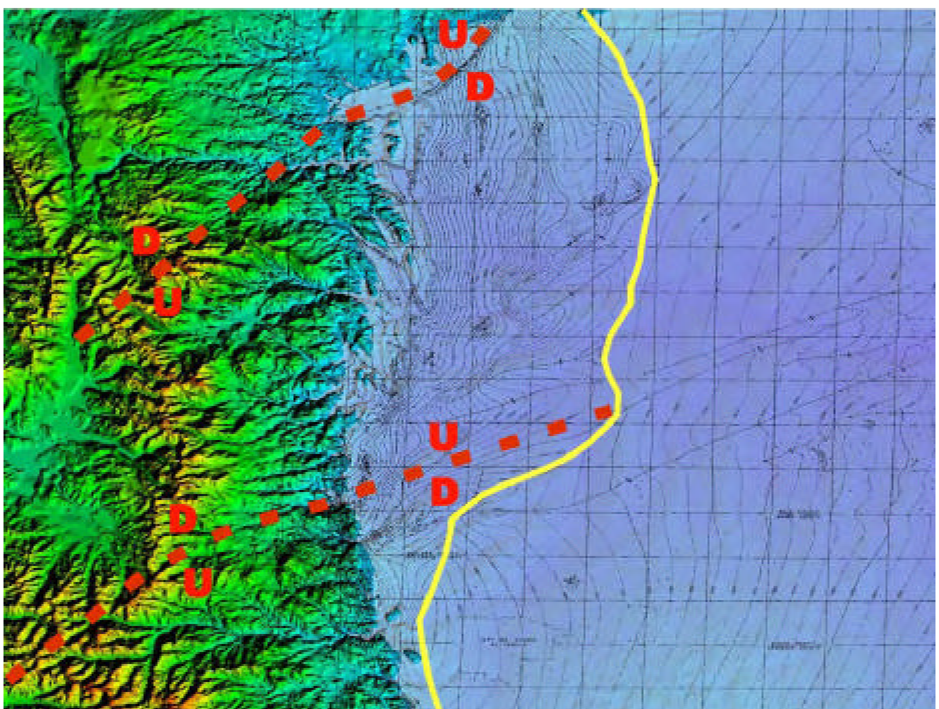
Meanders along the Cache la Poudre and Big Thompson River systems near the north end of the Front Range developed early during uplift of a broad composite dome capped by the summit of Longs Peak, and the meanders were progressively incised during subsequent uplift.

Modern gradients along meandering segments that extend as much as 25 miles into the dome exceed 100 feet per mile; the upper ends of the meandering courses have been obliterated by Pleistocene glaciers. Major uplift of the dome was thus post-Ogallala Formation in age and took place during the Pliocene and into the Pleistocene.

At the south end of the Front Range a structural platform, more than 20 miles across and surmounted by the prominent Pikes Peak protrusion, also developed during formation of the incised terrain. Ancestral South Platte River flowed south from the vicinity of Florissant to the Arkansas River near Canyon City. It was a meandering stream that occupied a low-gradient valley. It became antecedently entrenched along the flank of a rising topographic and structural ramp that offset upper Oligocene volcanic units at the west margin of the Pikes Peak platform.

The depth and character of middle and late Miocene erosional incision indicate the position and relative uplift of the various structural blocks that make up the composite Front Range. Previously proposed evolutionary models that suggest simple epeirogenic uplift of the Front Range in late Cenozoic time seem greatly oversimplified. Whether changing climates influenced geomorphic form, tectonic uplift was the dominant factor."

Finally, Matthews (2004) proposed that Neogene block faulting has occurred in the Front Range, particularly along two regional lineaments that he interprets as scissor faults (Fig. 2-2).



Fig, 2-2. Digital elevation model of the northern Front Range merged with Dakota (Muddy J) structural contour map from Haun (1968). Red dashed lines are regional lineaments interpreted as scissor faults by Matthews (2005). These lineaments separate the northern Front Range and Denver Basin into large blocks. Yellow line is axis of Denver Basin.

2.3 The M6.6 earthquake of 7-8 Nov. 1882

The existing historical research done on the 1882 earthquake (McGuire et al., 1982; Oaks and Kirkham, 1986) relies almost entirely on newspaper accounts. However, none of these newspapers were located near the epicenter, estimated by Spence et al. (1996) to be about 13 km north of Estes Park (Fig. 2-3). We could make better estimates of the source of the 1882 earthquake, its magnitude, and near-field effects if we could locate better descriptions of earthquake effects from the epicentral region.

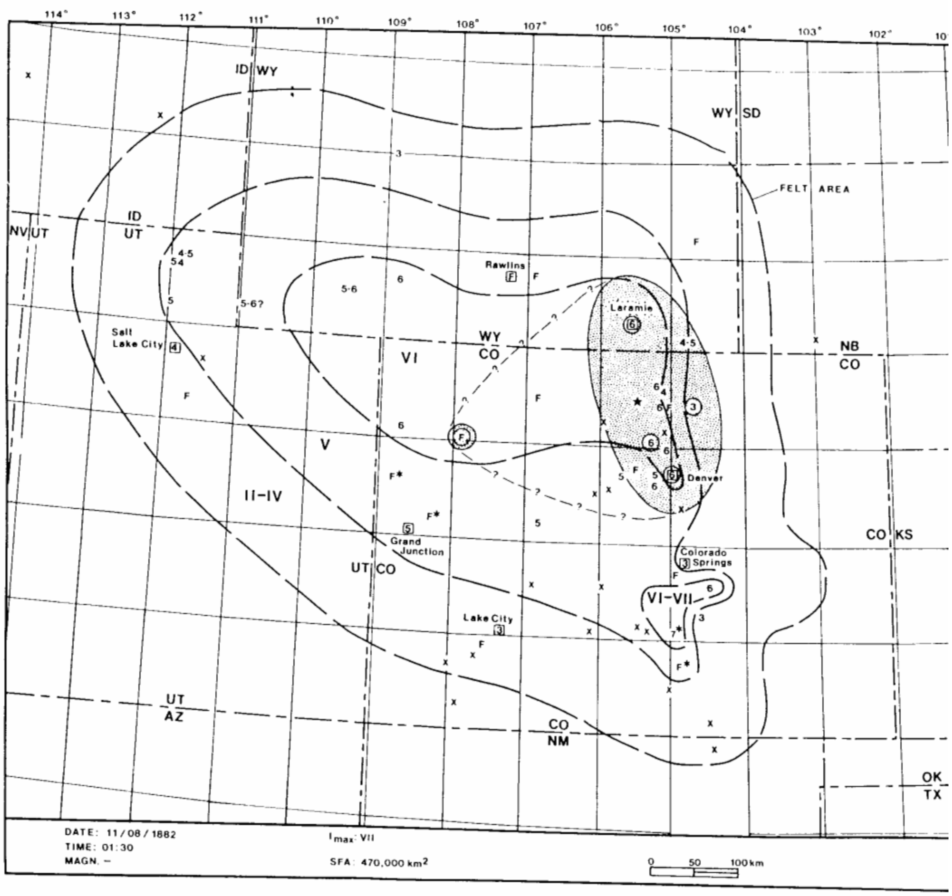


Fig. 2-3. Modified Mercalli Intensity map of the Nov. 7, 1882 earthquake (M6.6). Felt area of the M~5 Nov. 8 aftershock is shaded. Star at center of shaded area is the estimated 1882 epicenter, at 40°30'N, 105°30'W, with an estimated error of ±0.5°. From Kirkham and Rogers, 1986.

In 1882, there were at least 11 homesteads in Estes Park, the earliest of which dates to 1859. The Estes Park Post Office was established June 2, 1876, and the Estes Park school district was created in 1883, the year after the earthquake. The largest commercial establishment in Estes Park in 1882 was the Dunraven, or English, Hotel, built in 1877. The hotel was managed for its owner, Lord Dunraven of Ireland, by Theodore Whyte, an Irish mining engineer and Dunraven's local factotum in Estes Park. Theodore Whyte and his family lived in Lord Dunraven's "cottage" adjacent to the hotel until 1896, at which time he left the valley and died in New England a few years later. Obtaining Whyte's diaries or correspondence was one of our prime goals, but we failed to locate them.

Our historical researcher looked for diaries, letters, County records, and other previously unsearched sources that record events of Nov. 7 and 8, 1882. The first sources searched are the archives of the three museums in Estes Park, the McGregor Ranch Museum, the Estes Park Historical Museum, and the Rocky Mountain National Park museum. The McGregor Ranch was established in the early 1870s and Clara McGregor became the first postmaster in 1876. The McGregor Ranch Museum is part of the McGregor Historical Trust, and has a full-time curator and several volunteer assistants, who are currently inventorying the collected correspondence and diaries of the McGregor family. The McGregor Ranch lies north of Estes Park and was probably the closest habitation to the estimated epicenter in 1882. The Estes Park Historical Museum contains a large collection of early records and correspondence from Estes Park, but none of it yielded any mention of the 1882 earthquakes (Liesl Monroe, Curator, pers. comm.., 2001). Rocky Mountain National Park was not established until 1915, 33 years after the earthquake, but the museum does contain records of landowners from the Park area who were bought out by the Federal Government in 1915, including the Spragues, who operated Sprague's Hotel in Moraine Park beginning in 1877. The holdings of all three museums failed to reveal any records that date from Nov. 7-8, 1882.

2.3.1 Probability of Surface Faulting in the 1882 Earthquake

Not all historic earthquakes of M~6.6 have caused surface rupture, so there is a real possibility that the causative fault in 1882 did not have surface rupture, which would explain why none was described afterwards. For example, the 1926 M6.6 Clarkston, Montana earthquake also did not have surface faulting, according to Pardee (1926). He states "Although no definitie scarp was formed, ground cracks were opened by the shaking along a line interpreted as the probable trace of the fault." Pardee (1926) reported that the cracks mentioned above were more or less continuous for a mile or more and in places formed a zone several feet wide I which the ground was broken and the clods were overturned (Pardee, 1926, his Plate 12A). If the 1882 earthquake was only accompanied by this type of cracking, in a remote area such as the upper part of the North Fork Big Thompson River, it may have gone unnoticed and the cracks would not be visible today.

However, other earthquakes of identical magnitude, such as the 1934 Hansel Valley, Utah earthquake, did produce surface faulting (8-10 km long, maximum displacement 50 cm). Pezzopane and Dawson (1996) analyzed all large, historical normal faulting earthquakes in the western USA and produced a histogram showing what proportion of earthquakes of various magnitude produced surface rupture (Fig. 2-4). They show that, for M6.5 and below, the majority of historic earthquakes have NOT produced surface rupture. Events of M6.6 and higher have generally produced either displacement, or cracking. Of the 3 historic earthquakes of M6.6 (1925 Clarkston, Montana; 1934 Hansel Valley, Utah; 1954 Rainbow Mountain, Nevada), the first had cracking and the latter two had bona-fide surface displacement. Thus, the difference between M6.5 and M6.6 is apparently very critical for surface faulting. The M6.6 magnitude estimated by Kirkham and Rogers (1986) is based on felt area, about which there has been considerable controversy. If this felt area is an overestimate, and the true magnitude was M6.5 or less, then there is a good probability that the earthquake was not accompanied by surface rupture.

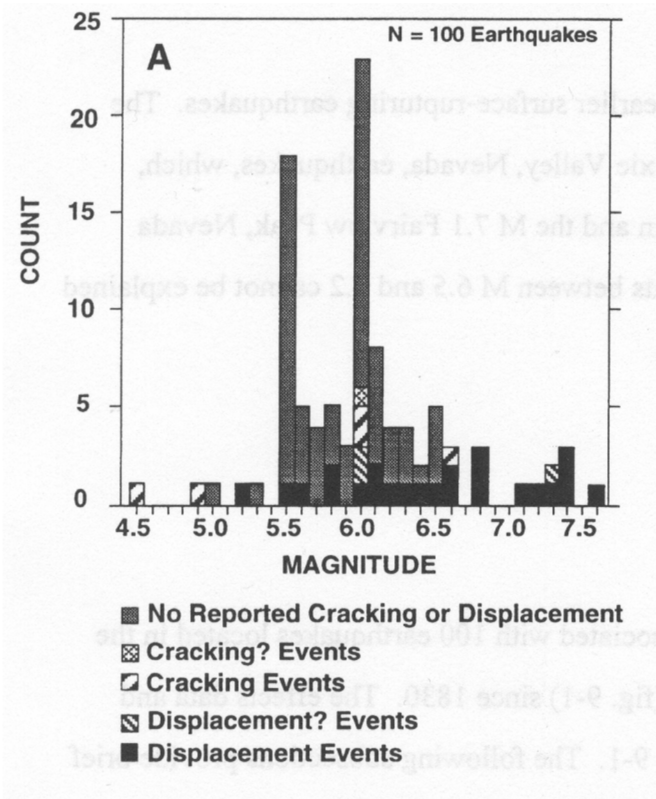


Fig. 2-4. Histogram of historic normal-faulting earthquakes in the western USA, showing if the earthquakes were accompanied by surface displacement or ground cracking. From Pezzopane and Dawson, 1996.

2.3.2 Earthquake-Induced Landslides and The Causative Fault

Because no recent fault scarps were reported in 1882, and we observed no such scarps during our photogeologic mapping, we looked for indirect indicators of seismic shaking such as landslides and rockfalls. According to Keefer (1984), historic earthquakes of M6.6 have caused landslides over areas ranging from 10-1000 km^2. The upper-bound area of ca. 1000 km^2 is equivalent to a circular area 36 km (22.5 mi) in diameter. That area is plotted on Fig. 2-5 along with the Eocene erosion surface mapped by Scott and Taylor (1986; red stipples) and the major Front Range faults in the epicentral area known at that time. The 1882 epicenter of Kirkham and Rogers (1986) falls nearly on the Thompson Canyon fault, but given the location uncertainty of ±0.5°, several structures could be the source fault, as explained next.

The toll wagon road from Lyons to Estes Park, which followed the present route of US Highway 36, was repaired in the spring of 1883 due to its impassibility, although this was blamed on “a particularly snowy winter” (Pickering, 1999) rather than on the earthquake. An alternative explanation is that a large number of earthquake-induced rockfall boulders had to be removed from the roadway. Much of this route traverses terrane underlain by the Silver Plume granite, which weathers to large (1-10 m) round corestones that would be highly mobile during string earthquake shaking. For example, the slopes around Pinewood Junction are covered with numerous round to subround boulders sitting on the ground surface. If the alternative explanation is true, it means that rockfalls were most common quite far SE of the 1882 epicenter of Kirkham and Rogers (1986). This in turn suggests that the causative fault was SE of the epicenter.

There are 5 large mapped faults within the epicentral area, which comprise the set of most likely sources of the 1882 event. These include 3 NW-trending faults: (1) the Thompson Canyon fault (Hutchinson and Braddock, 1987), (2) the "Olympus-Fall River fault" (informal name), and (4) the "Tahosa Valley-Forest Canyon-Specimen Mountain fault" (informal name). There are also 2 possible NE-trending sources: (4) the "Estes Park fault" (informal name), and (5) the regional scissor fault of Matthews (2004). Each of these faults is described in later sections of the report.

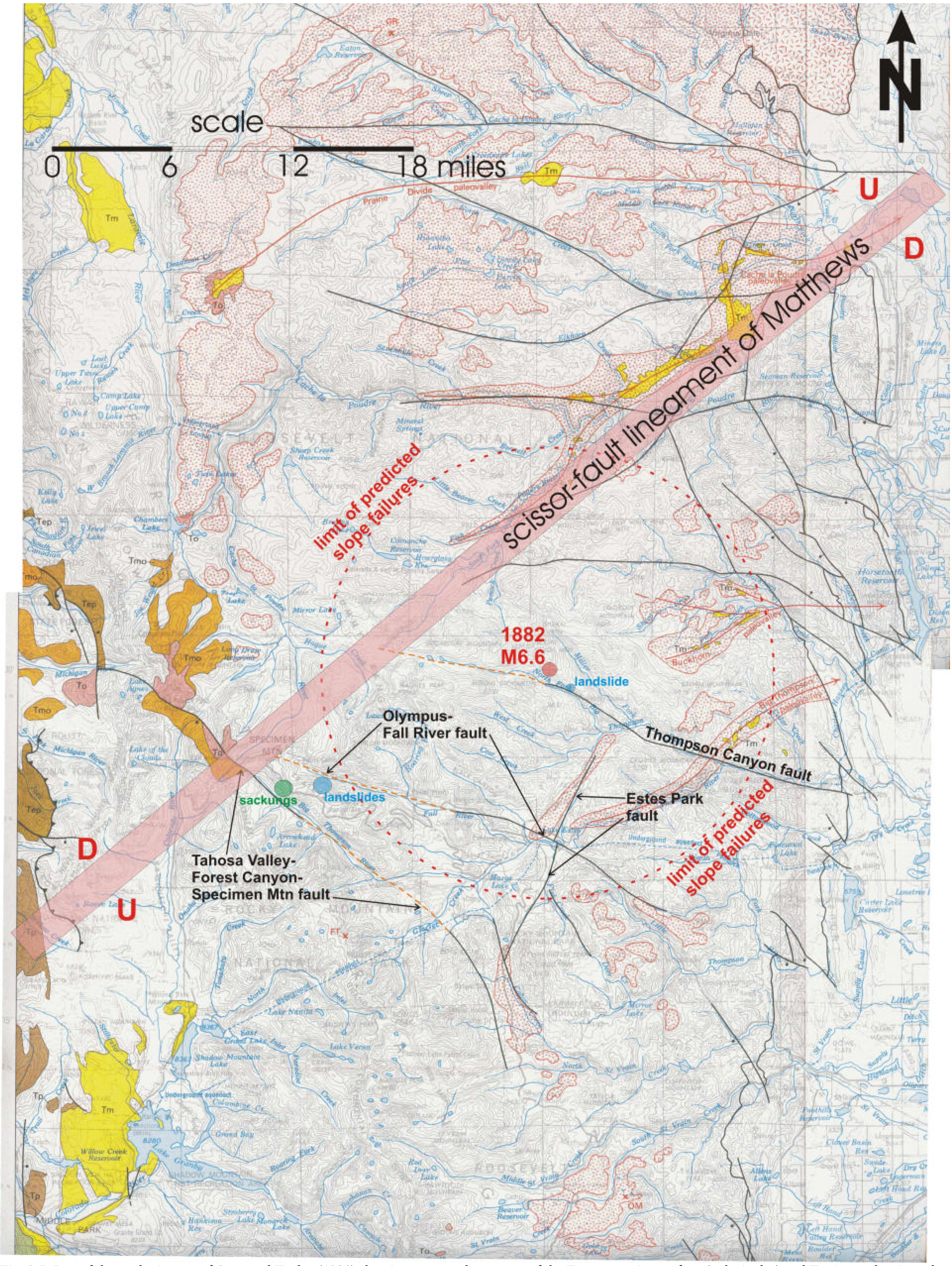


Fig. 2-5. Part of the geologic map of Scott and Taylor (1986) showing preserved remnants of the Eocene erosion surface (red stipples) and Tertiary volcanic rocks (orange, brown) and sedimentary rocks (yellow) in the northern Front Range. The 1882 epicenter is surrounded by a dashed red line enclosing 1000 km^2, the predicted limit of landslides for an M6.6 earthquake. The 5 most likely source faults are labeled in black. Orange dashed lines show extensions of the faults shown on later published maps (e.g., Braddock and Cole, 1990) or inferred from this study.

3. MICHIGAN LAKES FAULT RECONNAISSANCE

The CGS identified a suspected Quaternary fault in the western part of Rocky Mountain National Park, in the Never Summer Range, during their airphoto interpretation (Fig. 3-1). The anomalous geomorphic features that triggered their interest coincided with a north-trending fault mapped by O'Neill (1981) and Braddock and Cole (1990) at the head of the Michigan River, about 6 km south of Cameron Pass (Figs. 3-2, 3-3). This fault is part of a system of north-trending faults that generally lie near the crest of the Never Summer Range and which displace upper Oligocene rhyolite welded tuff, andesite porphyry and granodiorite (Braddock and Cole, 1990). Thus, the faults are Neogene. The faults terminate at the south end of the Never Summer Range, but may have an en-echelon relationship with the north-trending fault zone (shear zone) in the uppermost part of the Colorado River Valley (Kawuneeche Valley), which is thought by some to be a structural extension of the Neogene Rio Grande rift.

Fig. 3-1. Perspective satellite view of the Michigan Lakes (black areas in cirque at center) and the anomalous linear landform crossing the cirque in a N-S direction (red dotted line). View is to the south. Yellow lines in upper left show Trail Ridge Road in upper Kawuneeche Valley. Thin light-colored band in the forest opposite the road, which contours across the eastern face of the Never Summer Range, is the Grand Ditch. Image from Google Earth.

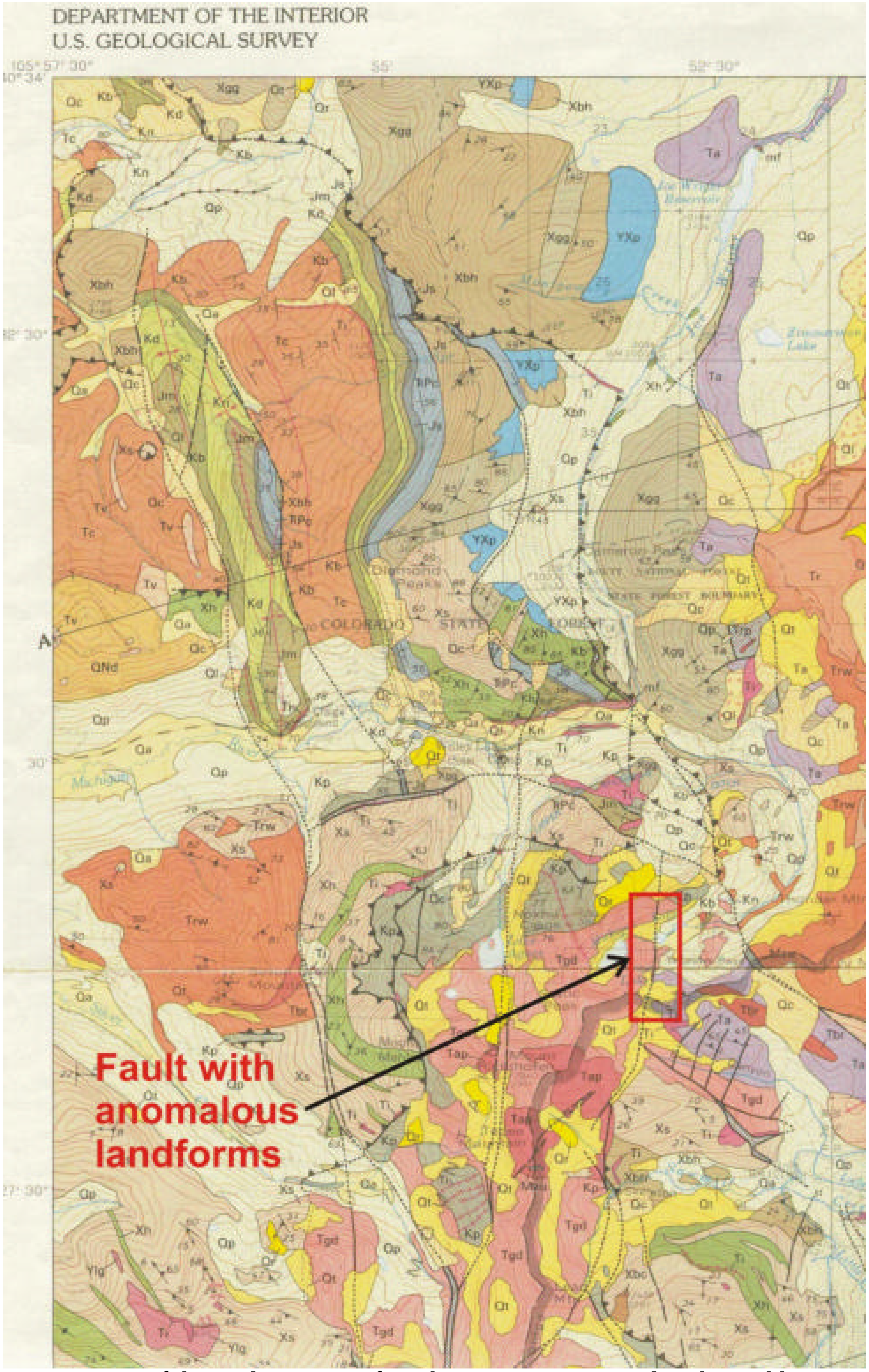


Fig. 3-2. Part of the geologic map of Rocky Mountain National Park roughly centered on Cameron Pass. Red box shows extent of fault with anomalous landforms (see Fig. 3.3).

