Neotectonic Setting of Colorado— A Transect From Denver to the Rio Grande Rift

Pre-Meeting Field Trip for the
Workshop on Paleoseismology, Active Tectonics, and Archaeoseismology
Focus Group on Paleoseismology and Active Tectonics
INQUA Terrestrial Processes Commission
30-May-2016

Pikes Peak (elevation 4303 m) in the Colorado Front Range, looking west from Garden of the Gods in Colorado Springs. Pikes Peak is composed of NepRoterozoic granite. Red rocks in foreground are arkosic conglomerates and sandstones of the Pennsylvanian Fountain Formation, tilted to vertical by uplift on the range-front reverse faults of latest Cretaceous to Paleocene age.

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Trip Sponsor:

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Education and Research in the Earth Sciences

Biographical Sketches of Trip Leaders:

Dr. James McCalpin has studied the rocks and dirt of Colorado since 1970, when he first went rock climbing in the Front Range and Sangre de Cristo. After obtaining a Bachelors in Geology from the University of Texas-Austin in 1972, he moved to Colorado and worked at the Colorado School of Mines Research Institute as a Senior Laboratory Technician. He was then lucky enough to enroll in the Geology Department of the University of Colorado-Boulder, where he received a Masters degree in “dirt geology” 1975 and joined the Friends of the Pleistocene. In 1976-77 he worked for U.S. Geological Survey in Menlo Park, California and Alaska, but then returned to Colorado in 1978 to attend the Colorado School of Mines, where he received his PhD in 1981. After a year as County Geologist of Jefferson County, Colorado, he taught geology at Utah State University from 1982-1991. But Colorado beckoned again, so he left academia and founded GEO-HAZ Consulting, Inc. in Estes Park to consult full-time on geologic hazards. In 2001 he moved to Crestone, Colorado and founded the Crestone Science Center, a nonprofit educational organization.

Dr. Vincent Matthews is known as “Mr. Geology” in Colorado. He is currently Principal of Leadville Geology LLC and recently was Interim Executive Director of the National Mining Hall of Fame and Museum in Leadville, Colorado. He retired as State Geologist and Director of the Colorado Geological Survey in 2013. Dr, Matthews received Bachelors and Masters degrees in geology from the University of Georgia and a PhD from the University of California-Santa Cruz, and holds Outstanding Alumnus Awards from both institutions. He has taught geology at five institutions of higher education. He was senior editor of the multiple-award winning publication, *Messages in Stone: Colorado’s Colorful Geology*, and the map *A Tourist Guide to Colorado Geology*. Dr, Matthews is a Senior Fellow of the Geological Society of America where he served as General Chair of the 125th Anniversary Meeting in 2015. He is the 2014 recipient of the Pioneer Award from the American Association of Petroleum Geologists. He lives in Leadville, the Two-Mile-High City.


COLORADO
Start
Denver
Crestone
End

PATA PRE-MEETING FIELD TRIP ITINERARY (Monday, May 30, 2016)

THE COLORADO PIEDMONT-GEOLOGY AND NEOTECTONICS OF THE FRONT RANGE, MORRISON TO KENOSHA PASS-SOUTH PARK-RIO GRANDE RIFT

The Pre-Meeting Field Trip (morning of Monday, May 30) travels from the hotel near the Denver International Airport to Crestone. The trip provides transport to Crestone for those Registrants who do not wish to rent a car in Denver or travel to Crestone by other means. The Field Trip bus will leave from the Best Western Plus-DIA hotel on Tower Road at 8 am. Estimated arrival time in Crestone is 1 pm. The Field Trip traverses four geologic terrains: the **Colorado Piedmont**, the **Front Range**, **South Park**, and the **Rio Grande Rift**.

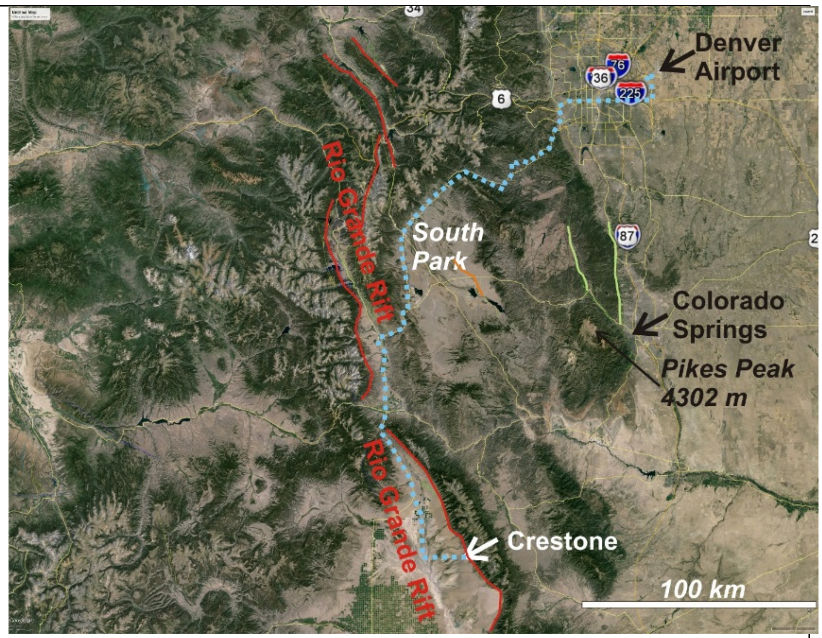


Fig. 1-1. Pre-Meeting Field Trip route (blue dotted line) starting at Denver Airport hotels. In the first 50 km we travel west across the Colorado Piedmont to the Front Range escarpment. Then we enter the Front Range (Proterozoic igneous and metamorphic rocks) and cross it (75 km) to South Park. South Park is a large alpine basin floored with Cenozoic, Mesozoic and Paleozoic rocks. We skirt the western edge of South Park for ~70 km, then turn west and cross into the Rio Grande rift.(20 km). Once in the rift we head south along the Arkansas River, up and over Poncha Pass, and into the San Luis Valley, a large compound graben. Crestone lies on the east rift margin fault (Sangre de Cristo fault).

The first segment travels west across metropolitan Denver which lies on the **Colorado Piedmont** geomorphic province, and the structural Denver Basin of late Cretaceous age. The Colorado Piedmont is home to 80% of Colorado's 5.4 million residents. To the west you will see the escarpment of the Front Range, which rises from elevations of 1600 m to 2500 m. Displacement on the frontal fault is as much as 4000 m. To the east, the Great Plains stretch 2000 km to the Mississippi River lowlands.

From the Piedmont we turn west into the **Colorado Front Range** on US Highway 285, crossing the upturned stratigraphic section at the western edge of the Denver Basin. The Front Range is a Proterozoic-cored basement uplift formed mainly in the late Cretaceous Laramide Orogeny of east-west compression. On our route we mainly travel on a 20-30 km-wide dissected Tertiary erosion surface cut on Proterozoic basement rocks, with the high peaks of the Front Range (>4000 m) occasionally visible to the west.

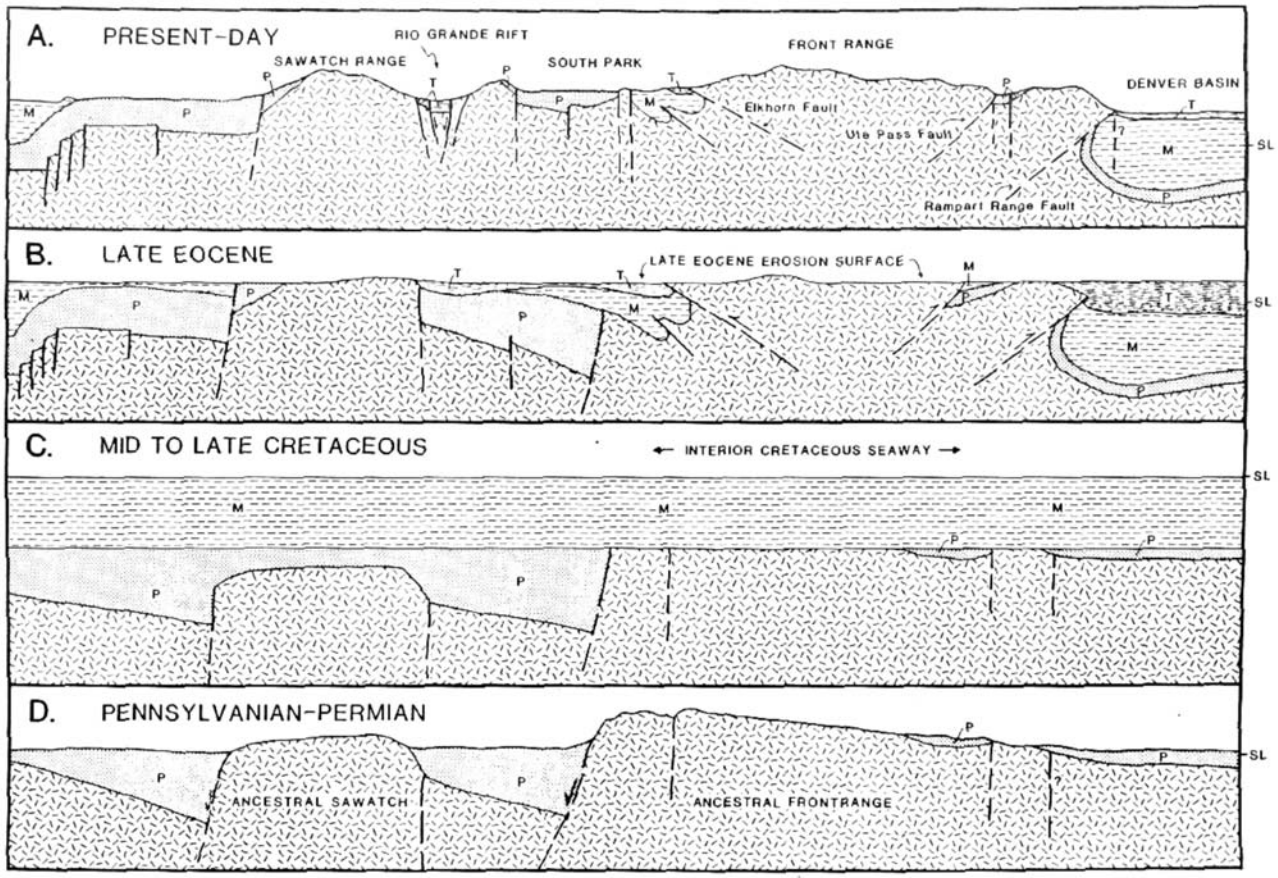


Fig. 1-2. Schematic east-west cross-sections through Central Colorado, from Rogers and Kirkham, 1986. From bottom (oldest) to top (youngest):
(D)- after the Ancestral Rockies Orogeny; block-faulted uplifts brought Proterozoic crystalline rocks to the surface; adjacent basins were filled with coarse-grained clastics (molasse; "P") up to 5000 m thick
(C)- after the erosion of the Ancestral Rockies and deposition of Mesozoic marine sediments ("M") from the Interior Cretaceous Seaway; the thickest unit (Pierre Shale) is 3000 m thick
(B)- after the late Cretaceous-to-Paleocene Laramide Orogeny, characterized by east-west compression and high-angle basement-cored reverse faults; the thick Mesozoic rocks are eroded off uplifted blocks, but are preserved in basins such as the Denver Basin (far right); eroded sediments accumulate as Tertiary clastics ("T") locally; by the late Eocene an extensive low-relief erosion surface ("peneplain") covers central Colorado, with an elevation of ca. 1000 m
(A)- regional Neogene upwarping raises central Colorado to elevations of 2500-4000 m, coincident with the development of the Rio Grande rift (26 Ma- to present); some older faults are reactivated in the Neogene stress regime of east-west extension

ROAD LOG (in miles)

Mile

0.0 DEPART 8 am from Best Western Plus-DIA hotel; drive N on Tower Road to Pena Boulevard, then W on Pena to junction with I-70

5.7 Turn R (W) onto I-70; drive for 10.3 mi to I-25

16.0 cross over I-25; continue W

30.0 junction with C-470; continue W

31.0 pass by the famous I-70 roadcut through the Dakota Hogback (am official "Point of Geological Interest"); exit directly west of roadcut, go beneath I-70 and around; get back on I-70 eastbound

32.0 exit to C-470 and proceed S along the mountain front

37.5 exit to US 285 (west); sign says to Fairplay; cross through the Dakota Hogback again and into the Proterozoic crystalline rocks of the Front Range

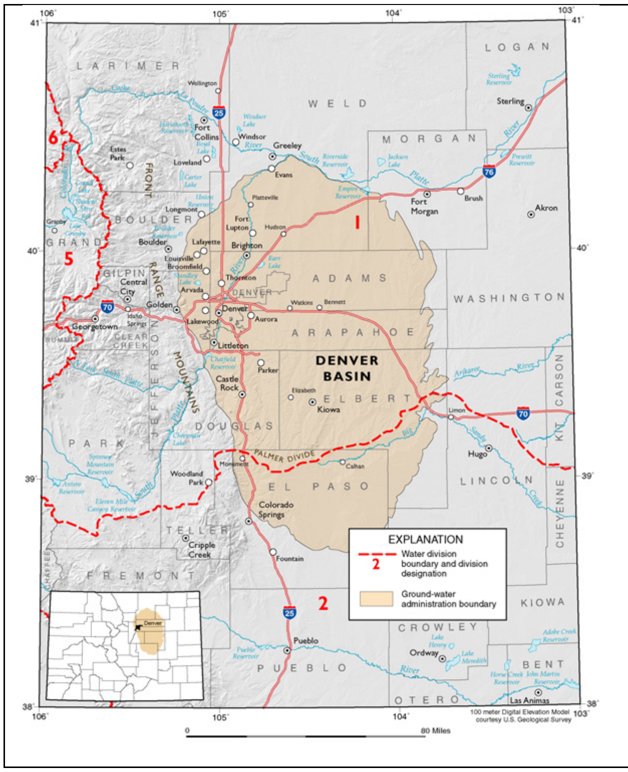
1-THE DENVER BASIN and the COLORADO PIEDMONT

Leaving the Denver Airport hotel complex, we travel west across Denver to the escarpment of the Front Range (Fig. 1-3).

Fig. 1-3. Route of first part of field trip (white dotted line) across Denver. Google Earth view looking WSW. White dash-dot line with arrow is the South Platte River, which flows northeast through Denver.