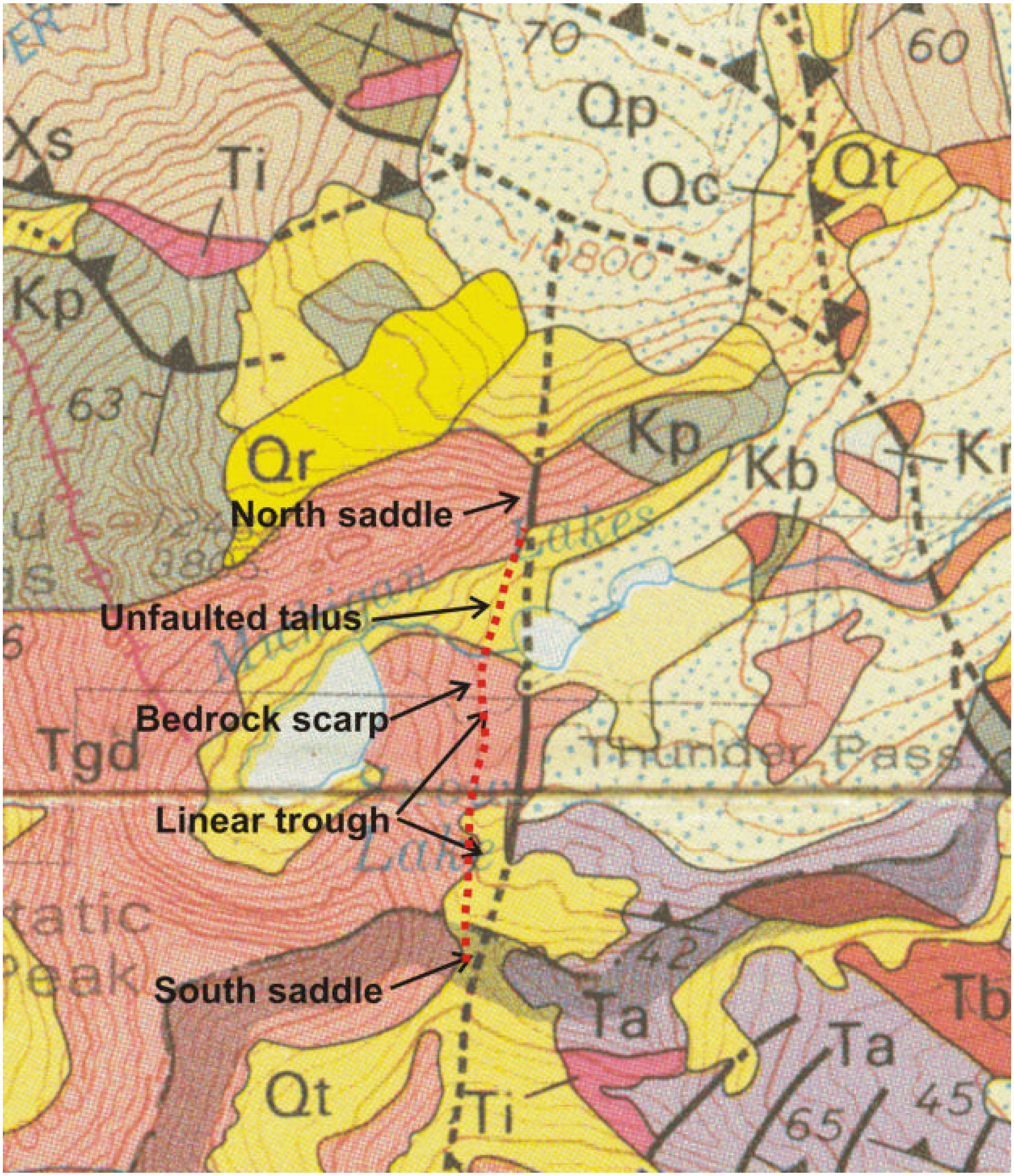


Fig. 3-3. Detail of geologic map of anomalous landforms, showing features mentioned in text.

The anomaly that caught the attention of CGS was a linear, N-S-trending gully in the southern half of the cirque (Figs. 3-4a through 3-4c). At the south saddle, this gully lined up with a steep east-facing scarp in talus Fig. 3-4d). Likewise, on the west side of the linear gully, the coarse talus abruptly stopped along a N-S line. North of the linear gully, an east-facing scarp in bedrock (Figs. 3-4a, 3-4c) lined up with the projection of the gully. All of these geomorphic features looked anomalous. However, no linear anomalies continued north of the bedrock scarp across a low talus blockfield (Fig. 3-4a).

Accordingly, we investigated the cirque on July 4, 2002. Due to the drought conditions during that year, the snowfield in the linear gully was almost completely gone. Therefore, we could see that the rocks abruptly stopped along a N-S line because that was the typ[ical lateral extent of the gully snowpack in more normal precipitation years. The talus crept and rolled down from sources to the west, but was prevented from traveling farther east by the thick snowpack that usually filled the gully. In 2002 almost all of the gully snow had melted, leaving the anomalous straight edge to the eastern margin of the talus deposit. If this abrupt termination of the talus had been a down-to-the-east fault, then talus would have existed on both sides of the lineament, but that was clearly not the case here. Therefore, we interpreted this lineament in the talus edge as a depositional feature.

At the head of the linear gully in the southern saddle, a steep 5-6 m-high scarp in the talus faced east. However, we interpret this scarp as the front of a rock glacier rather than a fault scarp, for the following reasons. First, if this were a fault scarp in talus, then talus would exist on both sides of the scarp. However, no talus exists to the east of the scarp. Instead, it appears as if the talus is overriding glacial till or colluvium that lies at the foot of the scarp. Second, if this 5-6 m-high scarp represented 5-6 m of down-to-the-east normal faulting, where did that faulting go to the north? The scarp ends less than 100 m N of the south saddle, but similar-appearing talus continues farther north to the cirque floor. If the scarp was a fault scarp, there is no explanation why the displacement would suddenly end in the same geologic deposit.

In summary, we think there probably is a bedrock fault at the location mapped by Braddock and Cole (1990). However, we did not see any evidence that the fault has experienced Quaternary displacement. The anomalous geomorphic features coincident with the bedrock fault could be explained adequately by various periglacial depositional processes.

Fig. 3-4a. Photo looking SSE up the trough (upper center, distance) on the south side of the Michigan Lakes cirque. The trough is occupied by a thin band of snow. To the right of the trough is a small stand of conifer trees perched on a steep east-facing slope of bedrock. Although this bedrock scarp lines up generally with the trough, there is no scarp or lineament extending across the block field in the foreground.

Fig. 3-4b. Photo looking SSW up the trough (center, distance) and the saddle in the ridge on the south side of the Michigan Lakes cirque. The trough is occupied by a linear snowfield that diagonals down to the lower right. To the left of the trough are two more linear gullies in grassier terrane that also contain snowfields. Note the steep front of the rock glacier front on the right side of the saddle, which mimics an east-facing scarp.

Fig. 3-4c. Photo looking N down the linear trough, into the Michigan Lakes cirque. Taken from near the saddle in the ridge on the south side of the cirque. The stand of conifer trees shown in Fig. 3-4a is at left center. The fault mapped by Braddock and Cole (1990) extends down the trough, past the right side of the conifer stand, across the talus, and through the saddle on the ridge north of the cirque.

Fig. 3-4d. Photo of the steep front of the rock glacier on the crest of the south saddle. View looking west.

4. ESTES VALLEY FAULT RECONNAISSANCE

The PI's preliminary mapping in the 1882 epicentral area has identified probable Neogene movement on the eastern margin fault of the Estes Park valley (Fig. 4-1), informally named herein the "Estes Park fault" (EPF). The EPF is 17 km long and trends N25-30°E. As mapped by Braddock and Cole 1990), the EPF displaces early Proterozoic schist (unit Xs) and middle Proterozoic Silver Plume Granite (unit Ysp) with an unknown sense of slip. The fault does not displace any mapped Quaternary deposits, and no rocks cross the fault of intermediate age between Precambrian and Quaternary. However, the EPF does appear to displace the late Eocene erosion surface about 150 m down to the west (Figs. 4-2, 4-3), forming the anomalous 13 km-long topographic depression that defines the Estes Valley. Scott and Taylor (1986) map the Eocene surface on the downthrown side of the fault in the Estes Valley (Fig. 2-4), but not on the upthrown side, where it has apparently been eroded away on the proximal footwall.

Fig. 4-1. Satellite image of the Estes Valley, Colorado, draped over topography. View to the north. Red arrows show the location of the "Estes Park fault" (EPF) on the eastern margin of the valley. Yellow arrows show the "Olympus-Fall River fault." Black area at center is Lake Estes, which lies at the intersection of the faults.

The longitudinal profile of the Big Thompson River clearly shows that the river gradient has been flattened on the downthrown block of this fault. Prior to construction of

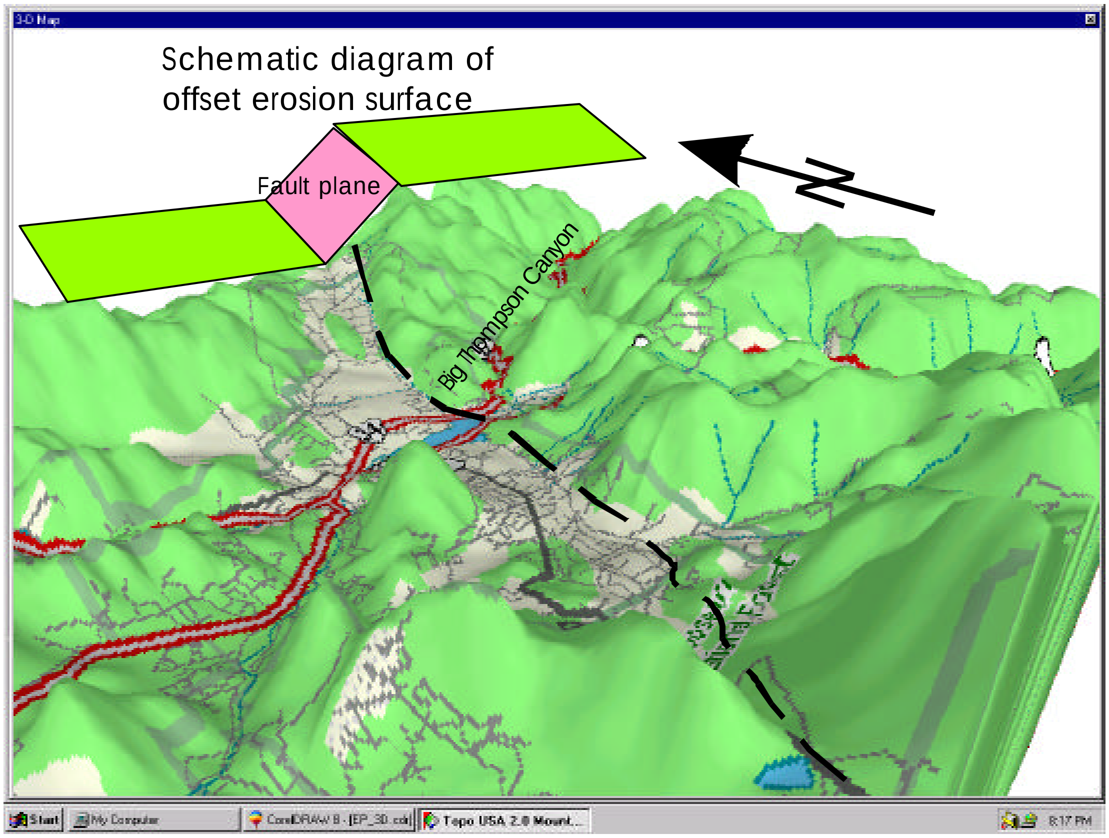


Fig. 4-2. Perspective view looking NE over the Estes Park Valley. White areas are grasslands, green areas are forest. The Valley is bounded by a fault- (or fault-line) scarp on its eastern margin. Fault shown by black dashed line, downthrown to left (west). Schematic diagram at top shows inferred correlation of late Eocene erosion surface (pea green) across fault scarp.

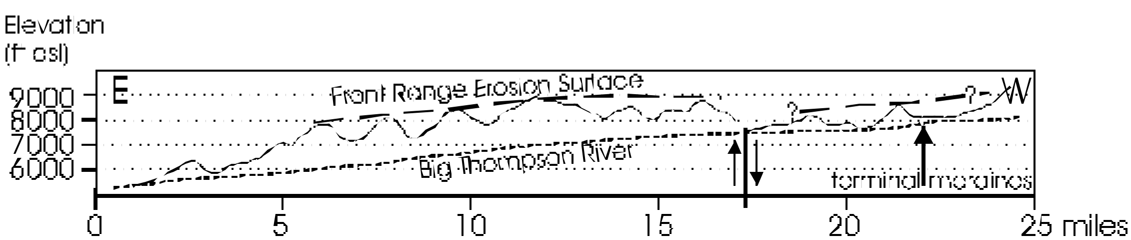


Fig. 4-3. Topographic cross-section across the EPF (right center, arrows showing inferred sense of slip). Log dashed line shows Front Range erosion surface and inferred displacement.

Lake Estes in 1952, the Big Thompson River west of the fault had a highly sinuous meandering pattern (Fig. 4-4) in a wide valley. Once the river crosses the fault, it incises into the late Eocene surface and adopts a much steeper gradient and steep V-shaped valley cross-section, indicative of vertical downcutting. This abrupt change of river channel pattern is similar to that produced by slow tectonic movements elsewhere in the world (Ouchi, 1985) and in laboratory-scale channels subjected to uplift (Schumm et al., 1986).

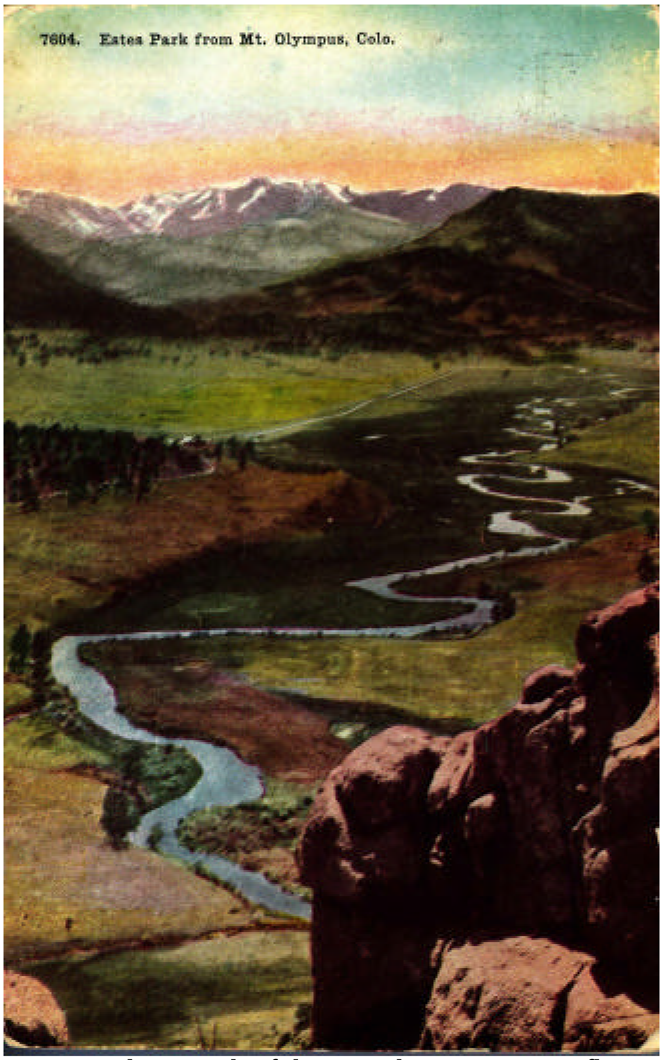


Fig. 4-4. Photograph of the Big Thompson River flowing east (toward the viewer) across the Estes Park valley, prior to construction of Olympus Dam and Lake Estes (1950s). Most of the low-gradient floodplain shown here is now beneath the waters of Lake Estes. This photo shows the anomalous low gradient of the river on the hanging wall of the EPF. The EPF runs from left to right across the center of the photograph, just beyond the cabin on the rock ridge left of the river. At the bottom of the photo the river enters the deeply-incised Big Thompson Canyon and its gradient increases sharply.

The EPF is of particular interest for two reasons: 1) it creates the largest topographic disruption of the Eocene erosion surface in the northern Front Range, and 2) the fault trace lies only 10 km east of the estimated 1882 epicenter. If the fault is a west-dipping normal fault, as suggested by the topography, then the 1882 epicenter could represent a 10 km-deep event occurring on a 45° west–dipping fault plane, or a deeper event that occurred on a steeper fault plane. Informal field reconnaissance by the PI prior to the start of this study located some anomalous scarp-like landforms along the fault trace in Quaternary colluvium. These escarpments lie on the eastern bank of Dry Gulch which parallels the EPF north of Lake Estes. Possible origins for these scarplets are: 1) lateral erosion by Dry Gulch, 2) man-made disturbance, or 3) tectonic offset.

4.1 Quaternary Geology Along the EPF

The EPF is divided into two sections, a northern section north of Lake Estes (Fig. 4-5) and a southern section south of Lake Estes (Fig. 4-6). In the northern section the fault is coincident (or nearly so) with the channel of Dry Gulch. In the southern section the fault may lie beneath Fish Creek, or may lie farther east at the head of a colluvial piedmont that lies at the base of granitic hills.

4.1.1 Northern EPF

The most significant Quaternary deposits along Dry Gulch are 3 terraces. Terrace t0 lies 2-2.5 m above the creek, terrace t1 about 5 m above the creek, and terrace t2 about 11 m above the creek (Fig. 4-7).

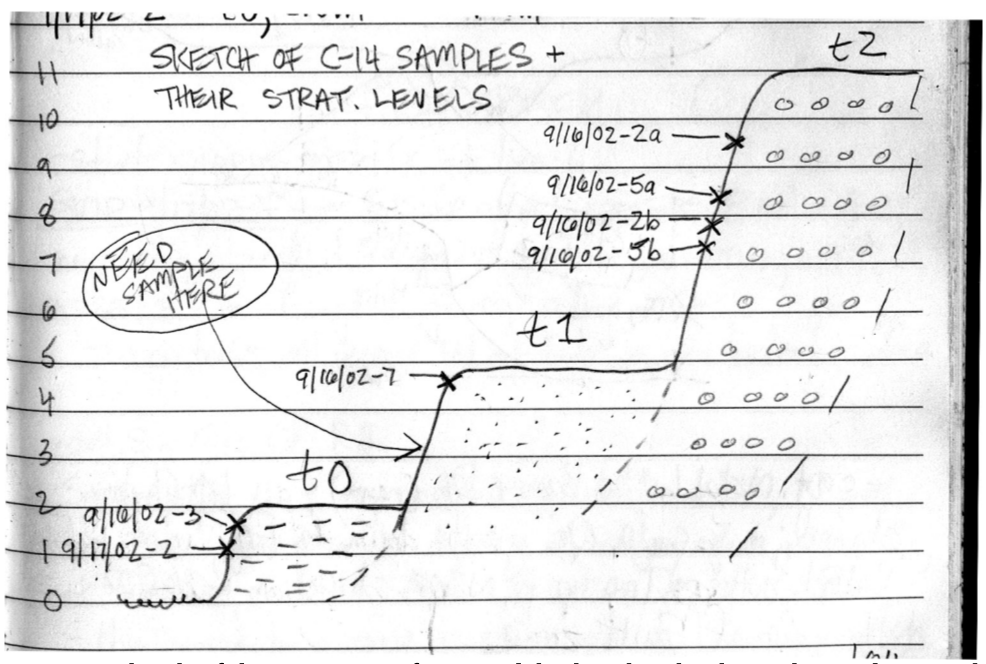


Fig. 4-7. Sketch of the 3 terraces of Dry Gulch, their height above the modern creekbed (in meters), and the location of radiocarbon samples collected. Stop 9/16/02-7d in Field Notebook 23.