THE DENVER BASIN—STRUCTURE and STRATIGRAPHY

Denver is underlain by a late Mesozoic basin (the Denver Basin) that contains as much as 4 km of Paleozoic through early Tertiary sedimentary rocks. The Basin is separated from the Proterozoic-cored Front Range by the Golden fault, a high-angle reverse fault with up to 4 km of vertical displacement. Fault-related folding has tilted beds of the Denver Basin steeply on its western edge, with the more resistant formations (Dakota Sandstone, Cretaceous; Fountain Arkose, Pennsylvanian) creating a series of linear strike ridges along the range front (Fig. 1-4). These are locally known as "hogback" ridges.



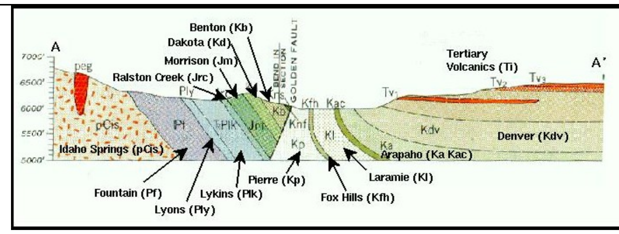


Fig. 1-4. LEFT: Map of the Denver Basin. RIGHT, TOP; schematic cross section across western margin of basin. RIGHT, BOTTOM; aerial photograph of the Dakota Hogback (center) and upturned beds at the western margin of the basin.

Before we turn south from I-70 onto C-470, we will drive through the spectacular roadcut of the Dakota Hogback (Fig. 1-5).

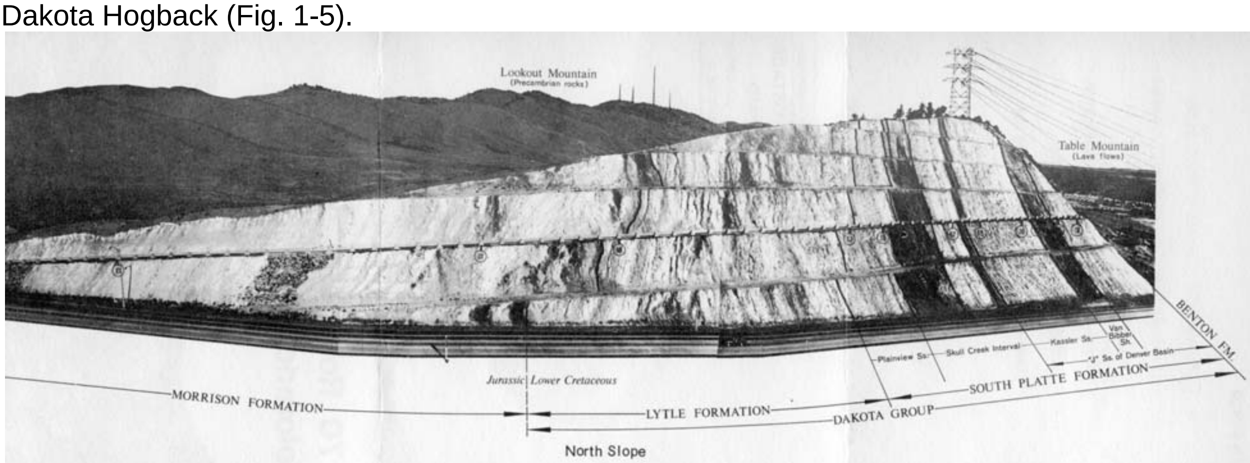


Fig. 1-5. Strata of the Morrison (Jurassic, at left) and Dakota (Cretaceous, at right) formations exposed in the I-70 roadcut. From LeRoy.

Interestingly, the surface trace of the Golden fault is difficult to find in many places along the range front. This is partly due to the presence of the thick (up to 3 km) Pierre Shale (Cretaceous) at the basin edge (Fig. 1-6). The Pierre Shale is a dark gray to black marine shale, massive to fissile, and not well consolidated. As a rock mass its deformation appears to have been more ductile than brittle.

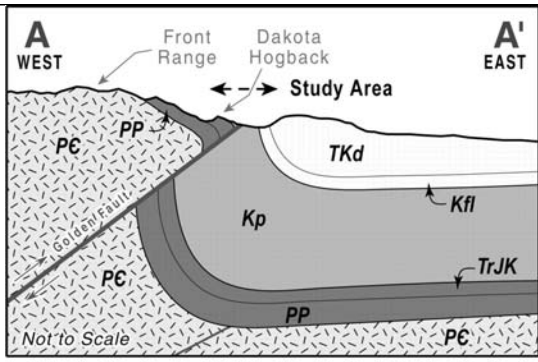


Fig. 1-6a. TOP: In some places the Golden Fault juxtaposes hard sandstones and limestones of the lowermost Cretaceous sequence against the massive, soft Pierre Shale (Fig. 1-6, TOP), so the fault trace is easy to locate.

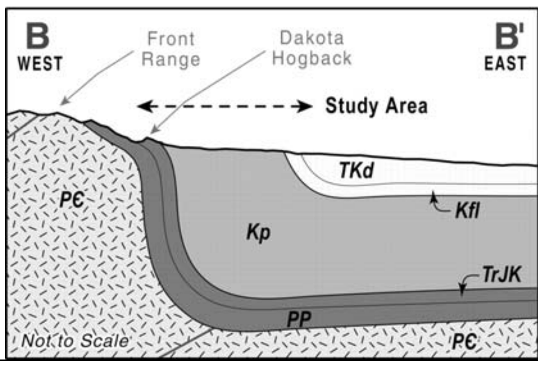


Fig. 1-6b, BOTTOM: In other places the fault juxtaposes Pierre Shale against itself at the surface, such that the fault is difficult to locate. Most of the Pierre Shale is covered with a thin layer of Quaternary deposits, which adds to the concealment of the structure. It is even possible that the fault does not daylight in many places. In such locations the range-front structure has been interpreted as a steep monocline.

NEOTECTONICS OF THE FRONT RANGE ESCARPMENT

Two projects in the 1980s attempted to assess whether range-front (Laramide) faults such as the Golden and Rampart Range faults had been active in the late Quaternary, and whether they posed any seismic risk. The first project was the Seismic Hazard Assessment of the Rocky Flats nuclear weapons facility, located near the range front between Golden and Boulder. The second project was the proposed Two Forks Dam on the South Platte River, southwest of Denver. In the absence of historic seismicity associated with this fault, the expected style of neotectonic fault slip was not known. Theoretically it could be assumed to be reverse slip (if the weak E-W compressional stress field of the craton dominated), or normal slip (if the weak E-W extensional stress field of the Rio Grande rift dominated).

Neither study was able to locate any unambiguous fault scarps on Quaternary geomorphic surfaces, either east-facing (reverse slip) or west-facing (normal slip). However, there was one fortuitous quarry exposure just north of Golden where mid-Quaternary alluvium was displaced by faults (Fig.1-7) The graben displaced Cretaceous bedrock and overlying alluvium nearly to the ground surface, but there was negligible net vertical displacement across the graben. This exposure, which has subsequently been destroyed by a housing development, was controversial and was therefore trenched by the Colorado Geological Survey. It was not located on the mapped trace of the Golden fault, but lay 210 m east of the trace. The displacement style was clearly not reverse faulting, but neither was it normal faulting. Instead, it was a series of near-vertical bedding plane faults that created a structure graben-like structure. While the marginal faults of the downdropped block are subvertical and parallel, most of the internal faults have an apparent reverse sense of motion, with overhanging dips increasing as the deepest part of the graben is approached. This structural pattern does not resemble that of trenched active reverse faults worldwide (e.g., McCalpin et al., 2009). However, the pattern is similar to that exposed in trenches across karst sinkholes (Gutierrez et al., 2009), where originally-vertical faults in the center of the sinkhole tend to topple toward the center with progressive subsidence, giving the deceptive appearance that they are reverse faults, when in fact they are toppled vertical or normal faults.