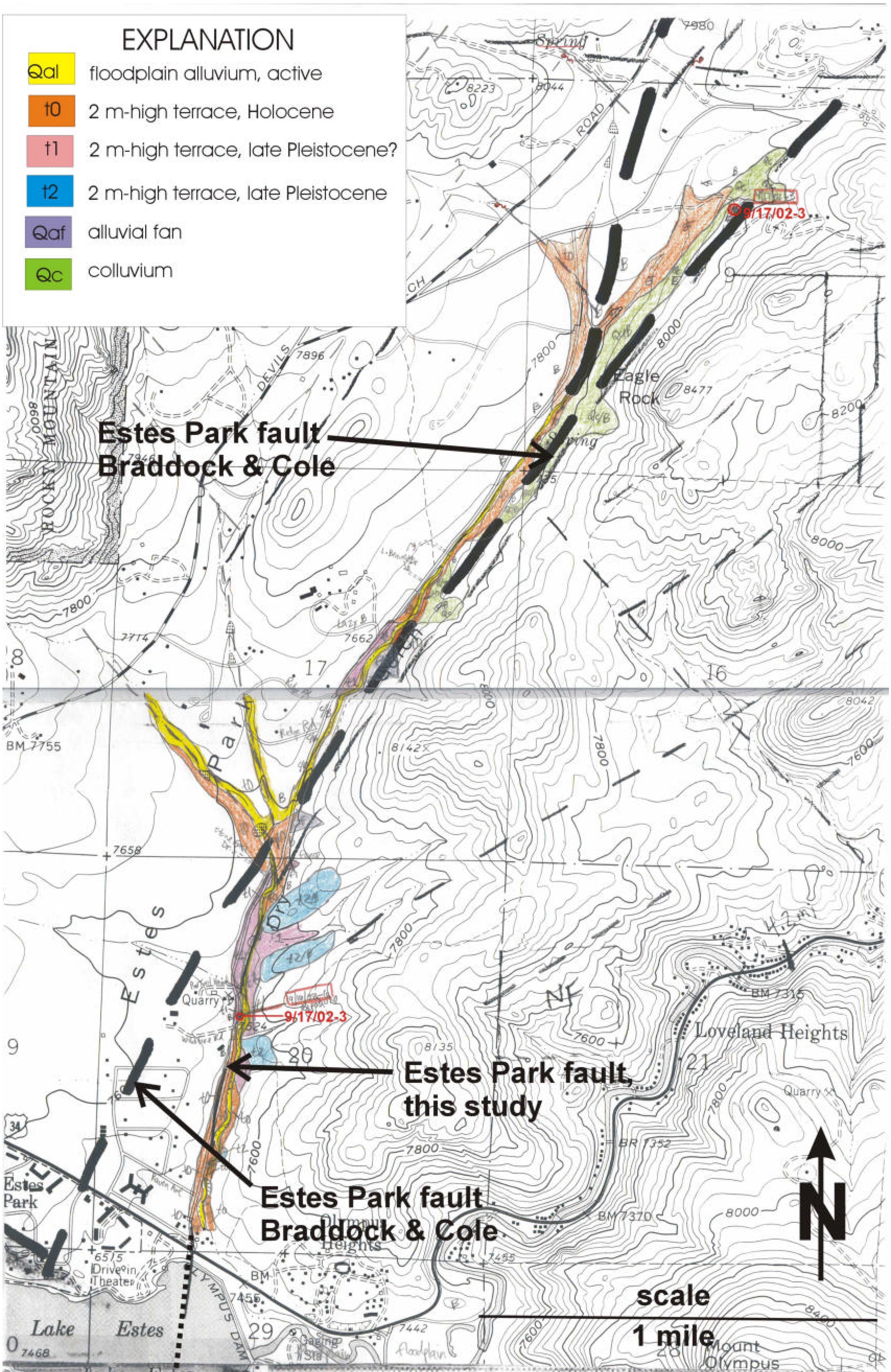


Fig. 4-5. Map of Quaternary deposits along the northern half of the EPF. Thick dashed lines show fault as mapped by Braddock and Cole (1990). Thick dotted line shows fault trace inferred by this study, which lines up with the fault trace mapped by Braddock and Cole (1990) south of Lake Estes.

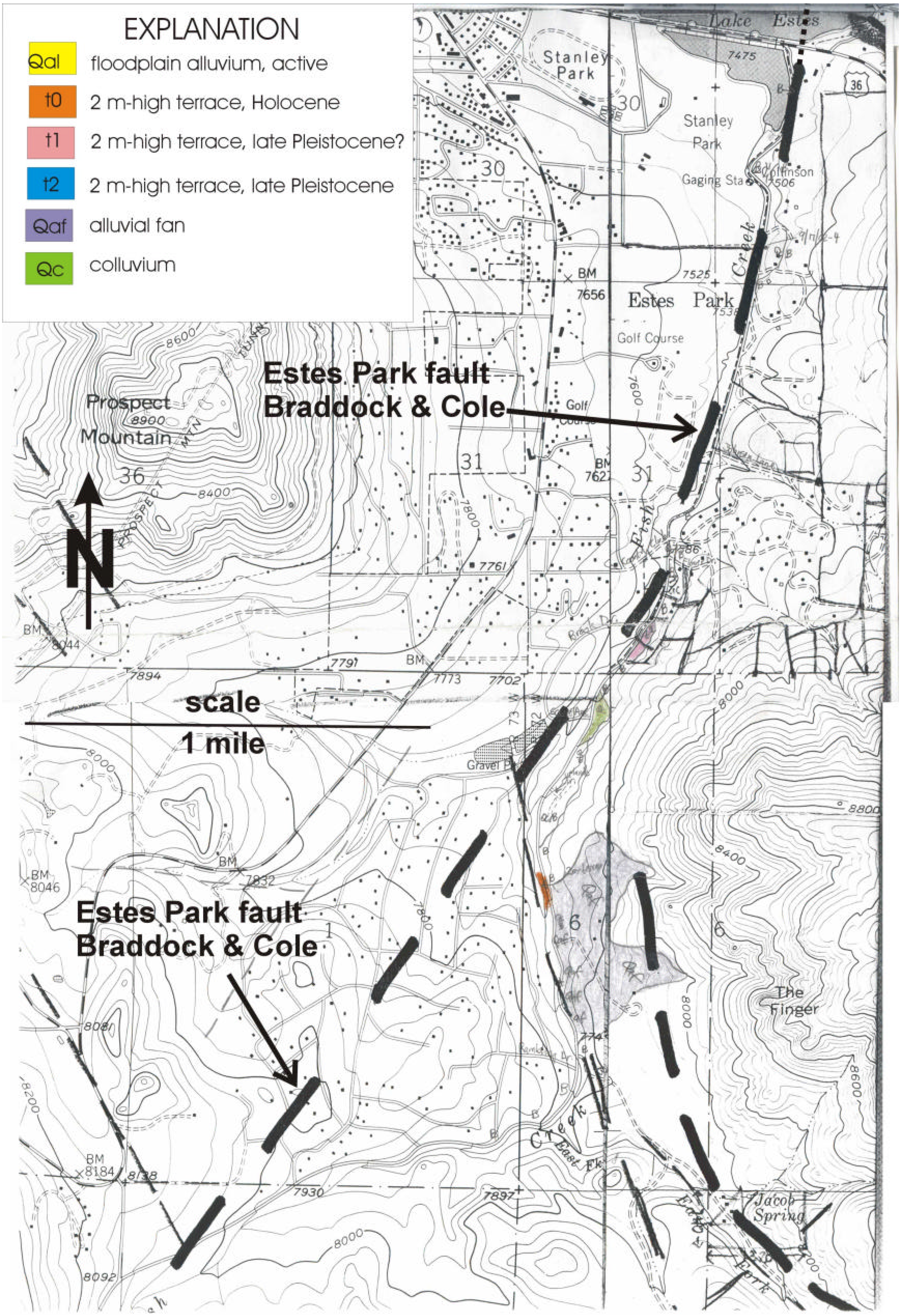


Fig. 4-6. Map of Quaternary deposits along the southern half of the EPF. Terraces are very poorly developed along Fish Creek. Thick dashed lines show fault as mapped by Braddock and Cole (1990). Thick dotted line at far north shows fault trace inferred by this study.

The youngest terrace (t0) lies about 2-2.5 m above the modern creekbed (Fig. 4-8) and exists in the northern and southern reaches of Dry Gulch, but not in the middle.

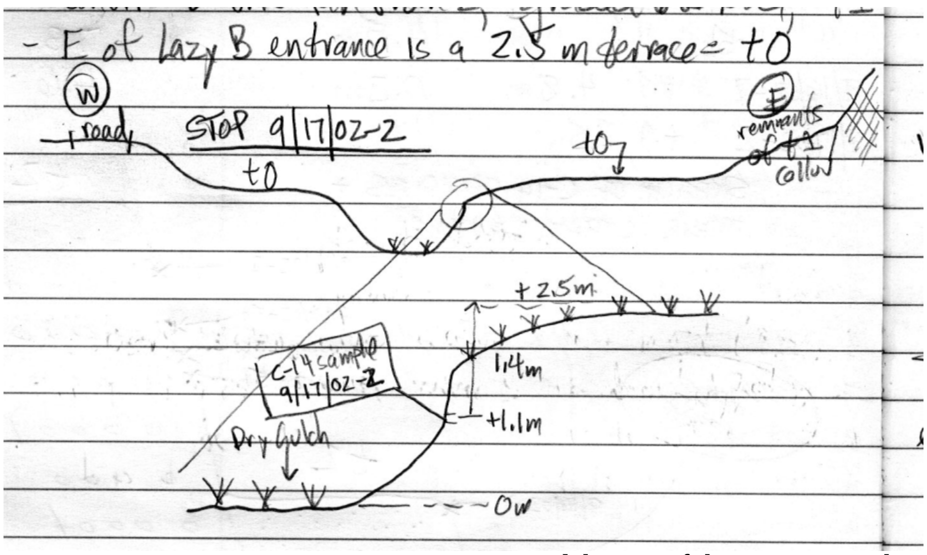


Fig. 4-8. East-west cross-section across Dry Gulch, east of the entrance to the Lazy B Ranch on upper Dry Gulch Road. At this latitude Dry Gulch Road lies on terrace t1, and terrace to flanks the incised creek channel. Stop 9/17/02-2 in Field Notebook 23.

This terrace displays only incipient soil profile development, and is thus thought to be Holocene. In places the terrace surface is underlain by a combined A horizon and peat deposit up to 40 cm thick (Fig. 4-9), which are in turn underlain by 40 cm of mottled clay. We interpret the clay and peat to represent swampy or marshy conditions that no longer exist in Dry Gulch. The existence of peat and mottled clay indicates ponded drainage and anoxic (reducing) conditions, possibly caused by beaver dams and ponds, although no beaver dams exist there today. At least at this Field Stop, terrace t0 appears to be a prehistoric marsh or swamp surface that has been subsequently incised about 2 m by the modern Dry Gulch.

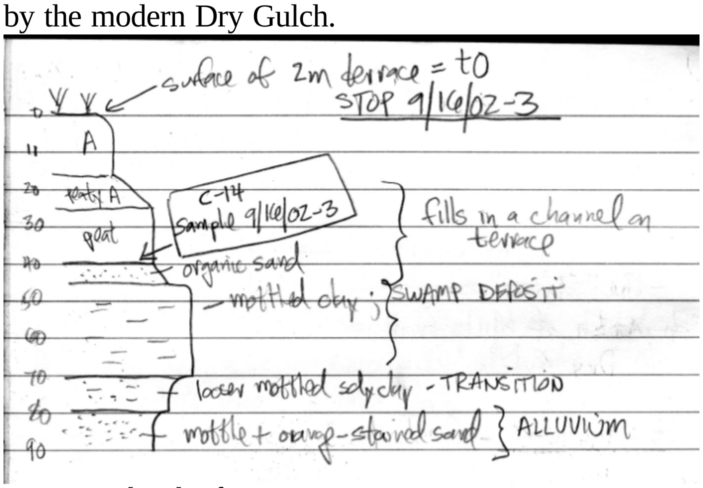


Fig. 4-9. Sketch of a streamcut into terrace t0, at Stop 9/16/02-3 in Field Notebook 23. Vertical scale is in cm. The overthickened A horizon (0-15 cm), peaty A horizon (15-25 cm), and peat (25-40 cm) overlie mainly mottled clay and sandy clay, which in turn overlies mottled sandy alluvium at the base of the cut. Stop 9/16/02-3.

The next older terrace, which lies 4.8-5 m above stream level (Fig. 4-10), is terrace t1. This terrace exists along the central reach of Dry Gulch (Fig. 4-5)

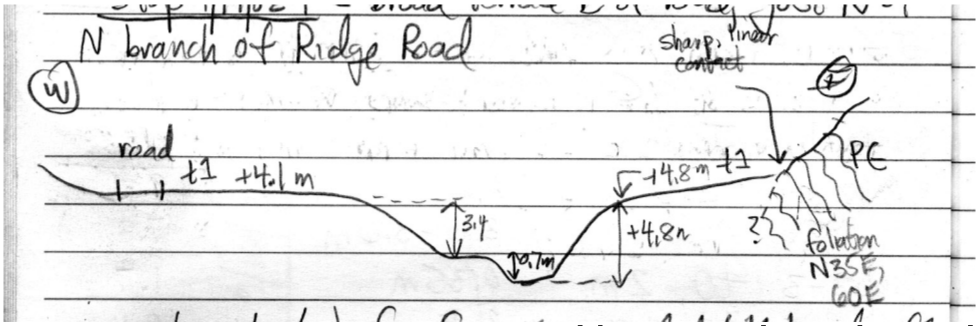


Fig. 4-10. East-west cross-section across Dry Gulch opposite Ridge Road. Dry Gulch Road is on the t1 surface here about 4.1 m above stream level, but due to the westward slope of the t1 surface, the terrace on the east bank is 4.8 m above stream level.

The terrace surface contains only a weak soil profile (A/C horizons), but the horizonation is complicated by overbank flood deposits. For example, at the location shown in Fig. 4-11, the terrace surface lies 4.8 m above stream level, yet is covered by a very fresh, 20 cm-thick deposit of granitic pea gravel and grussy sand that appears to be historic. This alluvium may have been deposited in the summer of 1976 during the Big Thompson flood. During that event Dry Gulch had an estimated flow of 4500 cfs and washed away part of the toe of Olympus Dam.

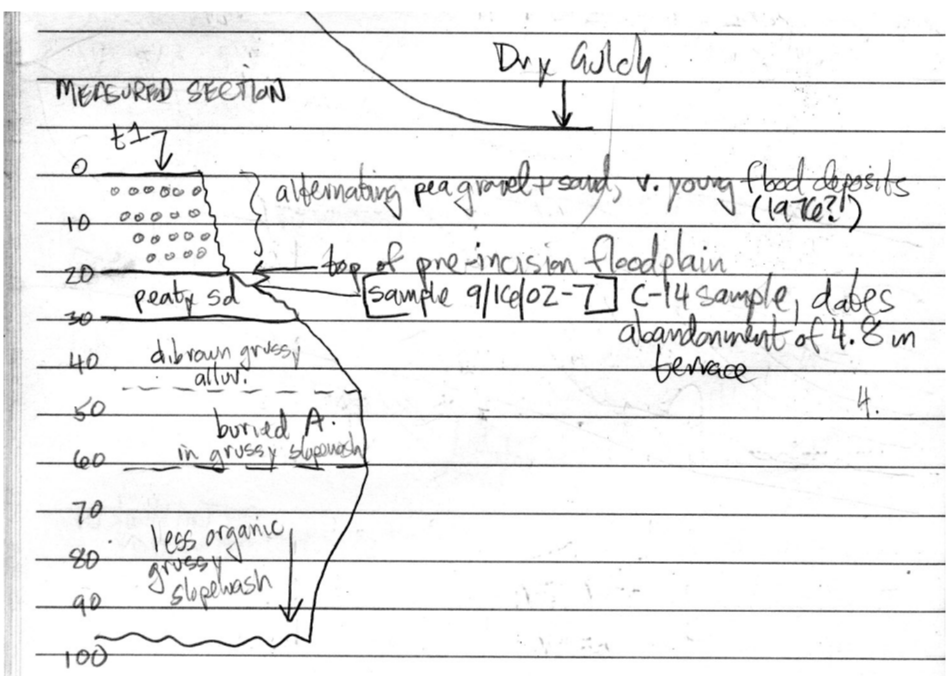


Fig. 4-11. Sketch of the uppermost 1.0 m of stratigraphy beneath the surface of the t1 terrace. Stop 9/16/02-7a.

Beneath the suspected 1976 flood deposit is a peaty sand overlying a dark brown grussy alluvium, which in turn overlies a buried A horizon. This sequence looks like a prehistoric analog to the 1976 flood deposits, and suggests that repeated episodes of overbank flooding have occurred along Dry Gulch.

The oldest terrace (t2) lies 11-16 m above stream level (Fig. 4-12), but exists only in four isolated remnants in the central reach of Dry Gulch downstream from Stone Gate Drive (Fig. 4-5), and only on the eastern side of Dry Gulch. The largest remnants are a set of paired terraces (Figs. 4-12, 4-13, 4-14) that extend up an unnamed eastern tributary drainage to Dry Gulch between Stone Gate Drive and Red Tail Hawk. Between the two remnants lies a tributary valley floor that projects to terrace t1 of Dry Gulch, at a height of 4.8 m above creek level. If the 4.5° west gradient of terrace t2 is projected over the (incised) modern stream bed of Dry Gulch, the terraces are 12.2 m above stream level (Fig. 4-13).

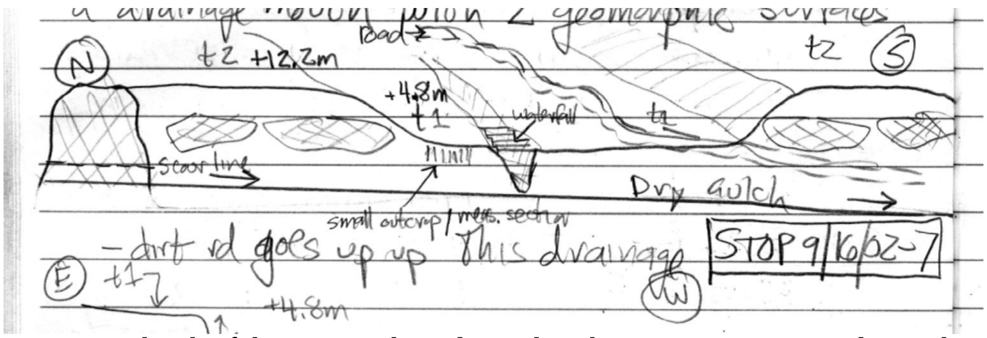


Fig. 4-12. Sketch of the geomorphic relationships between terraces t2 and t1 in the unnamed tributary drainage of Dry Gulch. View looking east. Compare to Fig. 5-14. Field Stop 9/16/02-7.

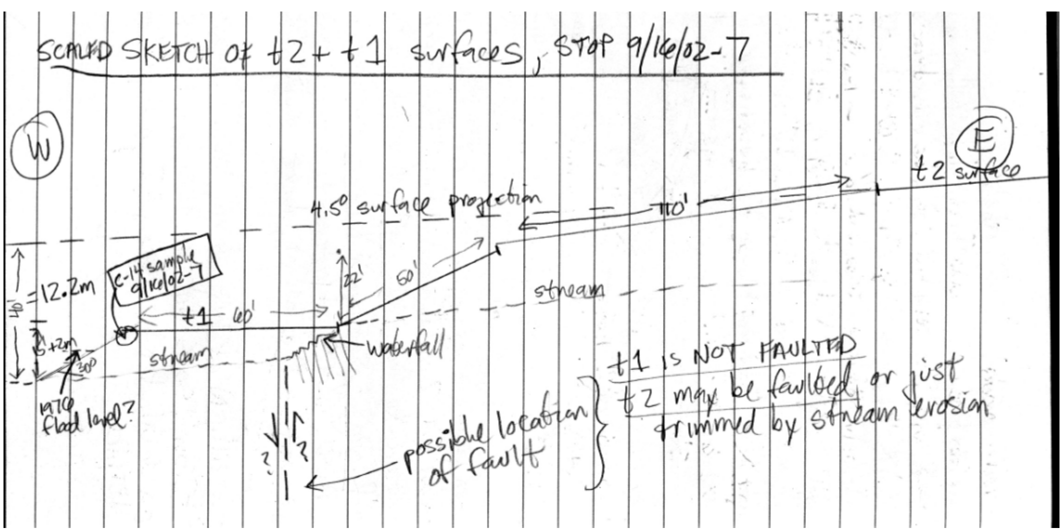


Fig. 4-13. Schematic east-west cross-section from Dry Gulch (at left) to the uneroded surface of terrace t2 (right) on the north side of the unnamed tributary drainage. The stream in the tributary drainage is unincised and flows on the t1 surface, until it reaches the base of the terrace riser between t2 and t1, At that location there is a dry waterfall that exposes Precambrian bedrock, and the stream incises about 5 m into the t1 terrace to reach grade with the modern incised channel of Dry Gulch. Field Stop 9/16/02-7c.

Fig. 4-14a. Photomosaic of terraces t2 and t1 in the unnamed tributary to Dry Gulch; view is to the east. In the middle distance, halfway between the stop sign and the parked vehicle, the unnamed tributary contains a dry waterfall that exposes Precambrian bedrock. This waterfall lines up with the t2 terrace fronts to the north and south, and may mark the location of the EPF.

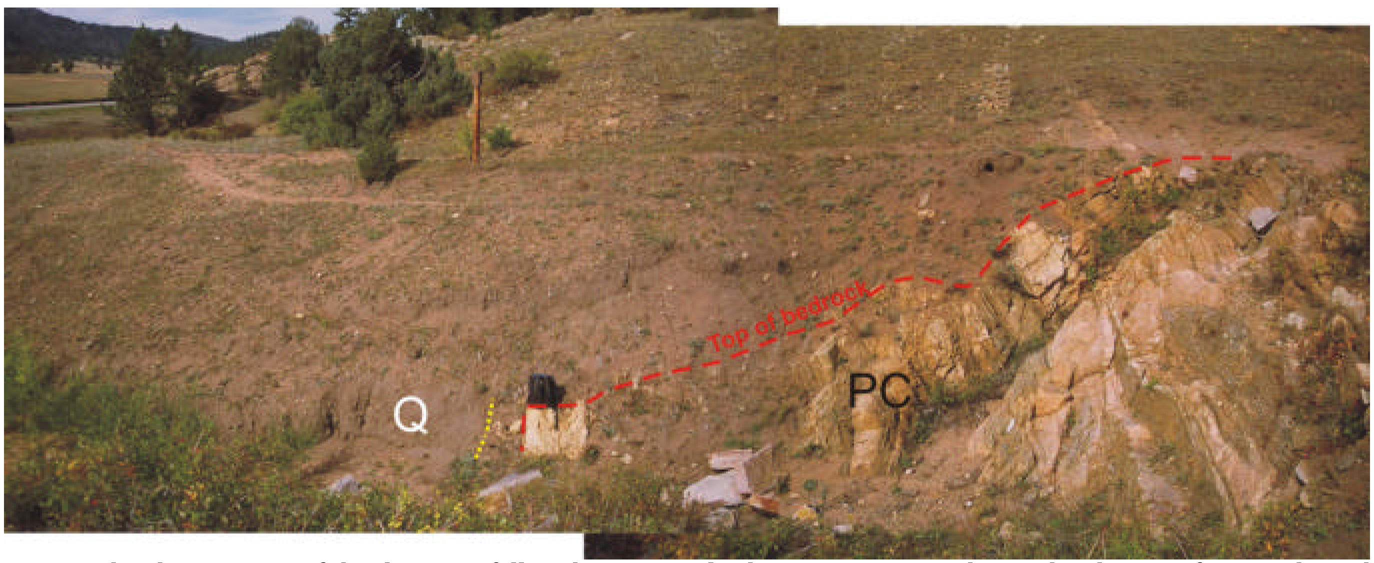


Fig. 4-14b. Photomosaic of the dry waterfall in the unnamed tributary; view is to the north. The top of Precambrian bedrock (red dashed line) descrnds gradually to the west, and then appears to be sharply truncated at the dotted yellow line, where it abuts Quaternary alluvium (Q). The yellow fault may be a trace of the EPF.

Terrace t2 is underlain by grussy-sandy alluvium similar to that exposed beneath terraces t1 and t0. There are no good exposures into t2 in the unnamed tributary gully, but both of the two southern isolated t2 remnants in Dry Gulch contain artificial exposures (Figs. 4-15 to 4-17). In the northern remnant (Figs. 4-15, 4-16) the t2 terrace lies about 11.8 m above stream level, and 8.3 m above terrace t1. Between 3.35 and 3.55 m below the terrace surface, there is a major disconformity marked by a 20 cm-thick beds of twigs and peat. This disconformity lies 8.35 m above modern stream level and separates an overlying section of grussy alluvium from an underlying section containing gravel lenses as well as sandy-grussy alluvium. Both sections contain weak buried soils, indicating that episodic sedimentation is the rule in Dry Gulch.