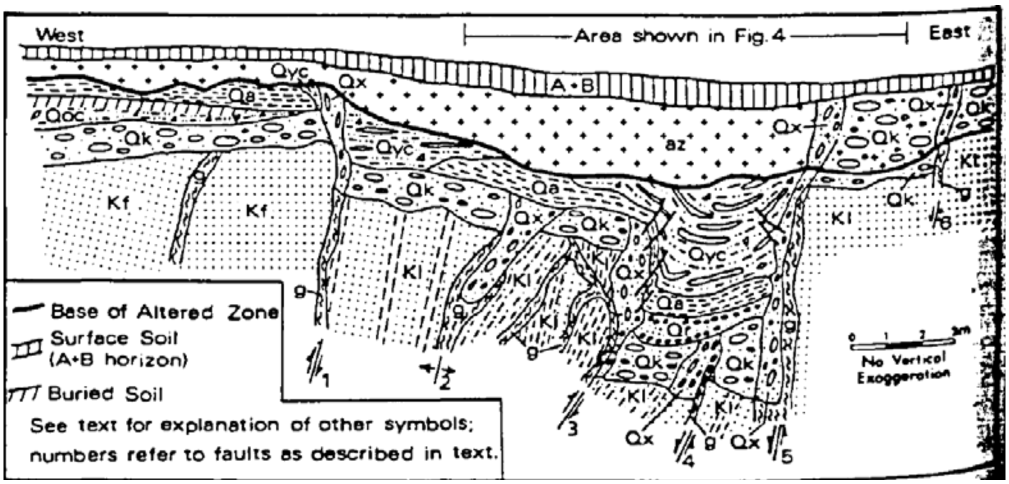


Fig. 1-7. Schematic cross-section through the fault exposure north of Golden, CO. From Kirkham, 1977.

At a second location just north of Colorado Springs (US Air Force Academy), a swarm of west-facing scarps displaced mid-Quaternary pediment surfaces. Several trenches were excavated, including the 500 m-long trench AF-1. Numerous normal faults were exposed in this trench (Fig. 1-8). Bedding of the (from east to west; Dakota (?) sandstone, Graneros Shale, and Pierre Shale) dipped west at 45°-60°, indicating that the section was overturned. Such footwall overturning is common along many parts of the basin margin. All exposed faults were bedding-plane normal faults, all dipping west and downthrown to the west. Dickson (1986a) interpreted these faults as evidence for extensional reactivation of the Rampart Range fault during the mid-late Quaternary

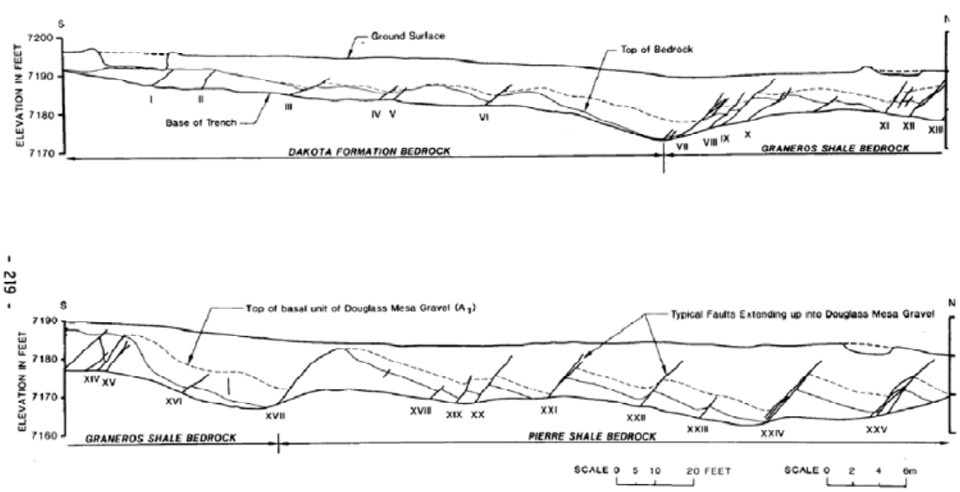


Fig. 1-8. Generalized log of trench AF-1 at the Air Force Academy. From Dickson, 1986.

A recent unpublished consulting study for a proposed dam SW of Denver exposed similar Quaternary extensional deformation near the Laramide basin-margin fault. In trenches no more than 10 m apart, there were extensional (normal) faults on a pediment surface to the west, but folds and reverse faults beneath a steeper, eroded slope to the east, which descended steeply to a small drainage (Fig. 1-9). As at the Air Force Academy, the bedrock exposed was west-dipping Pierre Shale on the overturned limb of the basin-margin monocline.