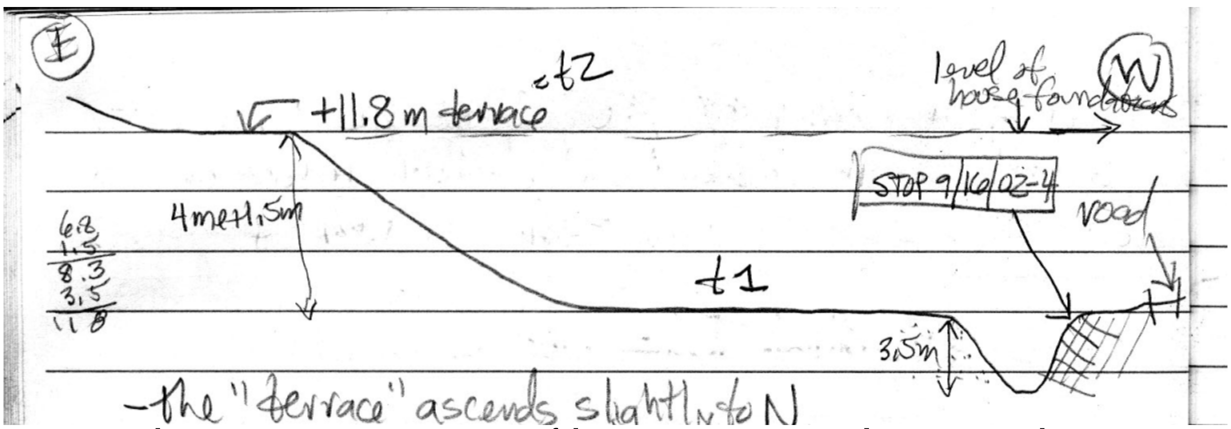


Fig. 4-15. Schematic east-west cross-section of the t2 terrace remnant and t1 terrace on the east side of Dry Gulch, south of Wildfire Road. Here terrace t1 is only 3.5 m above creek level. Field Stop 9/16/02-4.

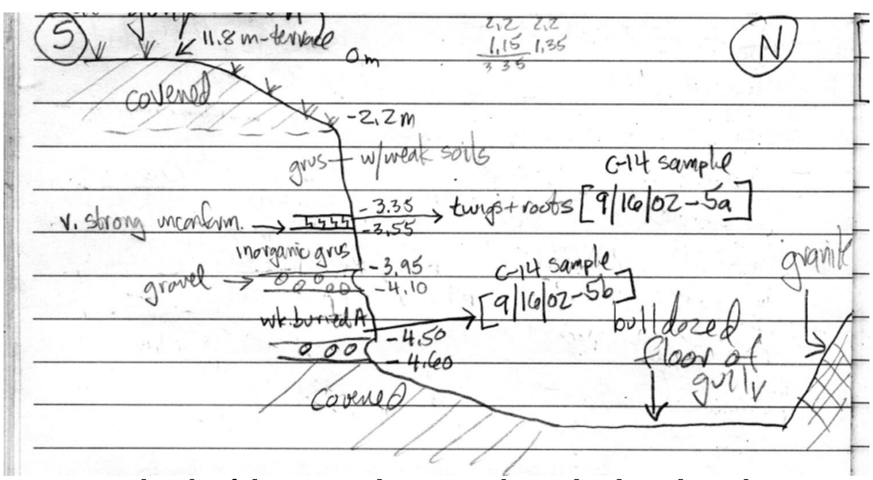


Fig. 4-17. Sketch of the exposed stratigraphy and paleosols in the uppermost 4.6 m beneath the surface of terrace t2, just south of Wildfire Road. The uppermost 2.2 m are covered. A strong unconformity lies 3.35 to 3.55 m below the terrace surface, marked by a 20 cm-thick layers of buried twigs and roots. Alluvium below the unconformity contains gravel layers. Stop 9/16/02-2 in Field Notebook 23.

An even more complete stratigraphic section is exposed in the southernmost terrace remnant of t2, about 500 ft N of Raven Drive (Fig. 2-4), where the terrace surface is 11.3 m above stream level. This section exposes the uppermost 3.7 m of stratigraphy beneath the t2 surface (Fig. 4-16). In that interval there are at least 6 buried soils (A horizons) separated by sandy-grussy alluvium. Two of these soils were sampled for future radiocarbon dating (9/16/02-2a, 02b). An overview of the 3 terrace levels here is shown in Fig. 4-18.

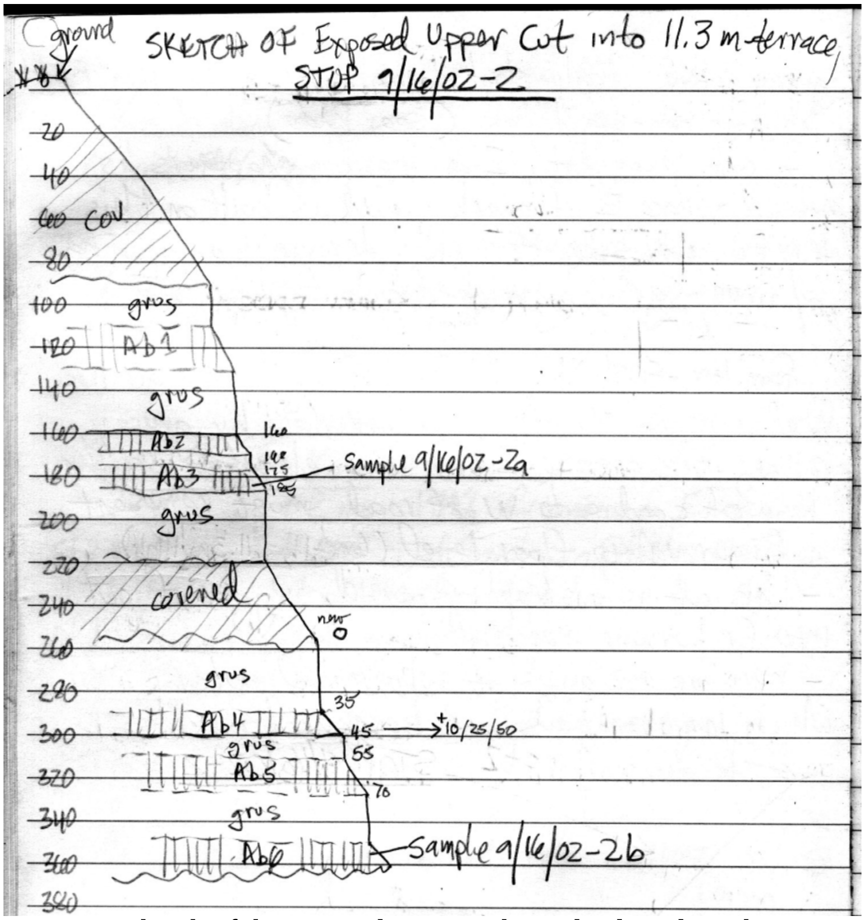


Fig. 4-16. Sketch of the exposed stratigraphy and paleosols in the uppermost 3.8 m beneath the surface of terrace t2, in a small t2 remnant about 500 ft N of Raven Ave. The surface soil is covered, and buried soils are numbered from the top down. All alluvium between paleosols is composed of a sandy grus. Stop 9/16/02-2 in Field Notebook 23.

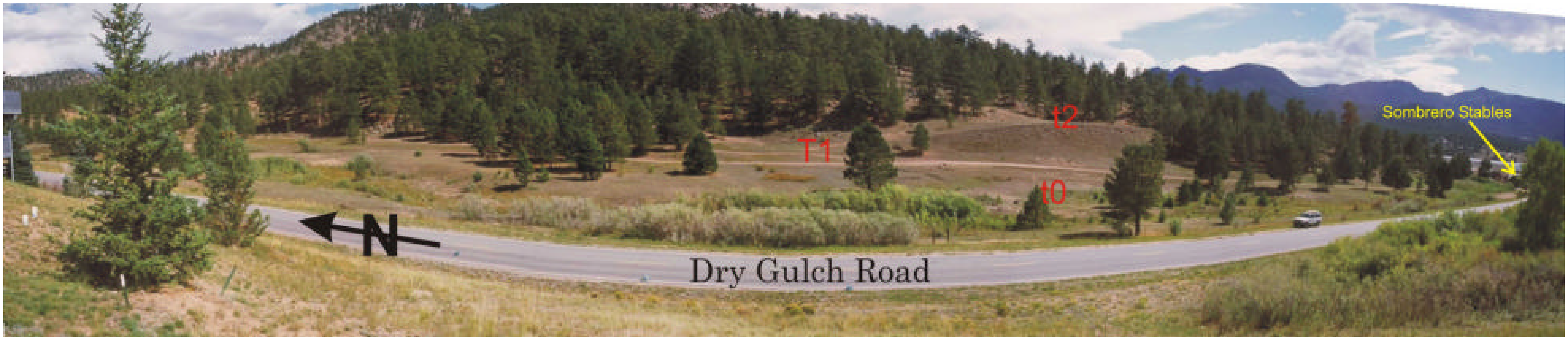


Fig. 4-18. Panoramic photograph of the lower reach of Dry Gulch, looking east. The stream flows to the right (south). The southernmost isolated remnant of terrace t2, 11.3 m above stream level, is at right center. Terrace t1 in the center is about 4.8 m above stream level, and terrace t0 is about 2 m above stream level. The mouth of Dry Gulch is at Sombrero Stables at far right.

4.1.2 Anomalous Deformation Features Exposed Beneath Terrace t1

About 50 m N of the mouth of Wildfire Road, on the western side of Dry Gulch, there is a 2 m-deep gully that dissects the 3.5 m-high t1 terrace. This gully has been recently incised due to diverted runoff from Dry Gulch Road, and shows one of the best exposure of Quaternary alluvium. However, the exposure is anomalous in several respects (Figs. 4-18, 4-19).

First, most of the alluvium exposed is not light-colored, grussy, poorly-stratified, sand to pebbly sand as typically exposed on the eastern side of Dry Gulch. Instead, the younger channel material is very dark and organic-rich, with a wide range of grain sizes.

Second, the younger organic-rich channel is clearly eroded into an older, lighter-colored, denser alluvium that has no counterpart in the exposures east of Dry Gulch.

Third, the older alluvium is complexly deformed by both brittle and plastic deformation structures (Figs. 4-18, 4-19). The brittle deformation is expressed by abundant subvertical fractures, upward-flaring fissures, and rotated blocks of alluvium that contain paleosols. The plastic deformation includes apparent bending and squeezing of the rotated soil blocks, and a strange diaper-like intrusion of older alluvium into the bottom of the younger alluvial channel.

This gully exposure was the only one in which Quaternary post-depositional deformation was observed in the vicinity of the EPF. However, it was also the only exposure that was clean enough that such deformation could have been recognized. This coincidence suggests that similar deformation might be widespread in the Dry Gulch area, but simply not exposed.

This gully exposure was intended to be the subject of further study in the 2nd year of our study, but unfortunately that year was not funded by NEHRP.

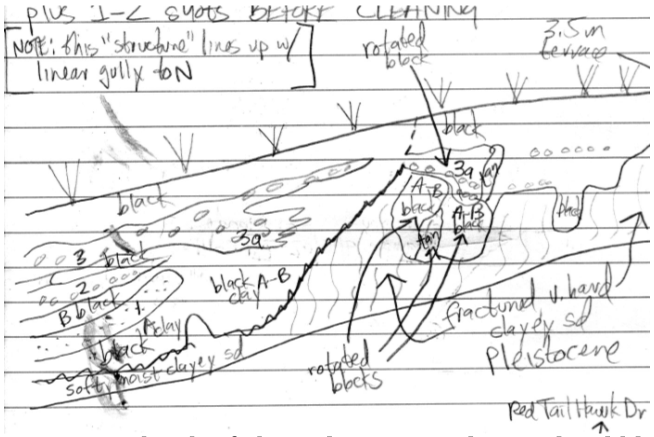


Fig. 4-18. Sketch of channel margin and rotated soil blocks beneath the t1 terrace on the west side of Dry Gulch, just north of Wildfire Road. Stop 9/16/02-6 in Field Notebook 23.

Fig. 4-19. Photomosaic of channel margin and rotated soil blocks beneath the t1 terrace on the west side of Dry Gulch, just north of Wildfire Road. Stop 9/16/02-6 in Field Notebook 23.

4.1.3 Southern EPF

The exact location of the fault in the southern EPF is unknown. Braddock and Cole (1990) map the fault beneath the active channel of Fish Creek, which drains NNE to Lake Estes. The fault turns to a more westerly strike south of the East Fork (Fig. 4-6), a major tributary that ascends to the SE and drains Little Valley. There may be an additional fault strand controlling the linear trend of the East Fork.

Very few alluvial terraces exist along Fish Creek, in comparison to Dry Gulch. One reason may be that Fish Creek transports less sediment that does Dry Gulch. Much of the drainage basin of Fish Creek is densely-forested north-facing slopes, in contrast to the open, grassy slopes of Dry Gulch. Fish Creek probably transports less sediment and has a less “flashy” stream response than does Dry Gulch, and more resembles a perennial stream. Thus, the strong temporal variations in sediment concentration necessary to create terraces may be less frequent in Fish Creek than in Dry Gulch.

The southeastern Valley margin east of Fish Creek also differs from the northeastern margin in its overall morphology. There is a large embayment east of Fish Creek that slopes gently east and hosts the Dunraven Heights subdivision. This area appears to be an old alluvial fan or pediment surface, and granitic bedrock is not observed in the area roadcuts. However, there is no clear fault scarp or disruption of this surface across the EPF. At this point we have insufficient data to date this surface, and well-developed paleosols were generally lacking in roadcuts, so a proper soil-stratigraphic study would require backhoe soil pits.

Another difference with the Dry Gulch margin is the steepness and height of some of the hills east of Fish Creek, and the size of the alluvial/colluvial fans shed off their range fronts. Directly north of the confluence of Fish Creek and East Fork the range front rises rapidly from 7600 ft to >8800 ft, to a high summit northeast of The Finger. This rise of 1200 ft compares to a much smaller rise along the northeastern range front (from 7600 ft to 8150 ft, or only 550 ft). West of The Finger there is a wide colluvial-alluvial apron that descends 400 ft from 8000 ft to 7600 ft. It is conceivable that the trace of the EPF actually lies at the head of this apron, rather than beneath the bed of Fish Creek, as mapped. Alternatively, the rate of fault activity may be so low, that the present range front has retreated significantly east from a fault position beneath Fish Creek. With the present reconnaissance field data we cannot distinguish between these two hypotheses.

4.2 Summary of Neotectonic Observations

There are no unambiguous fault scarps cutting Quaternary deposits along the EPF. Such scarps, if they existed, might be hard to distinguish from terrace risers preserved in Dry Gulch. The only geomorphic feature possibly suggestive of Quaternary faulting is the truncation of the western ends of the t2 terraces in the unnamed tributary to Dry Gulch. This truncation could have been caused by either faulting or by erosional trimming by Dry Gulch. If it was caused by faulting, however, the faulting must be younger than terrace t2 and older than terrace t1, which is clearly not truncated.

The truncation is coincident with a ca. 5 m vertical drop in the top of Precambrian bedrock exposed in the channel of the unnamed tributary. Again, such a drop could be explained by either Quaternary faulting or erosion. The only way to distinguish between these origins would be to trench across the feature.

The small gully between Dry Gulch Road and Dry Gulch, just north of Wildfire Road, exposes some anomalous post-depositional deformation of unknown origin. The deformation is most likely related to slumping of a stream bank after rapid incision due to a 1976-type flood. However, the complexity of the structural features argues for more than one episode of deformation. Given the reconnaissance nature of the Year 1 effort, which was mainly devoted to surface mapping and geomorphic analysis, we could not excavate enough of this exposure to confirm its origin.

5. BIG THOMPSON VALLEY FAULT RECONNAISSANCE

The 1882 epicenter located by Kirkham and Rogers (1986) lies in the North Fork of the Big Thompson River (40°30'N, 105°30'W), near several parallel traces of the Thompson Canyon fault, which there is 1-1.5 km-wide. The Thompson Canyon fault (Hutchinson and Braddock, 1987) is a major NW-SE structure that extends from the range front to Icefield Pass in Rocky Mountain National Park, a distance of nearly 40 km (Figs. 5-1, 5-2, 5-3), in the valley of the Big Thompson River and North Fork.

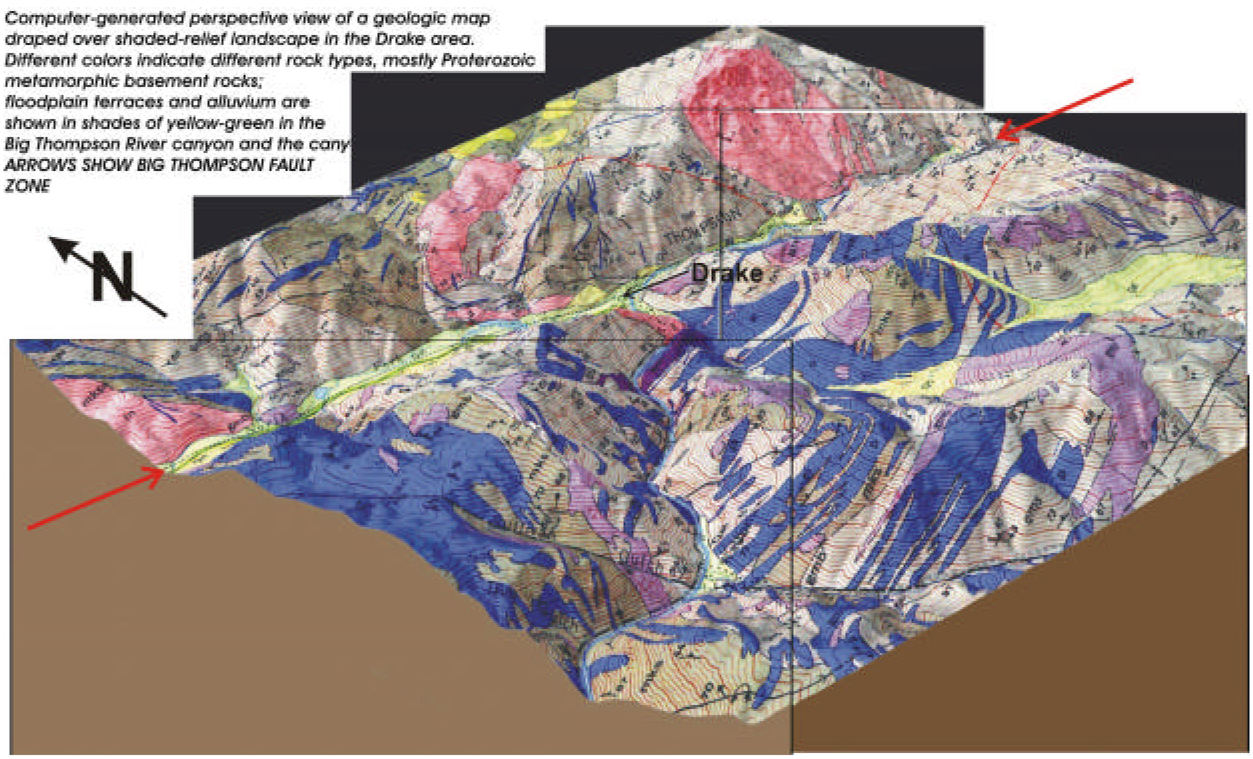


Fig. 5-1. Computer-generated perspective view of the Thompson Canyon fault (between red arrows) around the town of Drake. From Cole, 2004.

We investigated several field sites along the Thompson Canyon fault, where Quaternary deposits exist that might yield evidence of Quaternary faulting (Fig. 5-2). These sites are described beginning at the northwest end of the fault, where Quaternary glacial deposits of the north fork cover the valley floor and bury the fault (Fig. 5-3), and proceed to the southeast. A cluster of anomalous landforms exist on or near the fault trace in the vicinity of the estimated 1882 epicenter. First, a postglacial landslide ("landslide" on Figs. 5-2, 5-3) detached from the north wall of the North Fork and slide down into the valley bottom. Second, an upslope-facing scarp (sackung) lies about 1.5 km east of the landslide. Third, a prominent fault saddle exists at the head of Dunraven Gulch. Therefore, we made a field traverse along the valley bottom from the "Dunraven saddle" to the glacial outwash area (Fig. 5-3).

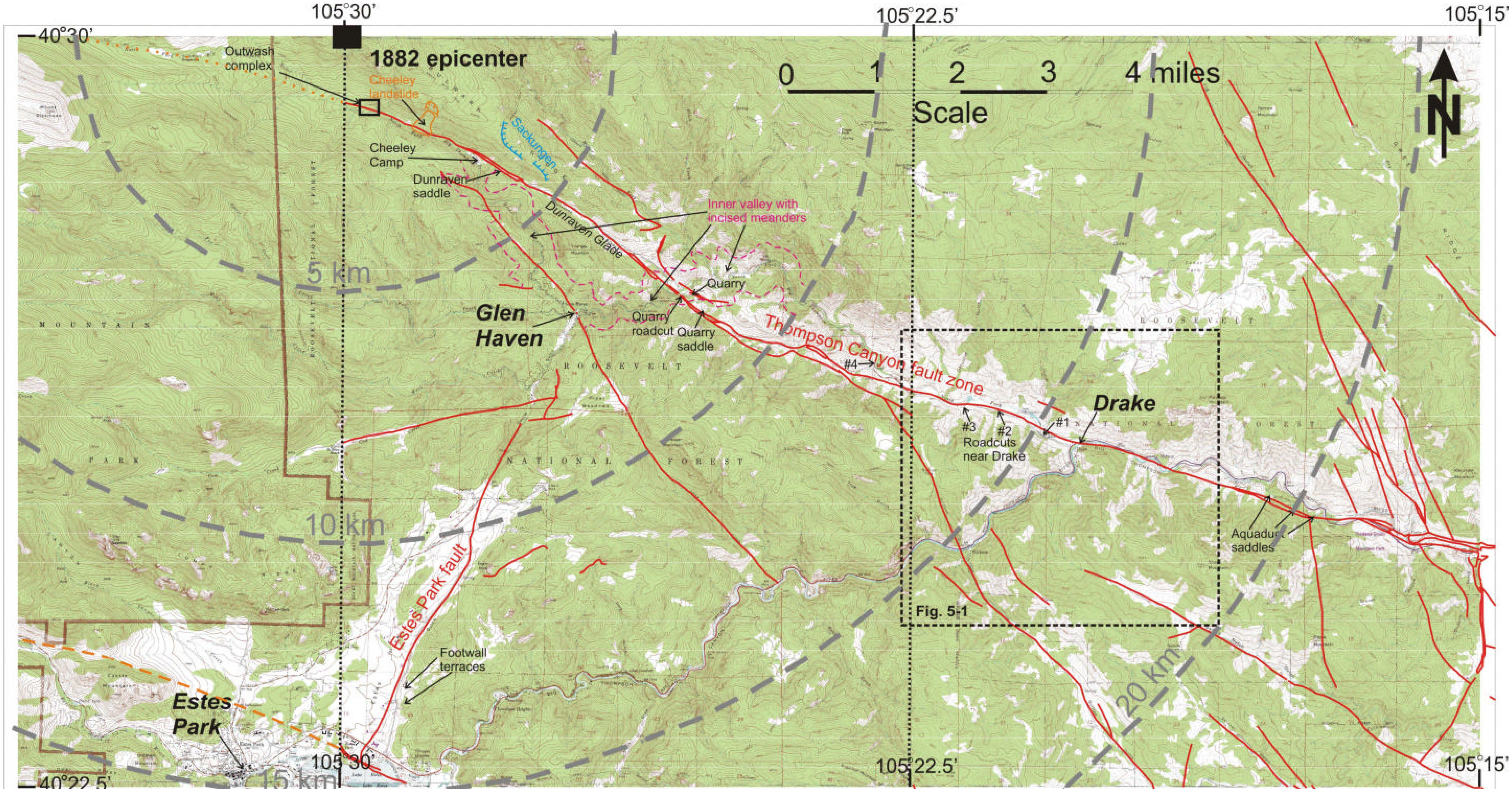


Fig. 5-2. Published faults (in red) in the Glen Haven (center), and Drake (right) 7.5' quadrangles, from Morgan (2003). All faults from the database are shown as solid lines, but the original geologic maps from which they were compiled may have used dashed or dotted lines. Orange dashed and dotted lines show the extensions of major faults into the Estes Park 7.5' quadrangle (far left), as mapped by Braddock and Cole (1990). The field localities visited along the Thompson Canyon fault are labeled. Gray dashed lines show various distances from the estimated 1882 epicenter of Kirkham and Rogers (1986).

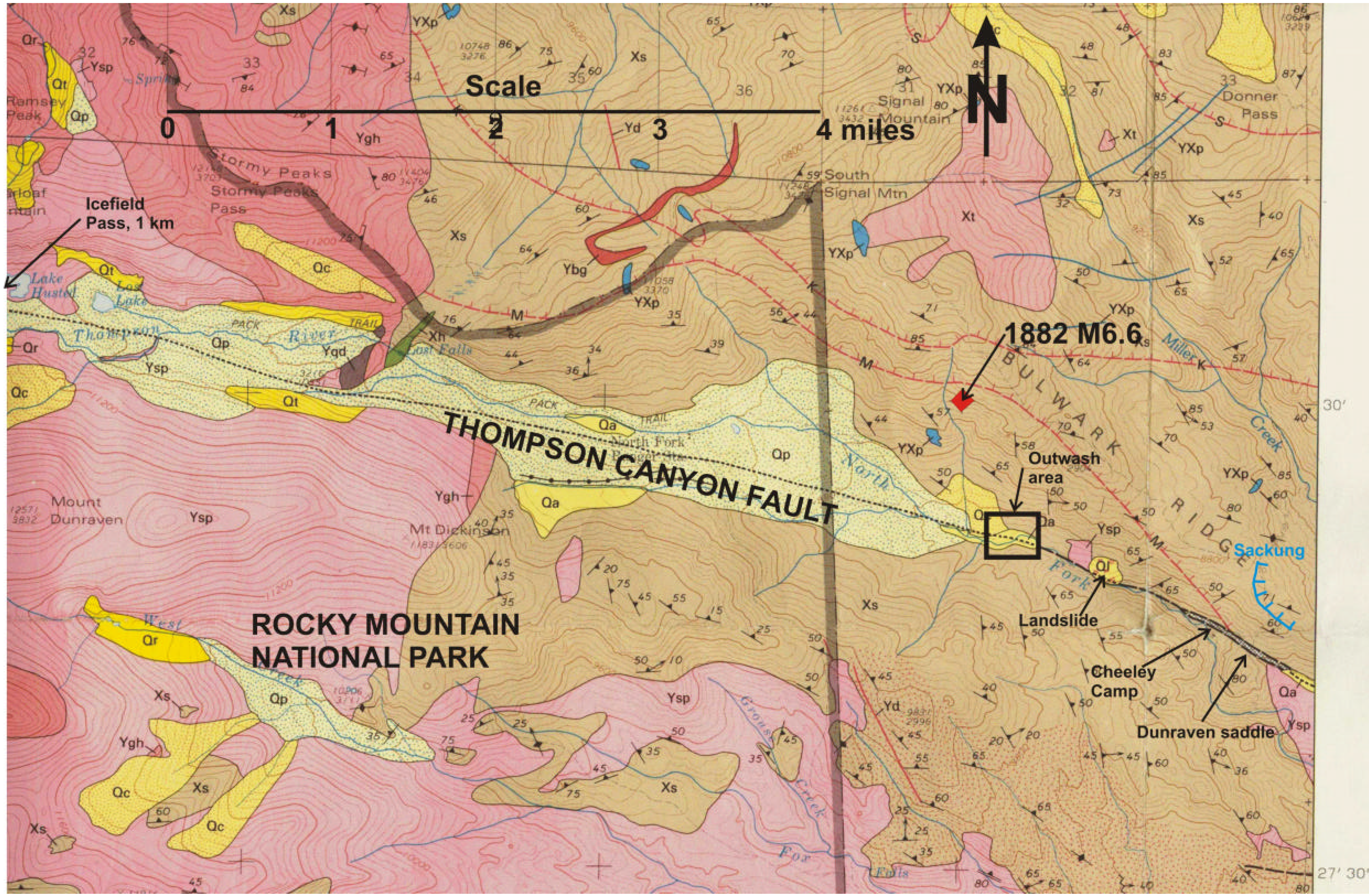


Fig. 5-3. Geologic map of the far western part of the Thompson Canyon fault, from Braddock and Cole (1990). The estimated location of the 1882 epicenter is at right center. Field locations described in this study lie along the fault to the SE of the epicenter.

5.1 North Fork Big Thompson River moraine/outwash complex

The terminal moraine of the North Fork Big Thompson River lies just east of the boundary of Rocky Mountain National Park, at about 8600 ft elevation (Fig. 5-3). Directly downstream from the terminal moraine the valley floor is covered with glacial outwash, mapped as Quaternary alluvium (Fig. 5-3), for a distance of about 1 km. Braddock and Cole (1990) map the Thompson Canyon fault as concealed beneath the Quaternary alluvium and till, and approximately located in the Precambrian bedrock to the east.

We made a field reconnaissance of the outwash area to look for any evidence that the outwash or till was displaced by faulting. Between the post-glacial landslide (discussed next) and the Pinedale terminal moraine, the valley bottom of the North Fork contains two terraces (Fig. 5-4). Neither terrace displays obvious fault scarps.

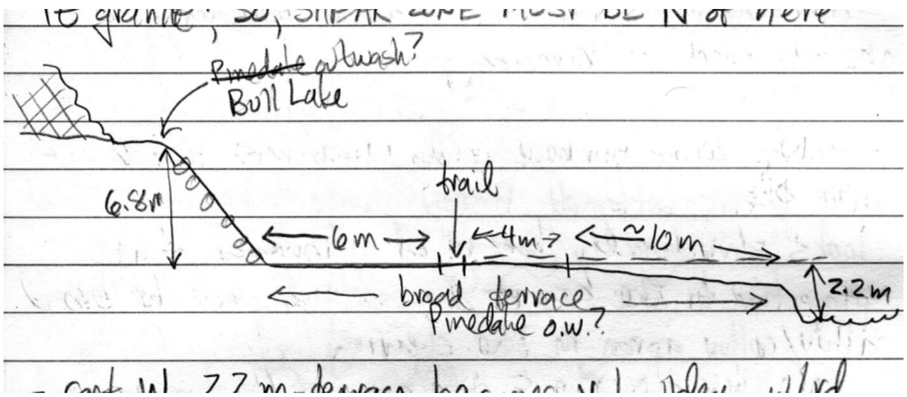


Fig. 5-4. Sketch of alluvial terraces in the North Fork, upstream of the post-glacial landslide but downstream of the Pinedale terminal moraine. View is to the west (upstream). The broad, undissected terrace 2.2 m above stream level is interpreted as late Pinedale outwash. The higher terrace 9.0 m above stream level is only partially preserved , and is interpreted as early Pinedale (?) outwash, although the figure shows it labeled as Bull Lake. Field Stop 9/14/02-1.

The part of the outwash complex that we studied, east of the Pinedale terminal moraine, lies entirely on the north side of the stream and is transected by the North Fork trail. In the western part of the area the stream flows ENE, then bends to NNE at right center, then exits the area flowing ESE (compare stream bends in Fig. 5-3 with 5-5). There is a footbridge over the stream at the bend between the ENE and NNE reaches. The outwash area contains two terraces, at 1.2 m and 7.8 m above stream level (Fig. 5-5). These lower terraces is small and lies directly north of the stream, whereas the higher terrace underlies most of the open, grassy area. The northern edge of the upper terrace is overlain by younger colluvium and alluvium from a N50W-trending swale to the NW. In the SW corner of the area a low, linear, bouldery ridge rises a few feet above upper terrace. This ridge has a very high surface boulder frequency and surface rocks are not very weathered. It appears to be the crest of an eroded moraine ridge that was buried by aggradation of the upper (early Pinedale?) terrace.

At the western edge of the area a flat-crested, bedrock-cored ridge protrudes into the upper terrace. The southern margin of this ridge is marked by a linear band of large angular blocks of weathered granitic gneiss, with random foliation directions, which forms the western part of a lineament that parallels the Thompson Canyon fault. The eastern part of this same lineament is the linear terrace riser segment between the upper and lower terraces that trends

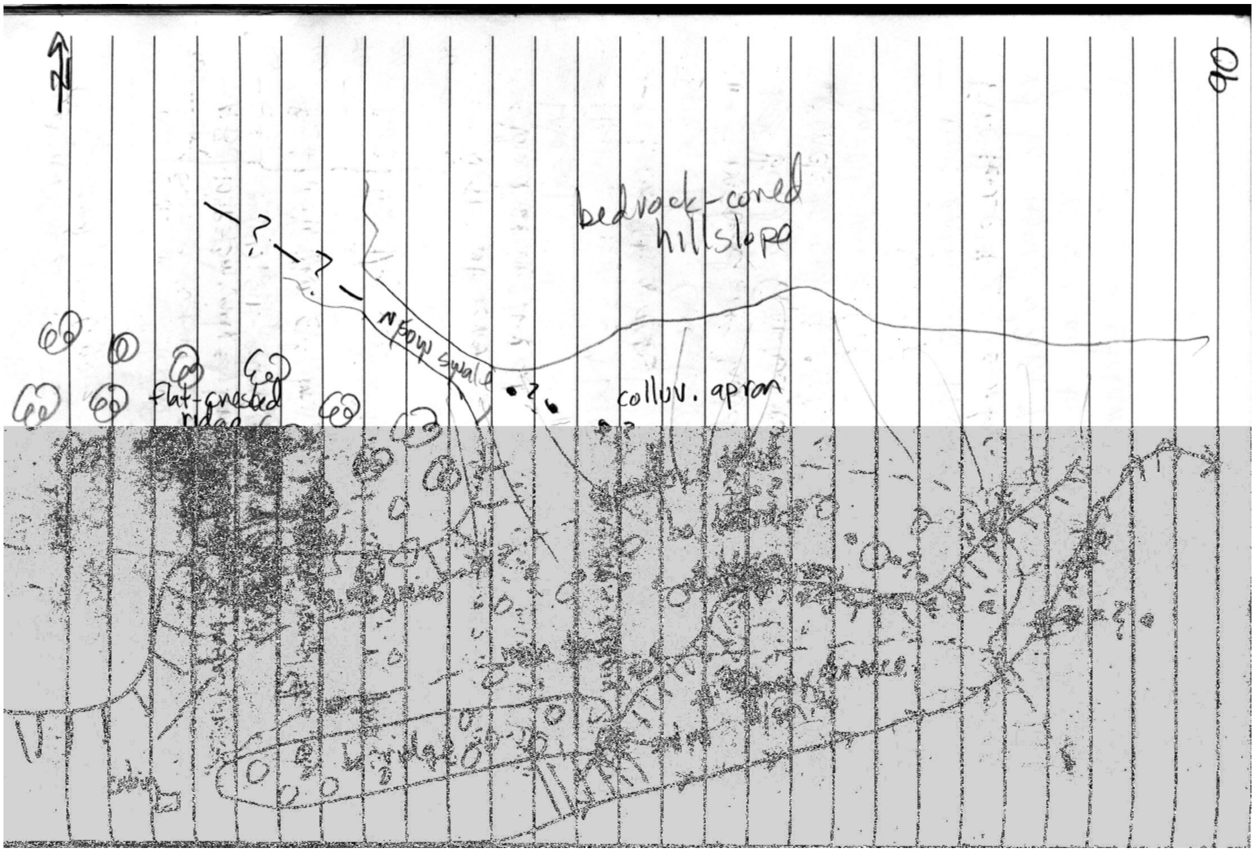


Fig. 5-5. Sketch map of the outwash area east of the Pinedale terminal moraine. Line with arrows is stream (lower right), dashed line is the North Fork trail, double line at creek is footbridge. The lower terrace (1.2 m above stream) is inferred to be late Pinedale. The higher terrace (6.6 m above the lower terrace, or 7.8 m above the stream) is inferred to be late Bull Lake (see soil profile). The higher terrace underlies most of the flat area here, and has buried a bouldery ridge (lower left) inferred to be a Bull Lake moraine remnant. The riser between the terraces is segmented into (from west to east) N30E, N80W, and N50E segments. The middle segment coincides with a lineament parallel to the Thompson Canyon fault (queried line of large dots). A second lineament trends N50W and ascends a tributary gully.

N80W (Fig. 5-5). We term this the main lineament. A second lineament trends N50W and ascends a small tributary swale at the NW corner of the area.

5.1.1 Age of the Terraces

South of Rocky Mountain National Park, Schildgen et al. (2002) studied Middle Boulder Creek, and observed that Bull Lake terraces (> ~100 ka) lie at 15 to 20 m above stream level, Pinedale terraces (30 to 10 ka) lie at 4 to 15 m above stream level, and Holocene terraces (< 10 ka) lie < 4 m above stream level. In the outwash area of the North Fork, directly downstream from the terminal moraine, there has probably been less net postglacial incision than in Middle Boulder Creek, so the height of each respective terrace would be expected to be less. For example, our 1.2 m terrace is interpreted as late Pinedale, whereas in Middle Boulder Creek Pinedale terraces are 4-15 m above stream level.

Our upper terrace 7.8 m above stream level would be Pinedale in age if it were located in Middle Boulder creek, and the high surface boulder frequency and weak rock weathering of the ridge that it buries (and thus post-dates) also suggest a Pinedale age. However, the soil profile (Fig. 5-6) is more developed than a typical Pinedale soil. According to Birkeland et al. (2003) *"The characteristic soil on till of the Pinedale glaciation has an O and (or) A/Ej or E/Bw or Btj/Cox profile. Hue of the B horizon is usually 10YR, and most of the clasts within the soil are unweathered."* In contrast, *"The characteristic soil on till of the Bull Lake glaciation is an O and (or) A/E/Bt/Cox profile. The Bt commonly has a 7.5YR hue, clay content reaches a maximum of 16%, and about 20% of biotite-rich granitic and gneissic clasts within the soil is weathered to grus."*

The soil on the 7.8 m terrace matches Pinedale soils in regards to the horizon of maximum development (Bw) and the general weakness of soil structure (only the Bw1 horizon contains weak, medium subangular blocky peds; the other horizons are structureless). Even in that horizon of maximum development, the texture is gravelly loamy sand, which is very slightly sticky and nonplastic. The soil departs from Pinedale characteristics in its color (7.5YR rather than 10YR) and the thickness of the reddish Bw horizons (45 cm). However, all the clasts in the lower 3 soil horizons are stained orange and red, which suggests some type of non-pedogenic, groundwater phenomenon is responsible for the anomalous red soil color. Overall, the soil profile suggests that the buried moraine ridge is early Pinedale, which implies that the 7.8 m terrace is also Pinedale.

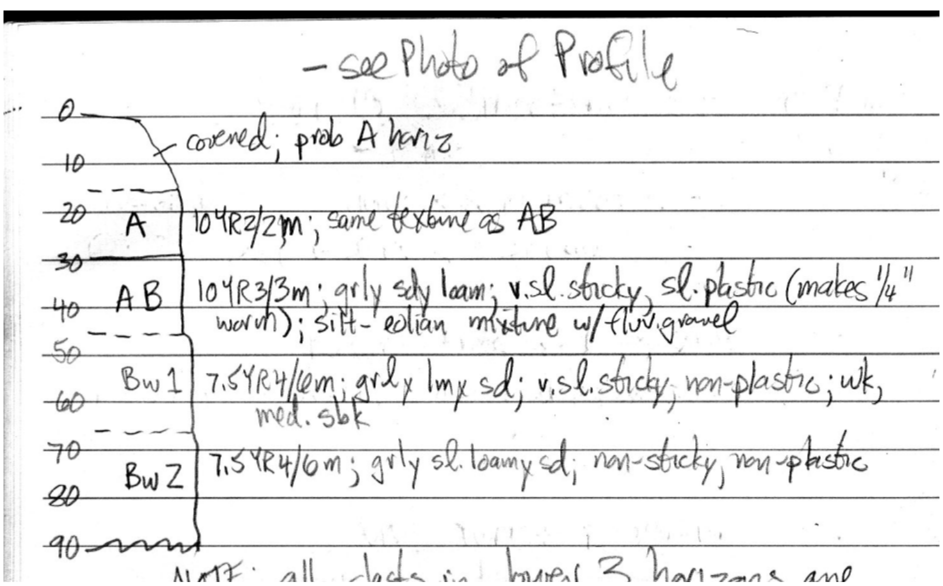


Fig. 5-6. Soil profile on the buried moraine ridge mostly buried by the 7.8 m-high terrace (see Fig. 5-5 for location). The parent material from 0-30 cm is eolian, from 30-45 cm (AB horizon) is a mixture of eolian and outwash gravel, and from 45-90 cm (Bw horizons) is outwash sandy gravel. All gravel clasts from 30-90 cm are discontinuously stained a weird orange or red color.

5.1.2 Quaternary Faulting in the Outwash Area?

The two lineaments shown in Fig. 5-5 (dotted, queried lines) do not create scarps with topographic relief across either the lower or upper terrace. However, the terrace riser between the upper and lower terraces has an anomalous N80W-trending reach in its center. This reach suggests the possibility that the terrace riser originally trended N30-50E, and was displaced in a right-lateral sense along a N80W-trending section of the Thompson Canyon fault. This same mechanism could explain why the flat-crested bedrock ridge protrudes into the upper terrace on the western side. However, no linear swale or other obvious geomorphic feature crosses the upper terrace between these two features. In addition, this explanation would require tens of feet of post-Pinedale strike-slip displacement, which we feel is unlikely for several reasons. First, the current seismotectonic regime in the northern Front Range should not support such a high slip rate and sense of slip on any fault. Second, if such large displacements had occurred so recently on the Thompson Canyon fault, it would have created geomorphic evidence elsewhere on the fault, and none has been observed.

The alternative explanation for the main lineament is that there are N80W-trending bedrock structures in the fault zone that have been exploited by erosion here. One likely possibility is that the rock north of the lineament is much harder (less fractured or sheared) than rock to the south. In that case, the protruding ridge and the eastward deflection of the terrace riser could be explained by differential erosion, with the stream unable to erode into the hard rock north of the lineament.

The only definitive way to distinguish between the two hypotheses outlined above (strike-slip faulting vs differential erosion) would be to excavate a trench on the upper terrace, oriented north-south, and crossing the two lineaments shown on Fig. 5-5. However, this trenching would be logistically difficult, because there is no road to the site, only a foot trail, and the site lies within the Arapaho-Roosevelt National Forest. Therefore, at this time the preferred hypothesis is differential erosion, with no evidence of fault movement in post-Pinedale time.

5.2 Dunraven Glade

Under the heading Dunraven Glade, we describe several geomorphic features in the 4 mi-long section of the Thompson Canyon fault between the Pinedale terminal moraine and the mouth of Dunraven Glade, at its confluence with the North Fork Big Thompson River. This western part of this stretch is a 1.5 mile reach of the North Fork Big Thompson River, extending from the Pinedale outwash area southeast to the saddle at the head of Dunraven Gulch (Fig. 5-7). The reaminder of the section is composed of Dunraven Glade, a linear, 2.5 mi-long, NW-trending valley that lies along a major fault trace of the Thompson Canyon fault.


Fig. 5-7. Photograph looking northwest up the North Fork from Dunraven Saddle.

5.2.1 Cheeley landslide and sackung

About 0.6 mi downstream from the Pinedale outwash area, Braddock and Cole (1990) mapped a landslide in the North Fork (Figs. 5-2, 5-3). This bedrock landslide has a well-defined headscarp between 8600-8800 ft elevation, or about 800-1000 ft above stream level. The landslide body is composed of huge blocks of Precambrian gneiss (mapped as biotite schist by Braddock and Cole, 1990). The landslide toe extends onto the floor of the North Fork and has forced the river against the opposite (south) valley wall. From this geometry, it appears that the landslide toe must have originally blocked the river. Three lines of evidence support this conclusion.

First, there is a 40 m-wide, 10 m-high band of landslide debris preserved on the southwestern side of the North Fork, across the stream from the mapped landslide.

Second, the reach of the North Fork directly upstream from the landslide toe is an aggraded flat about 70 m wide and 200 m long. The flat is sparsely forested and many of the trees in it have fallen over. A 60 cm-high streamcut into the aggraded material shows it to be very friable and loose sand with fresh mica flakes throughout and no surface soil development. This fluvial deposit appears to be very young, perhaps even historic. Clearly, the aggradation here is caused by the presence of the landslide toe blocking the North Fork.

Third, on the downstream side of the landslide toe is a unique bouldery, steep-gradient terrace that connects to the downstream margin of the landslide. This terrace is 6 m above stream level at the toe, but declines to 3.9 m above stream level farther downstream (Fig. 5-8), showing that its gradient is steeper than that of the modern stream. The terrace surface is covered with boulders up to 5 m in diameter at its head, declining to 2.5 m in diameter farther downstream.

We infer that this terrace was formed when the landslide dam was breached and the impounded water behind it rushed downstream in a catastrophic flood, hence we refer to it as the flood terrace.

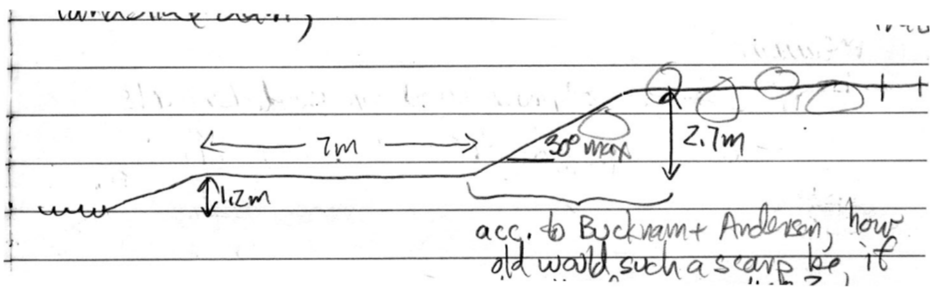


Fig. 5-8. Schematic north-south cross-section of the flood terrace directly downstream from the Cheeley landslide. North is to the right. The flood terrace at upper right lies 3.9 m above stream level and grades to the landslide toe. The riser between the 3.9 m terrace and a lower terrace 1.2 m above stream level slopes at 30. The 1.2 m-high terrace is cut into the 3.9 m terrace and clearly postdates it. GPS coordinates 459319E, 4481329N, UTM Zone 13, NAD27; page 86, Field Notebook 23.