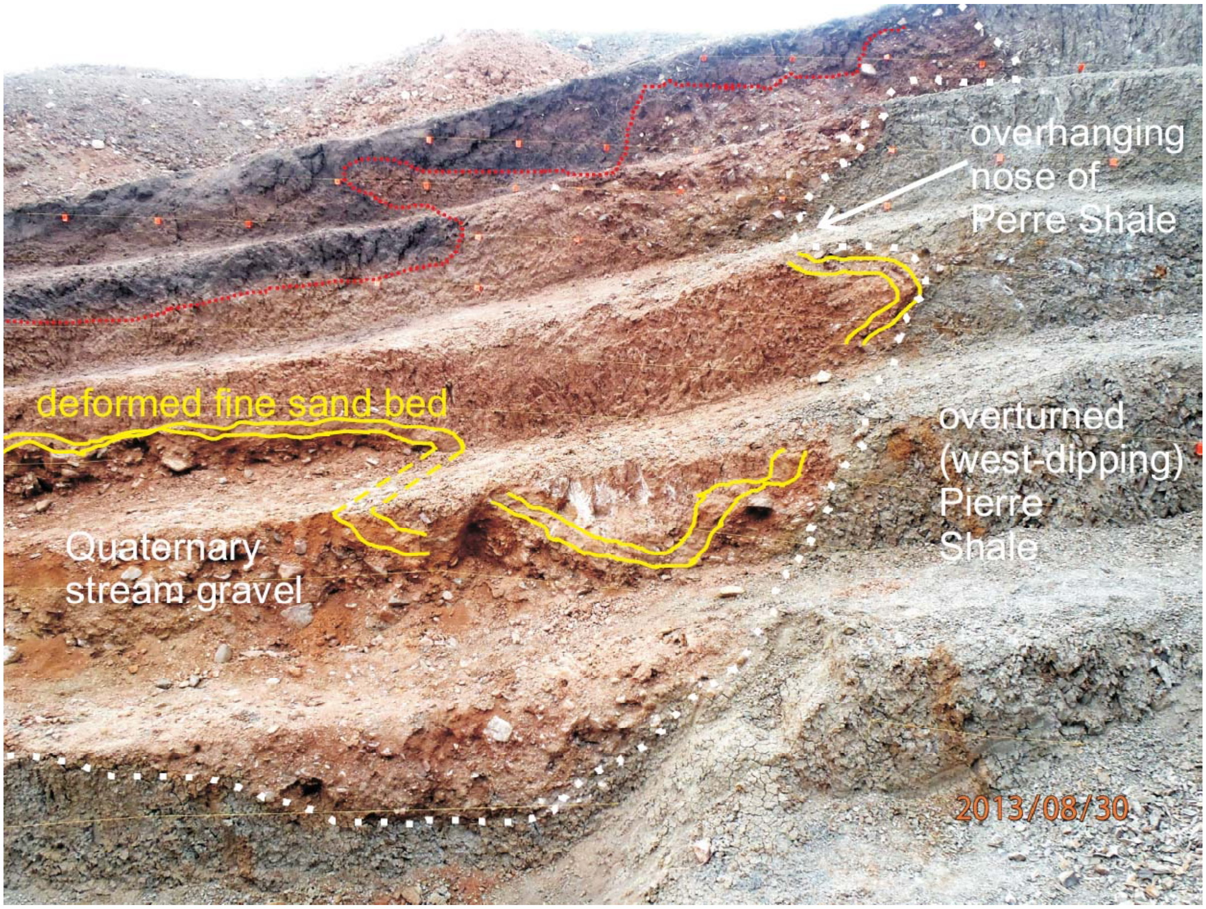
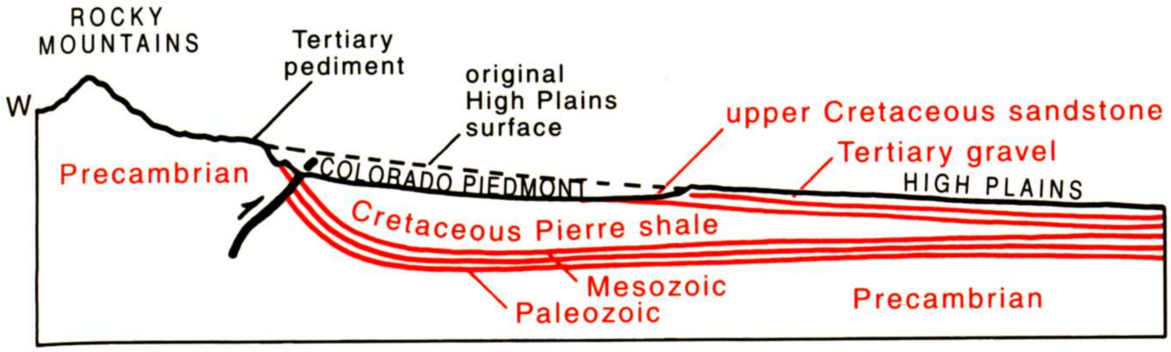


Fig. 1-9. A benched trench ca. 6 m deep SW of Denver showing plastically-deformed Pierre Shale underlying a steep erosional slope. My interpretation of the trenches here was that the Pierre Shale was sliding and extruding eastward downslope due to erosional oversteepening of this slope, inducing localized tensional faults farther west on the lip of the pediment surface.

MY CONCLUSIONS: I interpret the Quaternary“ faulting” observed at these three sites due to downslope landsliding and horizontal “extrusion” of the ductile Pierre Shale. The mode of extensional deformation observed at all three sites can be explained by almost pure east-west extension, rather than by normal neotectonic faulting, which should have a vertical component of slip. For example, the fault swarm at the Air Force Academy looks like a classic example of “bookshelf faulting”, where a series of fault-bounded blocks extent horizontally by rotating, like a group of books falling over on a bookshelf. This is easily explained by the Pierre Shale extruding laterally toward the steep erosional margins of the pediments. Admittedly this deformation occurred in the mid-late Quaternary, but I think it is gravitational (non-tectonic), rather than tectonic.

THE COLORADO PIEDMONT-- GEOMORPHOLOGY

The Colorado Piedmont is actually a broad lowland eroded down below the original level of the High Plains, as projected westward (Fig. 1-10).The conventional explanation for the regional geomorphology is that late Tertiary gravels had built up the High Plains as a continuous surface eastward from the Colorado front range, carrying away the detritus from the eroding late Cretaceous mountains of the Laramide Orogeny. Subsequently, streams near the range front had eroded through the Tertiary gravels and exposed the very soft Cretaceous Pierre Shale, at which point vertical erosion increased significantly.



Diagrammatic section across the High Plains and Colorado Piedmont.

Fig. 1-10. Schematic diagram of the Colorado Piedmont, erosionally inset below the High Plains. From Chronic, 2002.

This geomorphology is the opposite to that expected if the Front Range was being actively uplifted along its marginal reverse faults (Golden fault; Rampart range fault). In that case, the footwall would be a site of falling base level, filling up with thick Quaternary sediments eroded from the hanging wall, as is observed on active reverse faults worldwide. The fact that the downthrown side of the faults is a site of erosion, rather than deposition, suggests that there has been no significant fault movement on the range-front since the deposition of the tertiary High Plains gravel. Interestingly, recent data suggest that the Denver Basin may have tilted northward during the late Cenozoic. An intensely studied (>3,000 current indicators), major stream complex was flowing southeast during the late Eocene. Yet those same strata are presently 240 m higher than the same strata 63 km to the northwest (Keller and Morgan, 2013, 2016).

The Quaternary alluvial deposits form floodplains and flights of terraces, both along the mainstem of the South Platte River, and the numerous tributaries that flow out of the Front Range to eventually join the South Platte River (Fig. 1-11). The upper three surfaces are pediments (relatively thin gravels over bedrock), whereas the lower terraces are dominantly fill terraces (Louviers terrace, MIS 6; Broadway terrace, MIS 2). These pediments and terraces are quite well preserved along the range front, a testament to the erosive power of Quaternary streams from the Front Range. The streams, swollen with glacial meltwater and carrying hard crystalline clasts, had an easy time eroding the soft Cretaceous rocks such as the Pierre Shale (Fig. 1-12). The streams apparently even planed off harder strata such as the Dakota Sandstone.

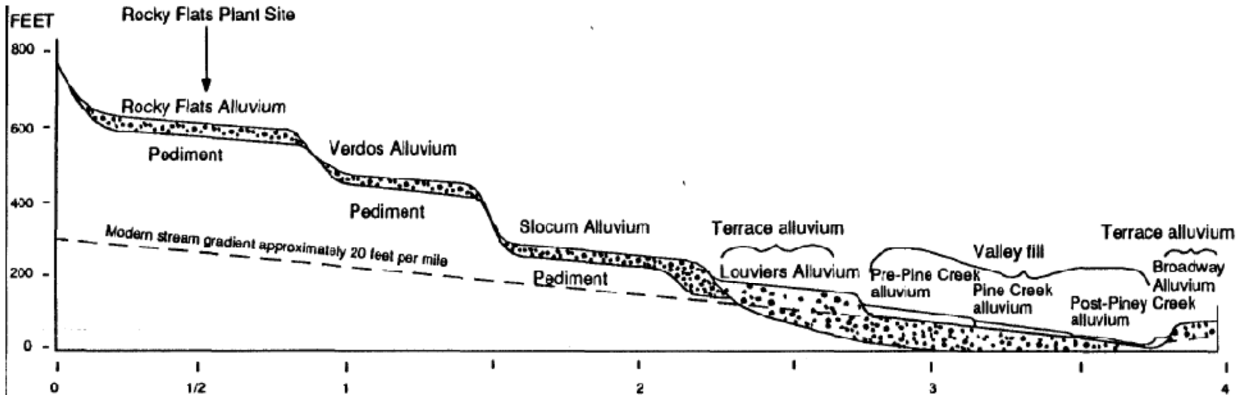


Fig. 1-11. Schematic cross-section of the Quaternary alluvial surfaces found in the Colorado Piedmont.