There are several possible ways to date the landslide. The best way would be to auger into the aggraded sandy alluvium upstream from the landslide and try to date the lowest post-landslide sediments. Presumably a sharp contact would exist between the post-landslide deposits (sand) and the pre-landslide alluvium (gravel). Some organic marsh or lacustrine sediments may also exist at that contact. This has not yet been attempted.

Less fruitful approaches would be to date the landslide deposit itself or the flood terrace. Both of these deposits are extremely coarse-grained, so it is unlikely that organic material could be sampled for radiocarbon dating. A very indirect method would be to calculate the diffusion age of the terrace riser (Fig. 5-8).

Until these more detailed tasks are attempted, we will not know the age of the landslide. Even then, however, there is no way to unambiguously relate the landslide to earthquake shaking.

From 0.75-1.5 mi downstream from the Cheeley landslide, the north valley wall displays two curved antislope scarps (labeled “sackungen” on Figs. 5-2, 5-3). These scarps lie 500-700 ft above stream level, north and northeast of the saddle at the head of Dunraven Glade. Their existence suggests that the north valley wall is pulling away from the rest of Bulwark Ridge and toppling southward. These antislope scarps are anomalous for the area, because the relief of Bulwark Ridge is quite modest at this site. Normally, for sackungen to form in response to glacial valley oversteepening, such as occurs at Iceberg Pass on Trail Ridge Road, there has to be about 1000 m of topographic relief between the ridge crest and the valley bottom. At Bulwark Ridge the relief is much smaller, on the order of 150-200 m. Elsewhere in the USA, sackungen form with this small amount of relief only where the ridge has been subjected to strong earthquake ground shaking, such as on ridges adjacent to the San Andreas fault in southern California (McCalpin and Hart, 2003a, 2003b).

In summary, both landslides and sackung are rather rare in the Precambrian rock of the northern Front Range, especially in areas of rather modest relief such as Bulwark Ridge. The two features may reflect failure of shattered rock in the Thompson Canyon fault zone, however, no wide zones of fault rock are mapped at this location. Such shattered rock zones are mapped by

Braddock and Cole (1990) elsewhere along the fault, but they are not associated with landslides. The other hypothesis is that Bulwark Ridge has been subjected to strong ground shaking. The landslide and sackung are only 2 km and 4 km, respectively, from the estimated epicenter of the 1882 event (Fig. 5-2, 5-3).

5.2.2 Fault Saddle at head of Dunraven Glade

The head of Dunraven Glade is a topographic saddle at about 8090 ft elevation, or about 370 ft above the North Fork (7720 ft elevation). Braddock and Cole (1990) map a 50-75 m-wide fault zone through this saddle, reflecting the main trace of the Thompson Canyon fault. The saddle has a smooth, concave-upward topographic cross profile (perpendicular to fault strike) that has slightly steeper slopes on the northern side. There are no visible fault scarps or topographic deflections in the saddle. When approaching the saddle from the NW or SE (along strike), outcrops of Precambrian gneiss can be traced to within about 10 ft of the elevation of the saddle crest. This suggests that the Quaternary (?) colluvial deposits beneath the saddle are probably no thicker than 10 ft.

Beneath the colluvium, there may be high-level alluvium of the North Fork overlying bedrock in this saddle. This supposition is based on the local stream geomorphology, which suggests that Dunraven Glade is an underfit valley, and is basically beheaded at Dunraven Saddle. The longitudinal profile of Dunraven Glade appears to "project into space" north of the saddle. Meanwhile, the present course of the North Fork departs southward from the Thompson Canyon fault and forms a series of meanders incised 370 ft below the saddle. Our interpretation is that the North Fork formerly flowed SE down Dunraven Glade, but was later (early Pleistocene?) pirated by a steeper tributary into its present course. If so, then there should be early Pleistocene alluvium beneath the colluvium in the saddle.

This point is important because, if true, it means there are Quaternary deposits potentially spanning much of the Quaternary period beneath the saddle. The presence of such old deposits would then maximize the chances of preserving faulted Quaternary deposits in the Thompson Canyon fault. During the 1980s-vintage neotectonic investigations for Two Forks Dam, most of the trenches were sited in fault-controlled saddles. Those trenches, surprisingly, often exposed a considerable thickness of colluvium and stranded high-level alluvium over Precambrian bedrock. A similar situation might exist at Dunraven Saddle.

Therefore, Dunraven Saddle would make probably the best trench site on the Thompson Canyon fault, to look for pre-late Quaternary faulting, for several reasons. First, a gravel road extends to the saddle crest, providing easy access for a backhoe. Second, the western half of the saddle is owned by Cheeley Camp, and the eastern half by the US Forest Service. Either of these landowners would potentially permit trenching. The only drawback to the site is that a buried telephone cable parallels the fault the entire length of the saddle, so any fault-perpendicular trench would encounter it. This problem could be resolved by breaking the trench into 2 segments at the phone line. Overall, the trench would have to be about 100 m long to span the flat part of the saddle.

5.2.3 Dunraven Glade

Dunraven Glade is a linear, 2.5 mi-long, NW-trending valley that lies along a major fault trace of the Thompson Canyon fault (Fig. 5-2). The Glade descends from an elevation of 8090 ft at its head to 7000 ft at its confluence with the North Fork, for an average gradient of 10% (ca.

5°). A dirt road extends the entire length of the Glade, to access a residential development named The Retreat.

The bottom of the Glade is filled with locally-derived, sandy-grussy alluvium, which grades up to colluvial aprons on the sideslopes. It appears that the dominant style of sedimentation in the Glade at present is slopewash and downslope creep of grussy weathering products from the sideslopes of the Glade toward its axis. There were no visible topographic anomalies or fault scarps in the Glade. Therefore, we did not identify any geomorphic evidence of Quaternary faulting in the Glade, not any potential trench sites.

5.3 Mouth of Dunraven Glade

At the confluence of Dunraven Glade and the North Fork Big Thompson River, there are several high fluvial terraces and artificial exposures into the Thompson Canyon fault zone.

5.3.1 Terraces and Incised Meanders of the North Fork Big Thompson River

The North Fork flows in an incised inner valley (pink dashed ine in Fig. 5-2) about 400 ft deep from near Dunraven Saddle, south to the mouth of Dunraven Glade, and downstream for about 5 km. Above the incised inner valley the slopes are more open and rounded. Within the inner valley the channel forms deeply incised meanders. Steven et al. (2003) described this incision as follows: *"Meanders along the Cache la Poudre and Big Thompson River systems near the north end of the Front Range developed early during uplift of a broad composite dome capped by the summit of Longs Peak, and the meanders were progressively incised during subsequent uplift. Modern gradients along meandering segments that extend as much as 25 miles into the dome exceed 100 feet per mile; the upper ends of the meandering courses have been obliterated by Pleistocene glaciers. Major uplift of the dome was thus post-Ogallala Formation in age and took place during the Pliocene and into the Pleistocene."*

The age of the incision of these meanders can be estimated from the fact that the North Fork Big Thompson River has incised about 250-275 feet (75-85 m) into Precambrian bedrock since the incision began. Schildgen et al. (2002) studied Middle Boulder Creek, and observed that Bull Lake terraces (> ~100 ka) lie at 15 to 20 m above stream level, Pinedale terraces (30 to 10 ka) lie at 4 to 15 m above stream level, and Holocene terraces (< 10 ka) lie < 4 m above stream level. Thus, if erosion rates have been approximately linear in the Quaternary, a terrace 80 m above stream level would be approximately 4 times as old as the Bull Lake terraces (150 ka) that lie 20 m above stream level. That comparison indicates an age of ca. 600 ka for the 80 m-high terrace. However, such a comparison is flawed because the Pinedale and Bull Lake terraces in the Front Range are mainly aggradational terraces, and their present height above the stream merely reflects postglacial stream incision through unconsolidated gravels. In contrast, the 80 m of incision leading to the incised meanders was stream incision through Precambrian crystalline rocks. Given that, the actual time when the incision started could be easily 2-3 times the 600 ka estimate. That range of ages (1.2-1.8 Ma) is similar to the age range suggested by Steven et al (2003).

Within the incised inner canyons there are small terrace remnants that may be Bull Lake or pre-Bull Lake in age. For example, north of the quarry, on the north bank of the North Fork, is a large terrace remnant 22.5 m above stream level. The local Volunteer Fire Station for The

Retreat sits on this terrace remnant. On the south side of the North Fork, above the quarry, there is a small terrace remnant at 25.5 m.

5.3.2 General Comments on Terraces

Quaternary river terraces provide a younger datum than the mid-late Tertiary erosion surface from which to assess Neogene fault movement. The most abundant terraces were evidently formed by glacial outwash in the Pinedale (ca. 15-35 ka) and Bull Lake (ca. 150 ka) glaciations (Porter et al., 1983), so are considerably younger than the mid-late Tertiary erosion surface.

Although no detailed work has been done on the terraces of the Big Thompson Canyon, Schildgen et al. (2002) analyzed terraces in Boulder Canyon, at the southern boundary of the larger CGS study area. They identified terraces as either: (1) Bull Lake (> ~100 ka; at 15 to 20 m above stream level); (2) Pinedale (10 to 32 ka; at 9 to 15 m above stream level); and (3) Holocene (< 10 ka; at < 4 m above stream level). Limited cosmogenic and 14C dating and soil development suggest that ~ 130 ka terraces in Boulder Canyon correlate with the Louviers Alluvium and that the 10 to 32 ka fills correlate with the Broadway Alluvium on the adjacent High Plains (Scott, 1965).

GEO-HAZ performed some preliminary mapping of pre-Bull Lake terraces and abandoned valley floors in the upper Big Thompson River drainage, very close to the estimated 1882 epicenter (40.5°N, 105.5°W), prior to the start of this study. A set of extensive abandoned drainage divides and accordant terrace remnants about 75-85 m above modern streams indicate that at least one major readjustment of the drainage network has occurred in Quaternary time.

5.3.3 Quarry Exposure and Roadcut

A large abandoned quarry lies on the south side of the North Fork, about 500 m east of the confluence with Dunraven Gulch, and is excavated completely in Precambrian bedrock. The quarry lies astride the western boundary fault of the Thompson Canyon fault zone, which is exposed on the south wall of the quarry (Fig. 5-9). The eastern half of the main quarry wall is all in oxidized, sheared rock, whereas the western half is in unozidized and fractured rock. Separating these two rock types is a discrete fault gouge zone about 30-50 cm wide, composed of multicolored green and red clay. The shear zone may extend farther east than the east end of the quarry wall. A gully upslope of the quarry is aligned parallel to the fault strike and is 25 m wide, which we infer to be the width of the shear zone here.

The sheared and fractured Precambrian bedrock is overlain by about 2-2.5 m of Quaternary colluvium. The colluvium maintains a constant thickness over the unxidized rock west of the shear zone, thickens over the fault gouge zone, and then appears to thin significantly over the sheared rock in the fault zone. This relationship is the reverse of that expected, because the sheared rock, being softer, should have eroded more easily and been overlain by thicker colluvium. Due to time constraints, the top of the cut was not cleaned off well enough to see if the Quaternary colluvium was faulted over the fault gouge zone.

Directly north of the quarry there is a long roadcut on the south side of County Road 43 (Fig. 5-10). The western part of this cut mainly exposes colluvium, which presumably correlates to the colluvium in the western part of the quarry. As in the quarry, the colluvium appears to thin rapidly in association with a steep fault zone, with the result that the colluvium is thinner over the weaker rock. Determining the exact cause of this thinning would require considerable.

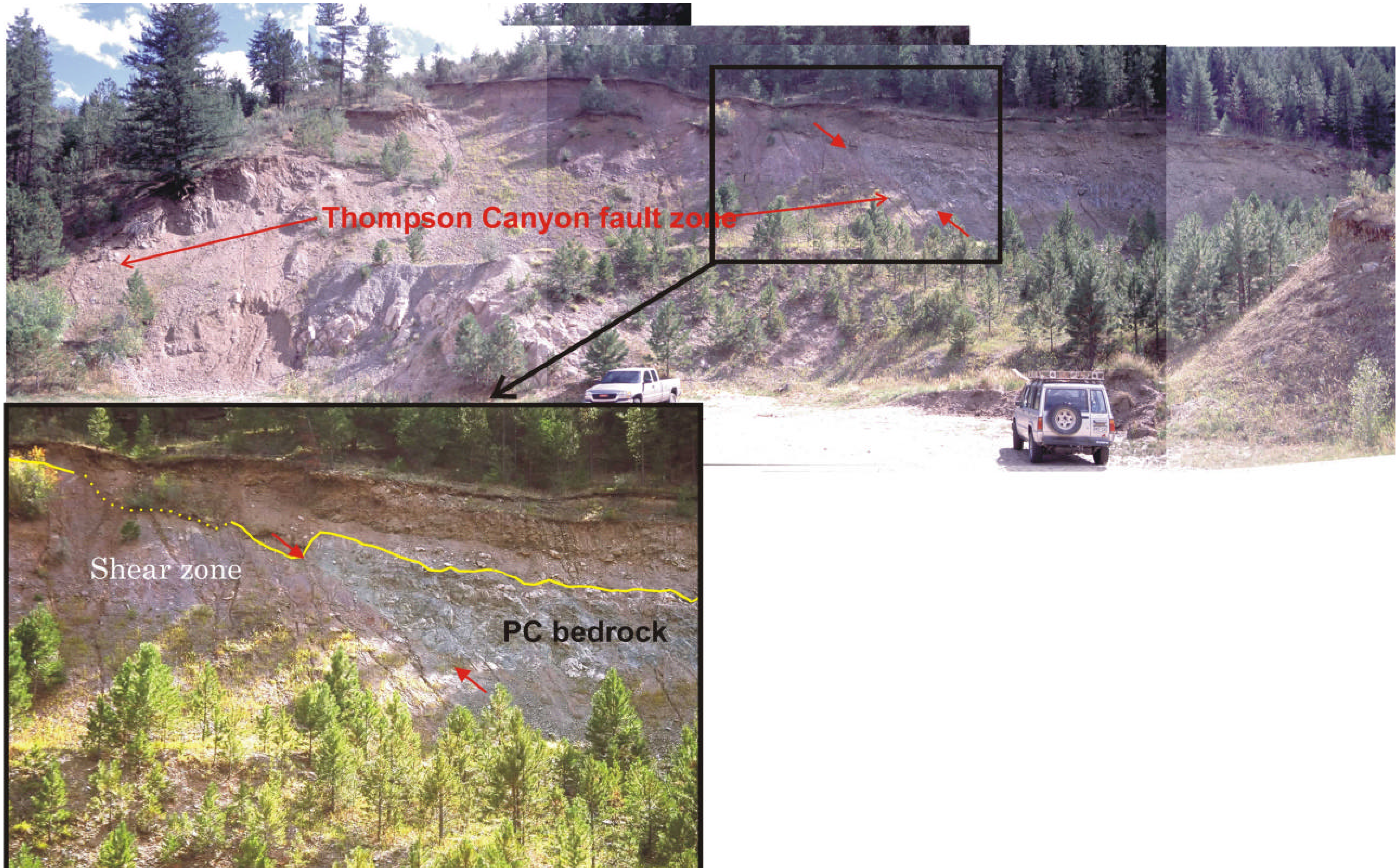


Fig. 5-9. Photomosaic of quarry in North Fork of Big Thompson River, opposite the entrance to the retreat, between Glen Haven and Drake, Colorado. The eastern (left) half of the quarry wall is in the Thompson Canyon fault zone. And the western half in intact Precambrian bedrock. The western margin fault is shown by red arrows. In inset at lower right, the base of Quaternary colluvium is shown by a yellow line, dotted where concealed.

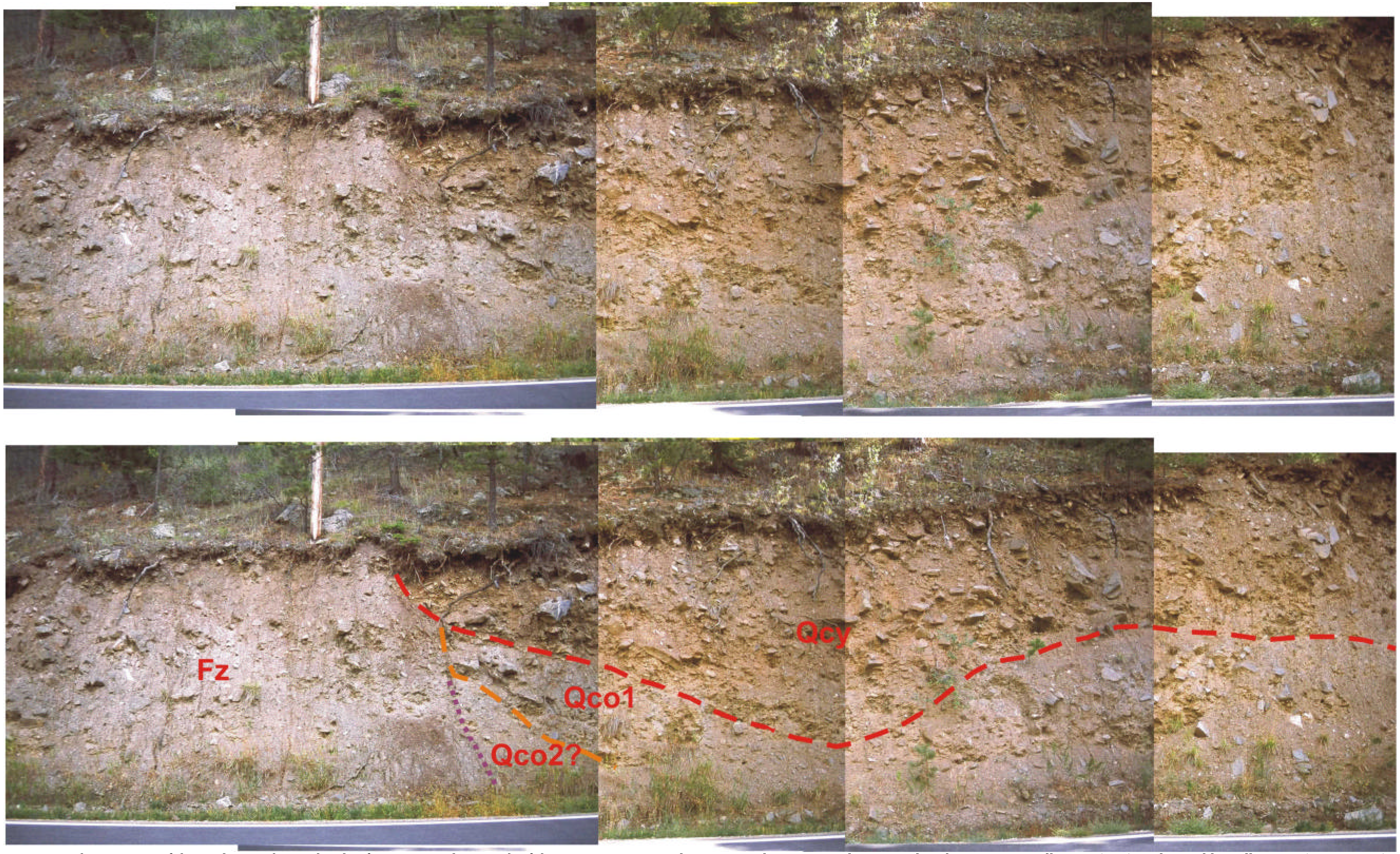


Fig. 5-10. Photo mosaic of the roadcut on the south side of County Road 43, north of the quarry. Upper panel, unannotated. Lower panel, annotated to show younger colluvium (Qcy), and two older colluviums (Qco1, Qco2). Fz= fault zone rock.

cleaning of the roadcut. However, the quarry wall exposes this same contact and is already disturbed, so that would be my choice for mechanized cleaning

5.3.4 Saddle South of the Quarry

South of the quarry the western boundary fault of the Thompson Canyon fault zone passes through a saddle about 60 m above river level (Fig. 5-11). This saddle is occupied by a large grassy meadow (Fig. 5-12) with a relatively sharp western boundary (red line in Fig. 5-12). Based on gully exposures and surface float, the sharp vegetation line and abrupt break in slope on the western boundary is a contact between Precambrian rock (forested) and grussy colluvium (grassland). The geomorphology suggests that this contact dips steeply east, but because it is not well exposed, it is unknown whether it is a depositional contact or a faulted contact. The break in slope is one of the sharpest we observed along the Thompson Canyon fault, so it is possible there is evidence of Quaternary faulting there.

Fig. 5-11. Photograph looking NW from the northern edge of the Quarry Saddle (foreground), up Dunraven Glade (center background).

The saddle has been incised by at least one large gully on the western side (Fig. 5-12). This gully is narrow and shallow west of the fault line scarp, but as soon as it crosses the scarp the gully rapidly deepens to 4 m and widens, becoming a 5 m-wide, flat-floored gully. There is no bedrock exposed on the walls of this gully, which implies that the colluvial deposits in the saddle are at least 4 m thick, at least locally. At the northern edge of the saddle (just beyond the

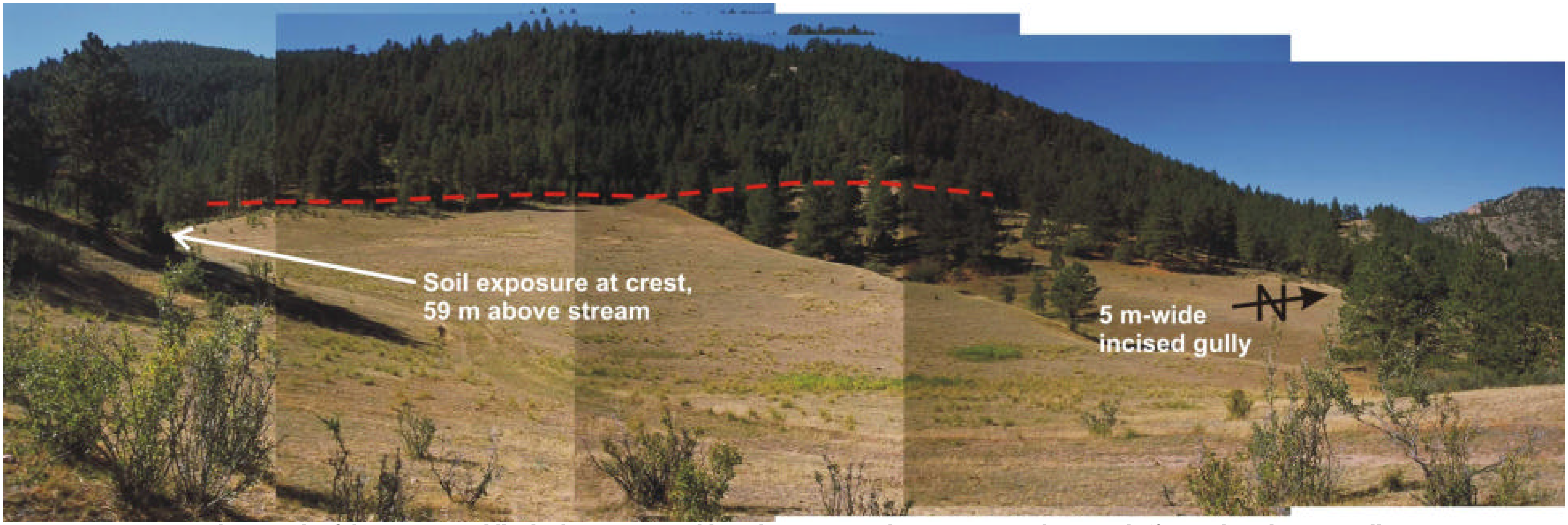


Fig. 5-12. Panoramic photograph of the Quarry Saddle, looking west. Red line shows contact between Precambrian rock (forested) and grussy colluvium (grassland), which may be a fault-line scarp.

right edge of Fig. 5-12), a bulldozer excavation 2 m deep exposed only colluvium, with a single block of pegmatite in the bottom that may have been subcrop.