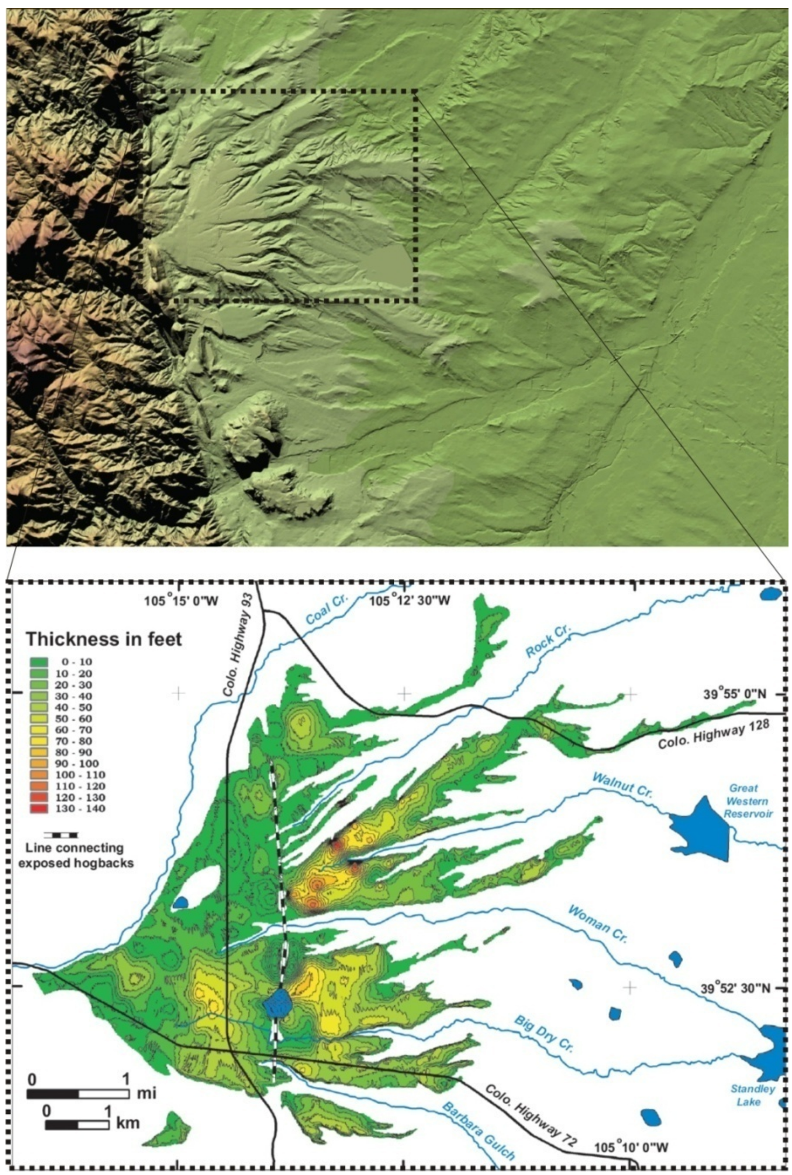


Fig. 1-12. TOP, DEM of the Rocky Flats pediment (in dotted box) between Golden and Boulder; BOTTOM, isopach map of gravel thickness on the Rocky Flats pediment. From Lindsey et al., 2005, USGS PP 1705.

In theory, these surfaces would act as “strain gages” to preserve the evidence of any neotectonic faulting or folding. However, no unambiguous fault scarps have been discovered. In the early 1990s there was a 150 m-long, 7-8 m deep “paleoseismic” trench excavated at the Rocky Flats nuclear plant, looking for the cause of anomalous elevation changes in the alluvium/ bedrock contact. When bedrock was exposed in the bottom of the trench, however, there were no faults in either the bedrock or the alluvium. The elevation changes were caused by harder beds in the Pierre Shale resisting erosion during pediment formation, such that there was a buried “strike ridge” in the bedrock surface beneath the pediment gravels (Fig. 1-12, bottom)

Another recent development has been cosmogenic surface-exposure dating of the pediments. Prior to this dating, the Rocky Flats pediment was assumed to be about 1 Ma, because it was higher (older) than the Verdos pediment (Fig. 1-11), which contained the 740 ka Pearlette Ash. However, cosmogenic dating revealed that a single continuous pediment surface does not yield the same exposure age (Fig. 1-13). Instead, the pediment dates oldest at its downslope fringes, where the surface was first abandoned by erosional incision, and youngest near the head of the pediment, where incision is minimal and deposition has occurred until relatively recently (mid-Pleistocene). This complication would have made dating fault scarps on the surfaces problematic, since the age of the surface varies.

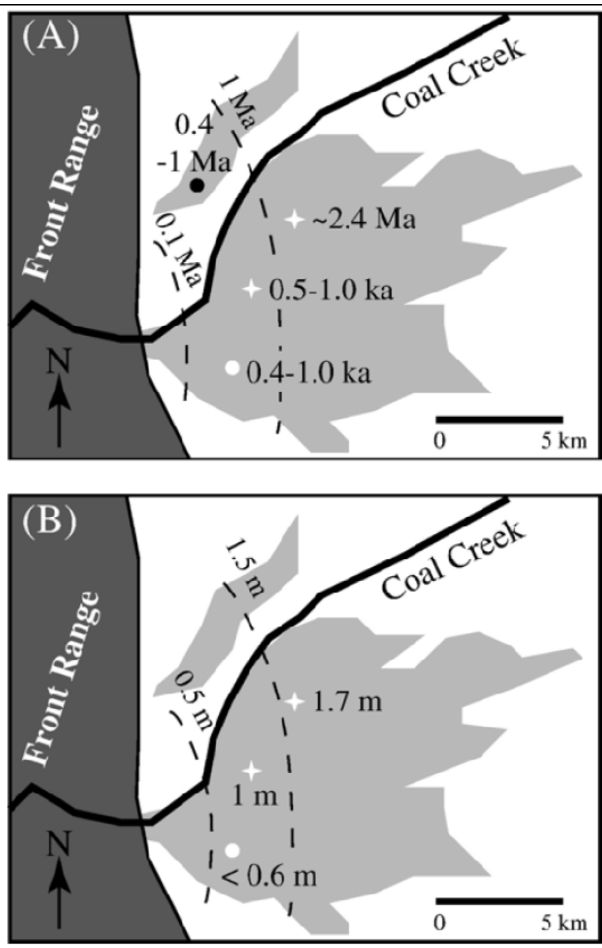


Fig. 1-13. (A) Cosmogenic ^{10}Be and ^{26}Al-based surface exposure ages of various parts of the Rocky Flats pediment. Variable ages may be explained by differential incision of tributaries in response to an eroding trunk stream. The profiles of streams draining the Front Range and Denver basin are transiently adjusting to the South Platte River that began incising into the eastern portion of the RF surface ~1–2Ma. Upstream propagation of incision waves causes diachronous abandonment of pediments near the mountain front, suggesting that no single age is appropriate for these extensive surfaces. Modeling of TCN depth profiles suggests that individual sites have complex depositional histories likely involving multiple depositional and stripping events. Because the time of abandonment of a given surface is determined by the power of its associated stream, surfaces at the same elevation above two different streams should not necessarily have the same age.
(B) thicknesses of recently stripped sediment on the Rocky Flats surface. Dashed contour lines show increasing sedimentary thicknesses away from the mountain front.