There are two possible origins for this saddle. The first is that the saddle was formed purely from differential subaerial erosion into a zone of shattered rock in the Thompson Canyon fault zone. The second is that the saddle is a remnant of an old fluvial landscape (perhaps even a course of the North Fork) that predates the incision of the incised meanders of the North Fork. For example, southeast of the Quarry Saddle is a 2 mile-long tributary drainage that parallels the North Fork but lies 200 ft above it. Conceivably, this gully follows the course of an ancestral North Fork Big Thompson River that flowed southeast down the trace of the Thompson Canyon fault, unlike the present North Fork that departs from the Fault in several sections of meanders incised about 400 feet (pink dashed lines on Fig. 5-2).

At the crest of the saddle, 59 m above stream level, the road passing through the saddle makes a roadcut about 2-3 m deep (Fig. 5-13). This roadcut exposes a thick, red soil profile developed on the apron of colluvium that defines the western slope of the saddle. Based on the red color (2.5YR to 5YR hues) and the >50 cm-thick textural B horizon, this soil is pre-Bull Lake in age (<150 ka). A pre-Bull Lake age is also indicated by the 59 m height above stream level, because Bull Lake outwash terraces typically are found within 15-20 m above stream level.

Fig. 5-13. Roadcut exposure of a soil profile at the crest of the Quarry Saddle, 59 m above stream level; view is to SW. Soil horizons and thicknesses are: A, 0-10 cm; B21t, 10-30 cm; B22t, 30-50 cm; B23t, 50-60 cm; B3, 60-90 cm; B4?, 90-130 cm; Cox, 130-160 cm.

In summary, the Quarry Saddle may be a remnant of a pre-Bull Lake erosional surface, or even channel of the North Fork, that lies above the western boundary fault of the Thompson Canyon fault zone. The western boundary of the saddle is a sharp topographic and vegetation break, and probably marks the boundary between sheared rocks beneath the saddle, and intact rocks west of the saddle. There is at least 2 m and probably more than 4 m of Quaternary deposits beneath the saddle, of early to middle Pleistocene age. Therefore, is there has been any fault movement on the western boundary fault in the Pleistocene, it should be recorded in this saddle. That makes the saddle a promising trenching target, at least for the purpose of disproving Pleistocene movement on the Thompson Canyon fault. This saddle is comparable to Dunraven saddle as a trench site, because it has good vehicle access; however, it is apparently privately owned and the owners may not see any advantage to letting us determine if it is a Quaternary fault. At the time of my reconnaissance on Sept. 20, 2002, a water well had been freshly dug on top of a small bedrock knob on the eastern side of the saddle (Ingram Drilling, Ft. Collins and Estes Park, 1-800-410-4542). Thus, there could be a house built on the edge of the meadow by this time.

5.4 Terraces Near Drake, Colorado

Kirkham and Rogers (1981, p. 60) state "A roadcut exposure in the North Fork of the Big Thompson River, just upstream from Drake, suggests the Thompson Canyon fault [not shown on the map of Colorado Quaternary faults] may have moved during the Quaternary." Interestingly, this roadcut was not studied subsequently, because at the time of Kirkham and Roger's (1981) research, the 1882 epicenter was believed to be in western Colorado.

Therefore we examined all the roadcuts within a few km west of Drake along County Road 43. Four exposures (labeled #1 through #4 on Fig. 5-2) yielded the most information, and are herein described from east to west.

The easternmost roadcut (#1) lies about 0.5 km west of Drake and exposes Pinedale(?) overlying Precambrian schist and pregmatite (Figs. 5-14, 5-15, 5-16). The basal erosion surface beneath the Pinedale gravel lies 6.3 m above stream level, the gravel is 4.6 m thick (top is 10.9 m above stream level), and is overlain by 1.0 m of locally-derived angular fan gravels and colluvium. The basal erosion surface is subhorizontal but has some downward undulations where the Precambrian rock type is softer, such as the small shear zone shown in Fig. 5-16. Therefore we assume the undulations are a primary erosional features and not due to post-Pinedale deformation.

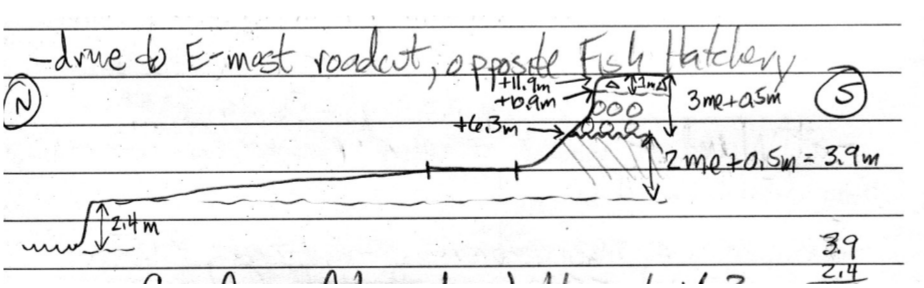


Fig. 5-14. Schematic north-south cross-section through roadcut #1 west of Drake, opposite the entrance road to the Fish Hatchery. Large circles show Pinedale (?) outwash overlying Precambrian bedrock. Squiggly line show the basal erosion surface.

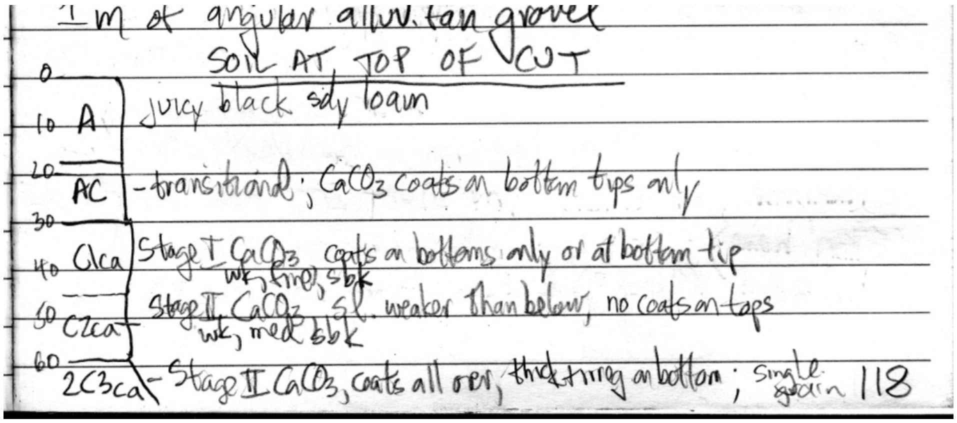


Fig. 5-15. Sketch of soil profile developed mainly in the locally-derived angular fan gravels that overlie the Pinedale(?) outwash. The profile does not contain a Bt or Bw horizon, but merely A/AC/C1ca/C2ca/ horizons in the locally-derived gravel and a 2C3ca horizon in the top of the outwash gravels.

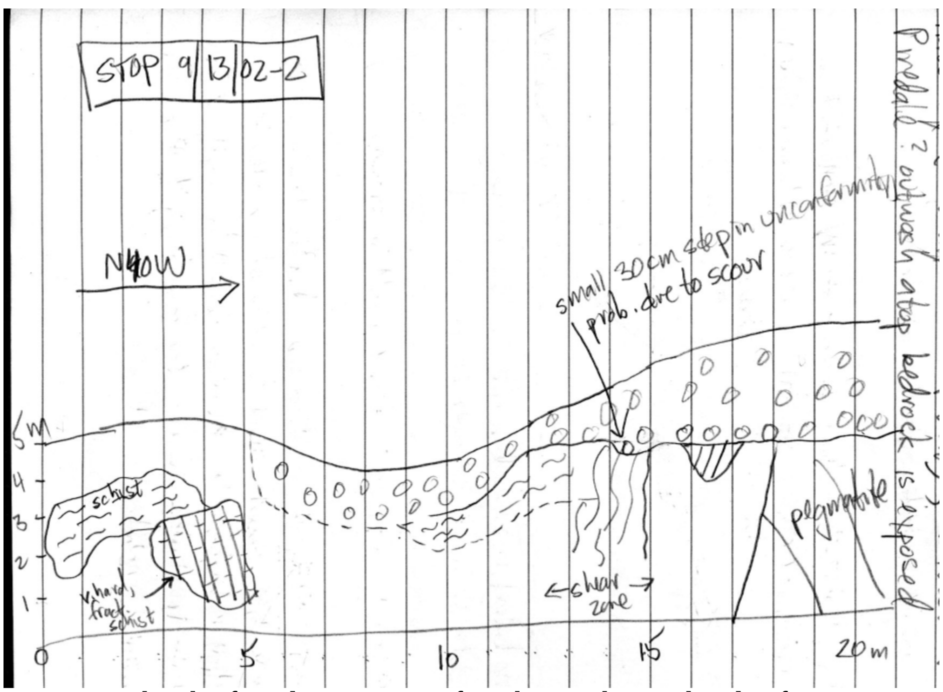


Fig. 5-16. Sketch of roadcut #1 west of Drake, on the south side of County Road 43, opposite the entrance to the Fish Hatchery and 15 m east. Location is shown on Fig. 5-2. The terrace alluvium at the top of the cut is interpreted as Pinedale outwash; its base lies about 5 m above road level, or about 7 m above stream level. Stop 9/13/02-2.

For a distance of about 1 km west of roadcut #1, several other roadcuts expose a similar geometry of Pinedale outwash overlying Precambrian rock. With increasing distance westward the basal erosion surface descends closer to the road. By roadcut #2, which is located in the area of Kirkham and Roger's (1986) suspicious exposure, the basal erosion surface has descended below road level (Fig. 5-17), and the terrace surface is about 6.5 m above stream level, or about

4.3 m below that at roadcuts #1 and #4. This westward decline indicates either than the basal erosion surface has a gentler overall gradient than the present North Fork, or that there is more vertical relief on the erosion surface than is apparent in individual roadcuts.

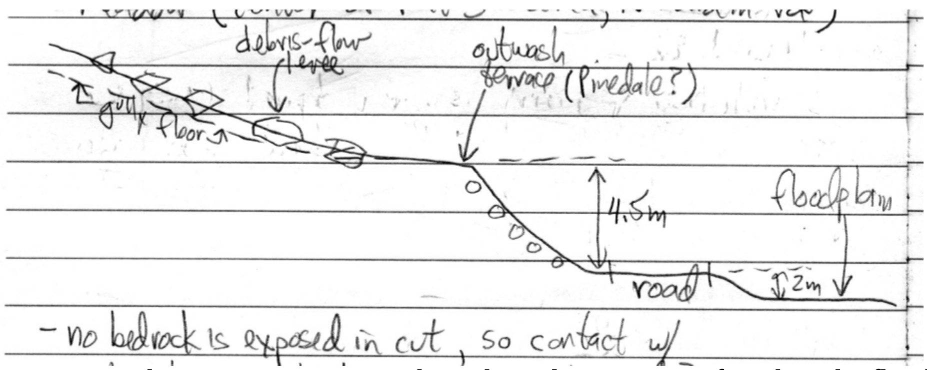


Fig. 5-17. Schematic cross-section through roadcut #2 west of Drake. The floodplain of the North Fork is at far right, County Road 43 right center, and a 6.5 m-high Pinedale (?) outwash terrace center. This roadcut is roughly in the center of the area where Kirkham and Rogers (1986) saw the possible faulting in Quaternary deposits. Stop 9/13/02-3.

The only exposure even faintly suggestive of Quaternary faulting lies on the eastern bank of a gully on the south side of CR 43 (roadcut #3 on Fig. 5-2). The gully lies 25 m west of the driveway and bridge to the Mountain Home Ranch. East of this gully the road curves around a resistant migmatite outcrop. The contact of Quaternary colluvium overlying the migmatite exposed on the eastern gully bank dips steeply, and MAY be the suspicious feature that Kirkham and Rogers observed. However, during my field reconnaissance on September 13, 2002, the banks of this gully were not clean enough to show whether this contact was simply a steep depositional contact, or something structural.

The westernmost roadcut that yielded good information (#4) lies at the entrance to the narrow canyon section that lies downstream from Glen Haven. Here County Road 43 is cut into a Pinedale(?) outwash terrace where the top of gravel is 10.7 m above stream level (Fig. 5-18), a similar height to that at roadcut #1. The outwash gravels are overlain by a thin deposit of silt-clayey overbank deposits (Fig. 5-19), and then by 3 m of sandy, locally-derived slopewash.

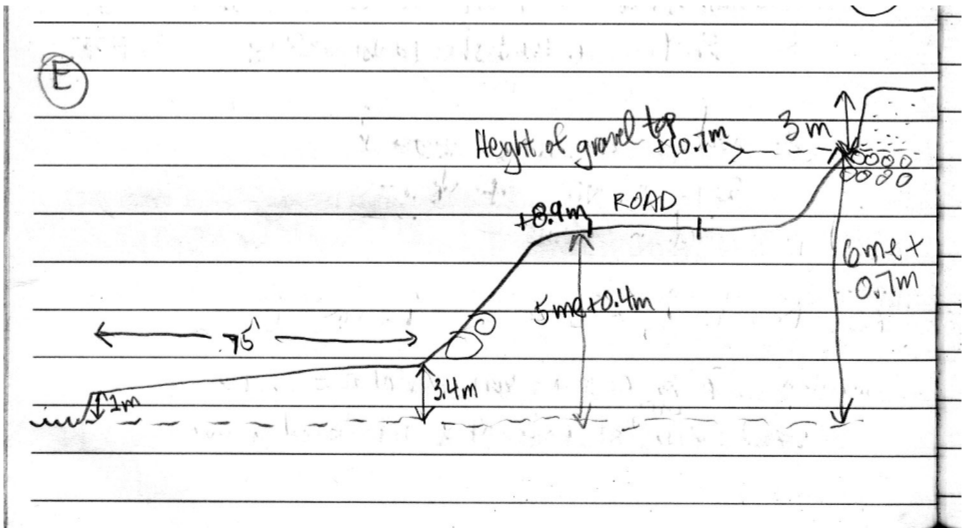


Fig. 5-18. Schematic east-west cross-section at roadcut #4 west of Drake. East is to the left. The North Fork is at far left, flanked by a sloping 75 ft-wide low terrace. County Road 43 is cut into a Pinedale(?) outwash terrace at 8.9 m above stream level, with the top of the outwash gravel (open circles) at 10.7 m above stream level. The outwash is overlain by 3 m of sandy, locally derived colluvium/alluvium.

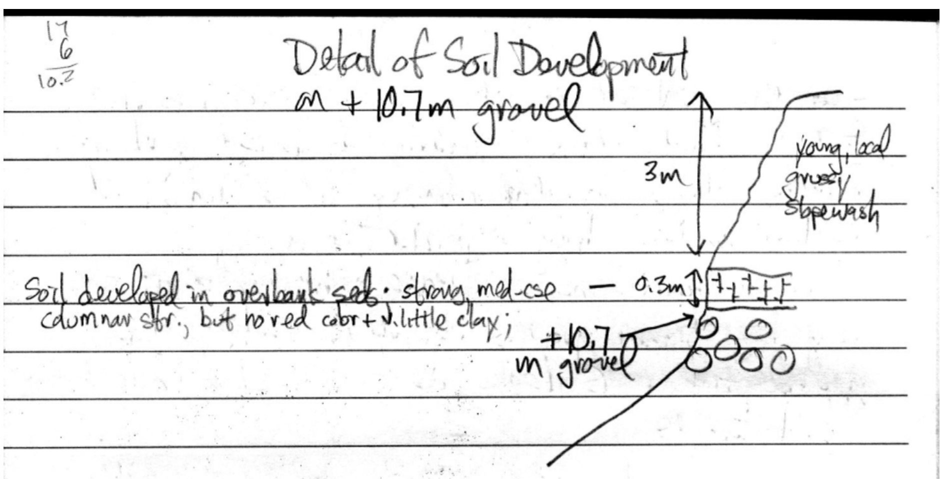


Fig. 5-19. Sketch of the upper 5 m of roadcut #4 west of Drake. There is a 0.3 m-thick fine-grained deposit between the Pinedale(?) outwash cobble gravels, and the overlying post-Pinedale grussy slopewash. Although this deposit displays strong, medium to coarse, columnar structure, it has no red color or clay films. Therefore, we consider the columnar structure to represent incipient post-Pinedale pedogenesis from wetting and drying of the fine-grained deposit.

The roadcuts west of Drake indicate two things about possible Quaternary activity of the Thompson fault. First, although some of the roadcuts expose faults in Precambrian bedrock, none of those faults displace the basal erosion surface beneath the Pinedale(?) outwash. Second, the height of this basal erosion surface is essentially the same between the easternmost roadcut (#1) and the westernmost roadcut (#4), despite the fact that they are 2.3 miles apart and on opposite sides of the Thompson Canyon fault. The implication of these two observations is that there has been no vertical displacement on the Thompson Canyon fault since the 10.7-10.9 m-high terrace was formed, probably in early Pinedale time (ca. 25-30 ka).

5.5 Aqueduct Saddles West of Viestenz-Smith Mountain Park

We made some reconnaissance observations along the southern boundary of the Thompson Canyon fault 2.3-2.8 miles downstream from Drake, in an area directly west of Viestenz-Smith Mountain Park (VSMP). In the western half of the ca. 3.5 mile-long section of the fault between Drake and VSMP, the fault is mapped beneath the channel of the Big Thompson River and is thus inaccessible to study (Fig. 5.2). In the eastern half, however, the fault ascends up to a prominent break in slope on the south valley wall, about 240-320 ft above stream level (Fig. 5-20). This area can be accessed via a dirt road that ascends from river level in VSMP. Drive into VSMP and park at the parking lot. Then ascend the Round Mountain Trail (City of Loveland) to the Foothills Nature Trail, which generally trends NW and follows a number of saddles along the fault zone. A 3-ft diameter aqueduct also follows the saddles, and is the reason for the existence of the access road.

Fig. 5-20. Photograph from Viestenz-Smith Mountain Park, looking NW up Big Thompson Canyon. Red dashed lines show the inferred limits of sheared rock associated with the Thompson Canyon fault. On published maps the fault is mapped at the southern (left) limit of the series of grassy benches see in the foreground. Note U-shaped valley cross-section in the distance, in front of the high peaks.

At Stop 1 in the Foothills Nature Trail pamphlet, rounded alluvial boulders are exposed in a roadcut overlying Precambrian biotite gneiss. This exposure is at an elevation of about 5800 ft, or about 100 ft (30 m) above stream level. Based on the heights of terraces in Middle Boulder Creek (Schilgen et al., 2002), this alluvium would be older than Bull Lake age.

Farther west on the trail is a 5 m-deep, 50 m-long trench where the aqueduct was laid in well below grade. The western half of this cut exposes subround boulder alluvium of Big Thompson Canyon at it base, at an elevation of about 5960 ft, or about 200 ft above stream level (5760 ft here). The stream alluvium is overlain by a massive sand (loess?), which in turn is overlain by local debris flow deposits.

Even farther west, at Stop 7 in the Foothills Nature Trail pamphlet, the trail is on the nose of a boulder-covered ridge that looks like a large debris flow that flowed in the direction N50E. The debris flow carries a well-developed surface soil that is very red (2.5YR4/6) sandy clay, moderately sticky, very plastic, with strong, medium, subangular to angular blocky ped structure. This degree of soil development in the local debris-flow deposit appears to be pre-Bull Lake, which confirms that the subjacent rounded stream gravels are also pre-Bull Lake in age.

None of the exposures visited showed any structural deformation. This lack is not terribly conclusive, because the exposures were discontinuous and were almost always parallel to the mapped trace of the fault, rather than perpendicular. As a potential trench site, this area has good access via the aqueduct service road, but several drawbacks. The first is that access would have to be through a park, the second (and more serious) is that any fault-perpendicular trench would intersect the aqueduct. Given these drawbacks, this site is inferior to the two saddle sites farther north (Dunraven Saddle, Quarry Saddle).

6. OTHER POSSIBLE NEOTECTONIC FAULTS

Besides the Michigan Lakes fault, Estes Park fault, and Thompson Canyon fault, there are two other large faults in the vicinity of the 1882 epicenter. The longer (and more southern) of these faults is informally termed the "Specimen Mountain-Forest Canyon- Tahosa Valley" fault, and the shorter (and more northern) the "Olympus- Fall River" fault.

6.1 "Specimen Mountain-Forest Canyon-Tahosa Valley" fault

The fault that displaces Oligocene volcanic rocks at Specimen Mountain (see Fig. 5-3) has long been known. This fault is a NW-trending normal fault, down to the SW, that displaces volcanic rocks and the underlying Eocene erosion surface down about 7500 ft to the SW. In addition, the fault displaces a younger post-Oligocene erosion surface, but onto the volcanics, down about 500 ft to the SW (Vince Matthews, pers. comm., 2006). Because this fault is demonstrably post-Oligocene, it is inferred to be related to extension related to the Rio Grande rift.

The fault is mapped by Braddock and Cole (1990) as continuing southeast, through Forest Canyon Pass and down the linear axis of Forest Canyon (headwaters of the Big Thompson River) in Rocky Mountain National Park. However, the evidence for the fault in Forest Canyon is not strong from a stratigraphic standpoint, because it is either concealed beneath Quaternary alluvium, or if in bedrock, does not displace contacts between the mapped Precambrian units. The fault was presumably continued down Forest Canyon mainly on geomorphic evidence. However, the fault is not mapped by Braddock and Cole (1990) as continuing to the SE end of Forest Canyon, but gor some reason terminates about 3 miles NW of the end of the Canyon.

If the fault had been extended to the end of the Canyon, it would have nearly connected to another mapped fault that continues through Storm Pass and into Tahosa Valley, where it bends southward. This structure is a major fault with associated wide gouge zones.

The Specimen Mountain and Forest Canyon sections of the fault were not investigated in this study, the latter due to the length of time it would have taken to hike down into Forest Canyon, and the lack of mapped evidence that a fault there had significant displacement. We did perform some reconnaissance on the Tahosa Valley part of the fault, as described below.