From Riihimaki et al., 2006

2-THE FRONT RANGE

Proceed east on I-70 from the I-70 roadcut to the C-470 exit. C-470 parallels the Front Range escarpment and, 0.6 miles south of I-70, crosses the Golden Fault, a high-angle reverse fault that accommodated Laramide uplift of the Front Range at ca. 70 Ma.

Exit C-470 west onto US 285. US 285 immediately cuts through the Dakota hogback, which affords excellent exposures, from east to west: Dakota Group (Cretaceous; yellowish-gray sandstone, dark gray shale, and conglomerate at base; near-shore and coastal deposits of the Cretaceous seaway) and Morrison Formation (Upper Jurassic; red and green siltstone and claystone, some beds of brown sandstone and gray limestone, fluvial and lacustrine, and host to uranium mineralization throughout the Colorado Plateau). The type section for the Morrison Formation is near Morrison, Colorado, which is famous for abundant dinosaur vertebrate fossils.

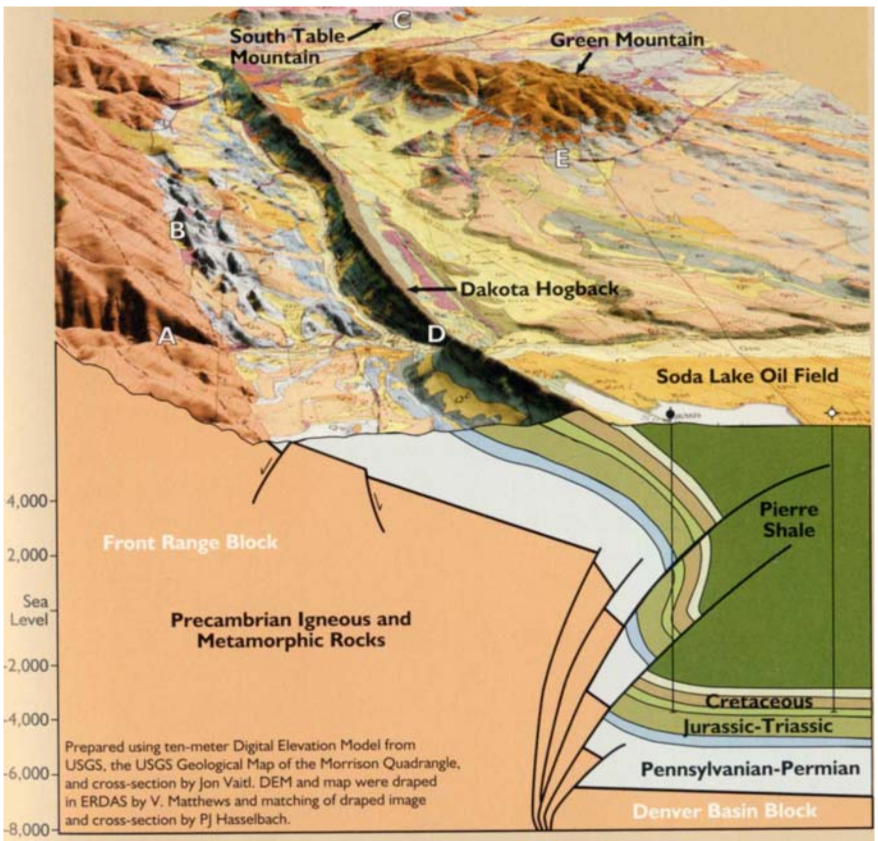


Fig. 2-1. Schematic block diagram of the Golden Fault near the mouth of Turkey Creek Canyon (US Highway 285), near our field trip route.

At 1.33 miles west on US 285 the road crosses red beds of the Fountain Formation (Middle Pennsylvanian to Lower Permian, representing alluvial deposits shed from the Ancestral Rocky Mountains). The Fountain Formation unconformably overlies high-grade, crystalline, Paleo-Proterozoic, meta-sedimentary and meta-igneous rocks exposed 1.73 miles from the C-470 intersection. This contrats with the Proterozoic/Pennsylvanian contact along I-70 to the north, which is a fault contact. The trip route follows US 285 southwest and primarily traverses Paleo- and Meso-Proterozoic, metamorphic and igneous bedrock.