In Tahosa Valley the fault is mapped by Braddock and Cole (1990) as either a wide zone of crushed fault rock in bedrock, or concealed beneath Quaternary deposits (Fig. 6-1). The Quaternary deposits include pre-Bull Lake till (unit QNd), Bull Lake till (Qb), and Pinedale till (Qp). The easiest way to access the fault zone is to drive west on the Long Peak Ranger Station road and then to turn south on the westernmost dirt subdivision road. Proceed to the end of that road to a locked chain and walk to the south end of the road (waypoint 4 on Fig. 6-1), where the road dead-ends into the flank of a Pinedale moraine. This point lies atop the westernmost concealed fault strand mapped by Braddock and Cole (1990). There is no evidence of faulting on the crest of the Pinedale moraine (waypoint 5 on Fig. 6-1).

We proceeded southwest from waypoint 5 until we reached the base of a high boulder-covered escarpment. At the base of the escarpment was a small clearing composed of a flat, grussy area (waypoint 6), which was trapped between the western escarpment and a small moraine ridge about 2 m high to the east. This scarp died out to the south, at the National Park boundary, so we traversed east along the boundary and encountered a saddle in the moraine crest (waypoint 7).

From waypoint 7 a series of N-S-trending swales (some as wide as 10 m) continues SE through waypoints 8 and 9, where the swale system is truncated by the active channel of the Roaring Fork. These swales essentially parallel the trend of the Tahosa Valley fault, but they are not that different from the trend of local moraine crests. There are two NE-facing scarps just north of the Roaring Fork that trend N60-70W, or parallel to the nearby moraine crest mapped by Braddock and Cole (1990). That trend is much more westerly than the N25W trend of the Tahosa Valley fault.

Overall, the evidence was weak for a tectonic origin of the swales and scarps. The simplest explanation for them is that they are primary glacial depositional features that just happen to trend northwest. There were no locations visited across the swales where a single, correlatable landform such as a moraine crest could be observed on both sides and said to be clearly offset. Therefore, we conclude that the Tahosa Valley fault has not had significant vertical displacement since before the Bull Lake glaciation, at least in the area visited.

6.2 "Olympus-Fall River" fault

The "Olympus-Fall River" fault is a name informally used herein for the NW-trending fault that trends through Olympus Dam at Estes Park, and continues northwest up the axis of the Fall River valley. Little is known of this fault, and it was not visited in the field during this investigation. The reason we mention it here is that this fault, together with the "Specimen Mountain-Forest Canyon-Tahosa Valley" fault, form the lateral boundaries of the large ridge that Trail Ridge Road occupies as it traverses the Continental Divide. That section of the ridge contains a series of sackungs between Rock Cut and Iceberg Pass, and is the only ridge segment in RMNP known to possess such extensive sackungs.

Granted, there is sufficient relief and glacial oversteepening on this section of Trail Ridge Road that the sackungs could have developed in the absence of earthquake ground shaking. Perhaps the rock mass in that section of the ridge is anomalously weak, lying as it does on a major NE-trending lineament mapped by Matthews (2003), and that weakness explains the concentration of sackungs. Alternatively, even if earthquake shaking had affected this area, the locus of sackung formation might still be the area of weakest rocks, rather than the area of the earthquake epicenter. These matters are discussed in more detail in the Conclusions section.

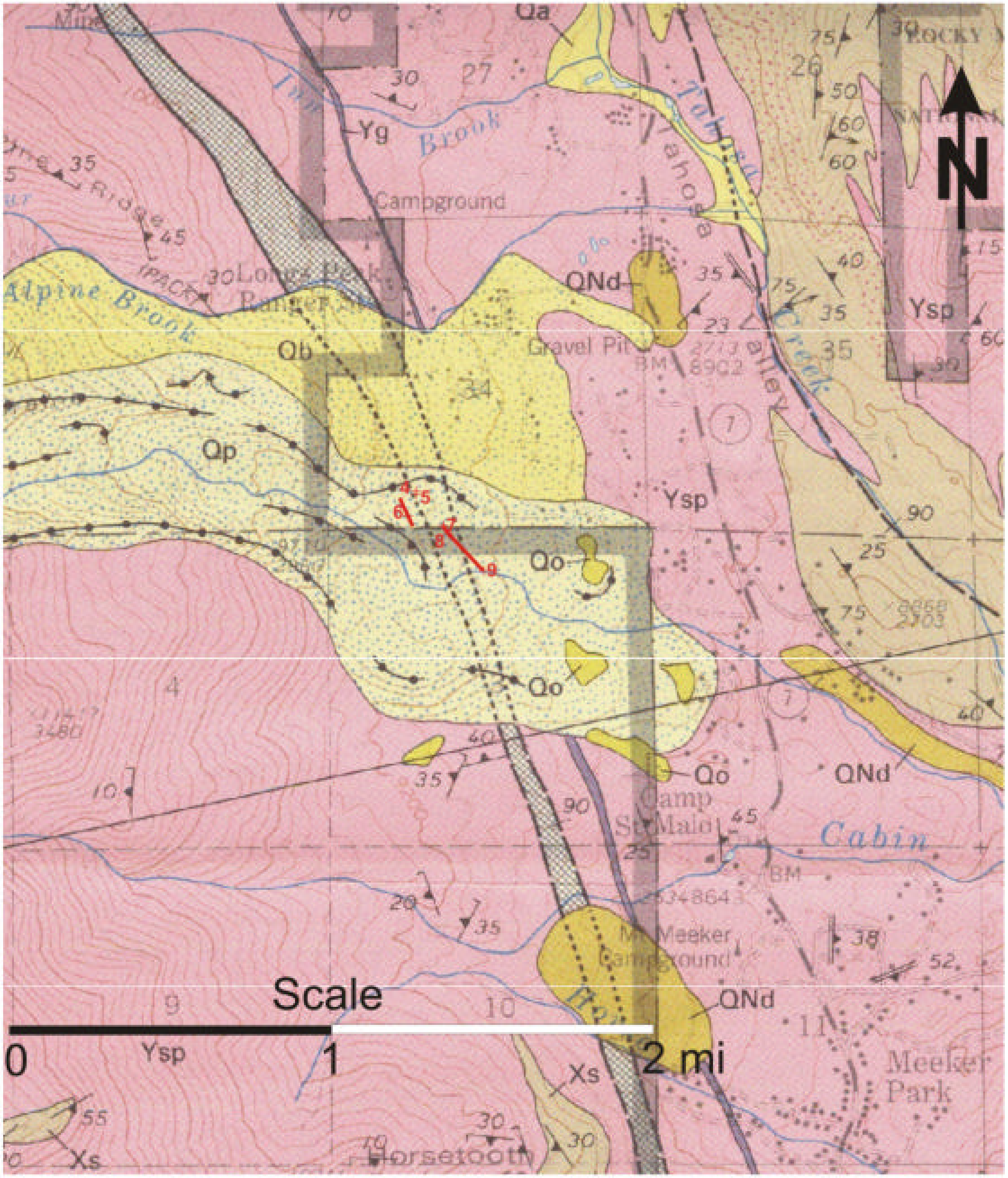


Fig. 6-1. Part of the Geologic Map of Rocky Mountain National Park (Braddock and Cole, 1990) centered on Tahosa Valley. Red crosses with numbers are GPS waypoints described in the text. Red lines show swale axes visited in the field. The Tahosa Valley fault is marked by wide shear zones (cross-hatch pattern) trending N25W across the middle of the map.

7. CONCLUSIONS

This reconnaissance investigation did not locate a historic surface rupture that could be attributed to the Nov. 7, 1882 M6.6 earthquake. Normal-faulting earthquakes of that magnitude typically produce a small surface rupture, but in 1/3 of historic cases, such an earthquake produced only sparse ground cracking that would be quickly obscured by erosion. Notably, earthquakes of M6.5 and lower typically do not result in surface rupture (Pezzopane and Dawson, 1996). Therefore, if there is any chance that the M6.6 magnitude estimate is actually an overestimate, then there is a good chance that the 1882 earthquake did not produce a surface rupture, certainly not one that could be located over 120 years later.

This study did document that the Lyons-Estes Park toll road had to be cleared of rocks in the spring of 1883, implying that an anomalously large number of rocks rolled onto the road during the winter of 1882. However, we could not locate any historic documents that mentioned the cause of the anomalous rockfalls, nor could we locate any written accounts of the earthquake from people living in Estes Park in November of 1882, despite an extensive search in local library collections and museums.

We did locate several landslides and sackungs in the epicentral area, which appear to have a higher spatial density than is normal in the Precambrian rocks of the northern Front Range. However, none of these slope failures appear to be historic, so even if they are related to strong earthquake shaking, it would be from prehistoric events.

Two of the faults studied have indirect evidence suggestive of, but not conclusive of, Quaternary fault movement. On the “Estes Park” fault (informal name used herein), the oldest set of Quaternary terraces in Dry Gulch are truncated at a downward step in the top of bedrock, very close to the mapped location of the fault. This truncation could also be explained by erosion, as could some anomalous deformation features in a small gully on the western side of Dry Gulch. The only way to rule out Quaternary faulting in any formal manner would be to trench one or both locations.

A large quarry into the Thompson Canyon fault near Glen Haven exposes the western boundary fault, and the overlying Quaternary colluvium has some peculiar relationships across the fault, both in the quarry and in the adjacent roadcut of County Road 43. Due to the reconnaissance nature of this study, neither exposure could be cleaned off well enough to confirm that the steep contacts in the colluvium were depositional rather than tectonic. We located at least two viable trench sites on the Thompson Canyon fault where early- to middle Pleistocene deposits overlay Precambrian bedrock, and would potentially record any fault movements in the Quaternary. These sites could be trenched if funding were made available.

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APPENDIX 1

Annual Project Summary
Seismic Sources and Neogene Faulting in the Northern Front Range, Colorado; Source Area of the 1882 (Mw 6.6) Earthquake: Collaborative Research with GEO HAZ Consulting, Inc.

Grant # 02HQGR0094

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Key Words: Neotectonics, Geologic Mapping/Tectonic Structures, Tectonic Geomorphology, Regional modeling

Investigations Undertaken

Preparatory to beginning the actual study, 1:40,000 photographic stereopairs of the northern Front Range were jointly acquired by the collaborative researchers and then scanned for digital use. ERDAS software was purchased by CGS that enables the collaborators to conduct stereoscopic photo analysis and digitally plot results as the work progresses. A 100- meter Digital Elevation Model (DEM) of the entire state was acquired from the USGS National Mapping Division. Using this data, CGS constructed a colored elevation model for tectonic geomorphic analysis in ERDAS (Figure 1). A LANDSAT Thematic Mapper image of the entire state was acquired from the Colorado Department of Transportation. This data provides a different viewing capability of the Front Range and can be draped over the DEM in ERDAS. Published faults in the Front Range from three different scale ranges (1:24,000-62,500; 1:100,000-125,000, and 125,000- 500,000) were digitized and compiled into four fault maps of the Front Range plotted on a DEM for publication (Figure 2).

To test the technique and tools, geomorphic features suggestive of faulting were identified in both central Colorado and the northern Front Range. These linear features had not been mapped by workers doing conventional mapping and were studied as test areas. The first test was conducted in central Colorado. This area was selected for several reasons: a.) it is a natural tie- in to the southern Front Range aspect of the study where previous workers mapped Neogene faults, b.) lineaments are more accessible by vehicle than the Front Range, c.) a variety of young deposits as well as the Precambrian basement are present, thus giving an idea of the age and nature of lineaments cutting different ages and types of rock, d.) Quaternary faulting has been documented on parallel faults, and e.) an earthquake swarm in 1986 was parallel to a major lineament that was not mapped as a fault.

The second test was conducted where a major, geomorphic lineament crosses the Continental Divide in the Indian Peaks Wilderness. As this is one of the more pronounced lineaments in the Front Range, it was important to determine if surface faulting was evident along it. Furthermore, published geologic maps do not show a fault in the critical area. Sackungen features were analyzed on Trail Ridge Road to determine if they could be confused with tectonic features. Prominent basement scarps in Fall River Canyon were identified and geo-referenced. Flood layers created in DEMs provided useful information on the identification of, and disruption of, erosion surfaces.

Results

Digitizing faults in the Front Range provided a basis for evaluating the completeness of fault mapping in the Front Range. The maps starkly illustrate the low level of knowledge of faulting in the literature (Figure 2). Some of the large-scale maps are crisscrossed with numerous faults whereas adjacent quads may show only three or four. The number of faults and their orientations on individual maps are clearly a function of how carefully individual mappers looked for evidences of faulting. These digital fault maps are being used as a layer to aid with the geomorphic analysis.

Field checking for evidence of faulting in the two test areas re-confirmed that the techniques considered for this study are quite viable. Geomorphic analysis pinpointed a number of areas to test for evidence of faulting. GPS locations of critical areas to be examined gave a very way to quickly locate key areas in the field and search for evidence of faulting.

In Central Colorado evidence of faulting along geomorphic linears was found in a variety of geologic conditions. Clear evidence of a significant fault between Tertiary volcanic strata and Precambrian crystalline rocks was found where the published 1:24,000 map (Olson, 1974) showed a depositional contact. Evidence of faulting was found where another 1:24,000 published map (Gaskill, et al, 1967) showed a suggestion of offset in Tertiary dikes, but no fault was mapped. Evidence of faulting was found in Tertiary volcanic strata where no offset was obvious on published maps and no faults were previously mapped. The field work also showed that other geomorphic linears in the area that had discontinuous faults mapped along them were probably part of one continuous fault.

The second test area was in the Arapahoe Pass area of the Indian Peaks Wilderness. Here one of the most prominent linears in the northern Front Range cuts across the Continental Divide with a N40W trend (Figure 1). Pearson and Johnson (1980) did not map a fault across the range at this point and mapped only a few minor faults with that trend. They emphasized a N65W trend in their focus on mineral resources. The field test revealed several important findings. First, where the linear cuts across the divide, a wide zone of brittle faulting with a strike of N40W exists. Second, the linear displaces both Proterozoic units and the Tertiary Caribou stock along its length. Third, the east-west ridge that forms Arapahoe Pass at the Continental Divide is controlled by brittle east-west faults both north and south of the pass. These faults are traceable for several kilometers and have prominent geomorphic expression. These east-west faults were also not mapped by Pearson and Johnson (1980).

These two tests demonstrated that the technique is quite effective for detecting and mapping Tertiary faults. They further demonstrate that the more prominent lineaments have greater offset and are probably the highest candidates for locating unmapped Quaternary faults.

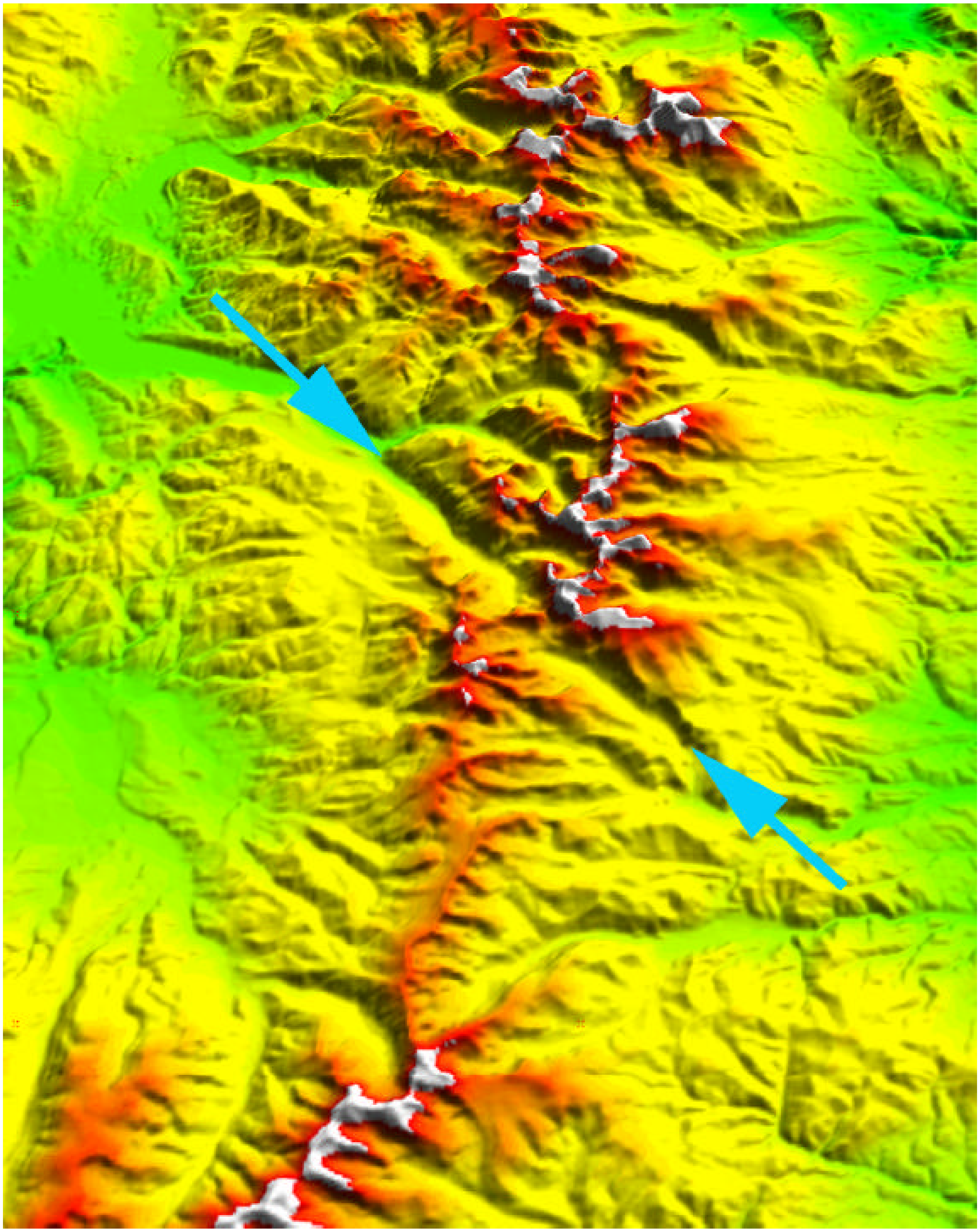

Figure 1: Oblique view of Digital Elevation Model (DEM) of the Indian Peaks part of the northern Front Range looking north. Blue arrows delineate northwest/southeast lineament crossing the crest of the range. Distance between arrows is 19 km. Note that the range crest north of the lineament is offset to the east from the range crest south of the lineament and that elevations along the crest are higher north of the lineament.

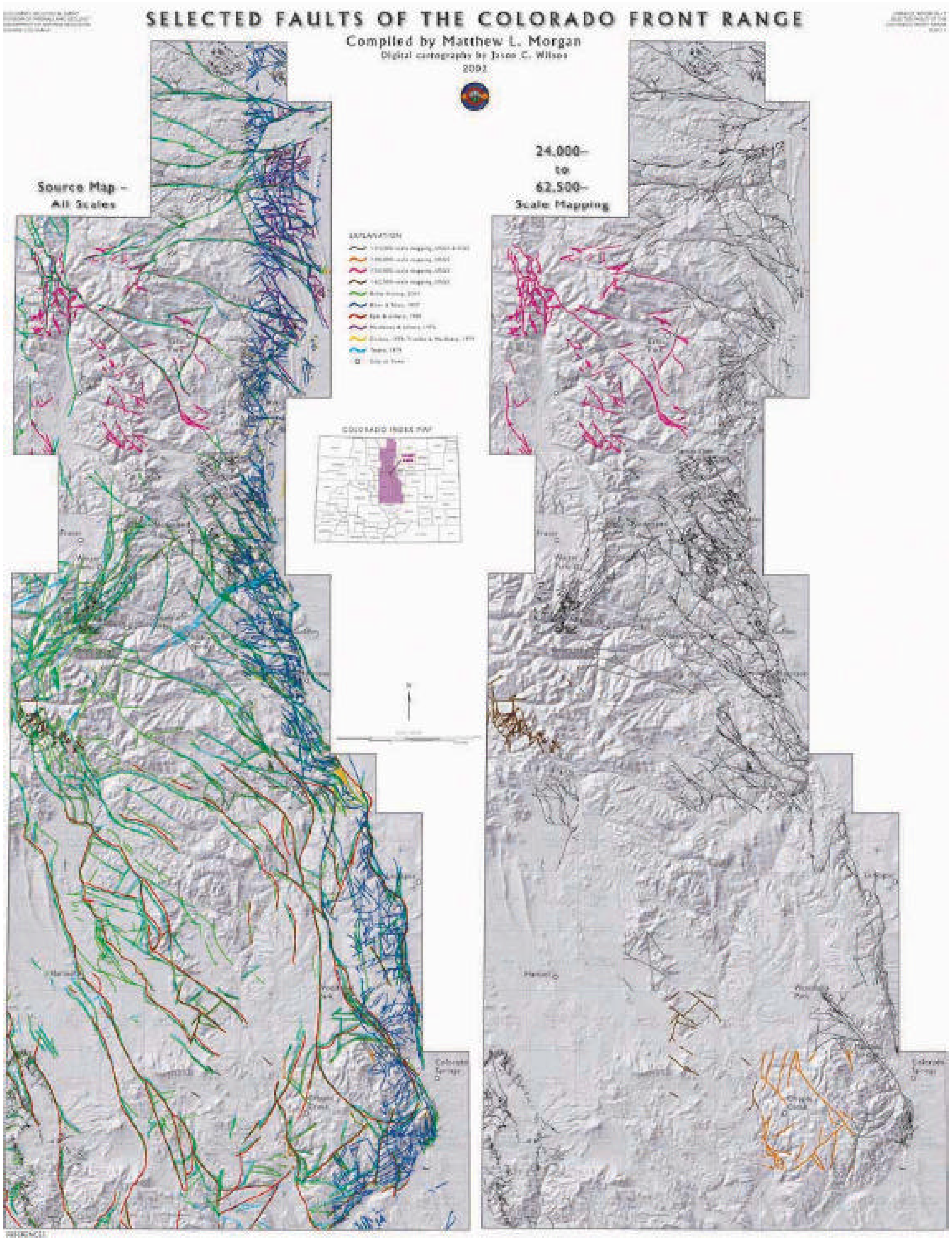

Figure 2: Example of two of four maps showing digitized faults in the Front Range. The other two maps display the faults from publications at smaller scales. These data will be made available to the public as hard copy and digital shape files.

Non-Technical Project Summary

Field tests conducted in central Colorado and the northern Front Range demonstrate that the use of geomorphology for detecting Tertiary faults is potent. These tests and a digital compilation map of published faults in the Front Range also demonstrate how incompletely many previous studies have depicted the faulting.

Reports Published

"Published faults of the Colorado Front Range" by Matthew L. Morgan is in final review before being released as a Colorado Geological Survey Open File Report. The maps and references will be in hard copy form on two 34' X 52" sheets. Shape files for the faults will be provided on CD-ROM.

Availability of Processed Data

The data for the published faults in the Front Range will soon be available in the publication described above from cgspubs@state.co.us or Melissa Ingrisano at 303-866-2611.

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