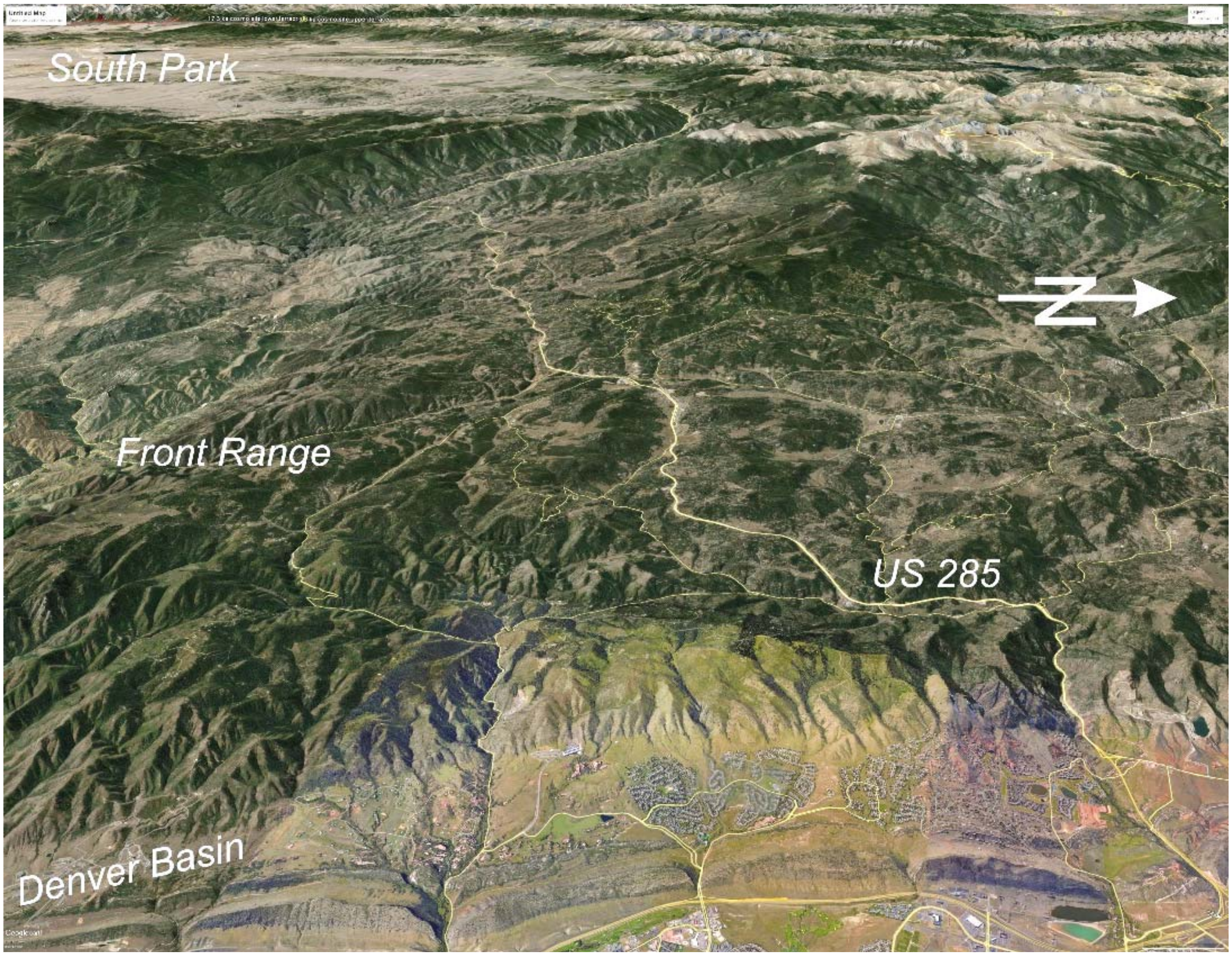


Fig. 2-2. Google Earth image of our route from the Denver Basin to South Park via US 285; view is to the SW. The high peaks of the Front Range lie at upper right. The dominant structural grain of the Front Range is defined by NW-trending faults. These faults cross US 285 at nearly a right angle, expressed as canyons excavated along these old shear zones.

Road log from Kirkham, 1981- mileage starts at the mouth of Turkey Creek Canyon.

0.0 Enter Turkey Creek Canyon. Proterozoic-Paleozoic contact on right.
2.4 Leave Turkey Creek canyon.
3.9 Road cut in the Floyd Hill fault zone. Note slope stability problems caused by the broken and crushed rock.
4.0 Cross North Turkey Creek.
4.3 Enter the Floyd Hill fault zone. Highway generally follows the fault for the next 1.5 miles. The Floyd Hill fault vertically offsets the late Eocene surface about 600 m.
6.2 Cross yet another unnamed northwest-trending fault.
11.1 Enter Aspen Park.
12.0 Evergreen turn-off. Kennedy Gulch fault crosses highway and continues northwestward up the valley to the right. For the next 0.6 miles the highway crosses this wide shear zone. Several exposures of this fault can be seen in road cuts in this area.

13.0 Leaving the Kennedy Gulch fault zone. The Kennedy Gulch fault offsets the late Eocene surface about 300 m.
13.9 Excellent exposures of Silver Plume Granite on right.
14.1 Conifer post office.
16.2 Valleys to left and right mark a fault zone with left-slip.
16.6 Crossing a northeast-trending fault. The valley to the left follows this fault to the Conifer post office and separates Silver Plume Granite on the right from gneisses on the left.
17.0 Cross Elk Creek at Shaffers Crossing
17.3 Crossing another northwest-trending fault. This one shows left-lateral displacement. Note shear zones in road cuts on the right.
19.1 Enter Pine Junction. Crossing the Pine Gulch fault zone. About 0.5 miles to the northwest, the Pine Gulch fault is covered by the Tertiary gravel exposed in the last road cut. The gravels are not offset.
19.4 Upper Tertiary stream gravels in road cut on right. Note the size of the larger clasts.
20.5 Crossing another northwest-trending fault zone with right-slip.
22.6 Crossing a broad northwest-trending fault zone that follows Deer Creek valley. Offset of the contact between Pikes Peak Granite of the Rosalie lobe and Proterozoic gneiss indicate a thousand meters of right-slip.
23.6 Crest of Crow Hill. Now we are on the late Eocene surface
25.6 Highway turns south to descend Crow Hill.
25.9 Entering Bailey; for the next 17 miles the highway lies in a valley following the NW-trending Shawnee fault zone. For most of this length the highway lies in an inner valley incised ~100 m below an older (pre-Quaternary) abandoned valley floor. This valley floor lies higher than the mid-late Quaternary terraces related to glaciations (10-30 m above modern stream level), but much lower than the late Eocene erosion surface.

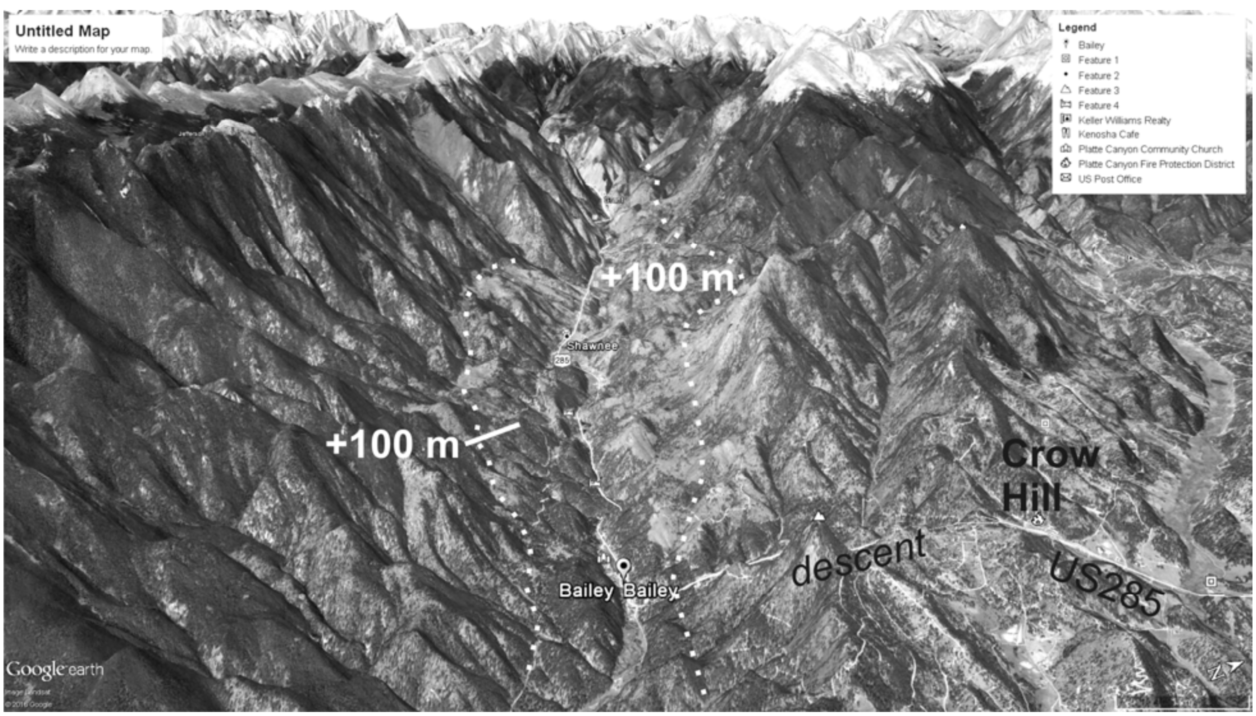


Fig. 2-3. Google Earth image looking WNW up US285 between Bailey and Grants, annotated to show the floor of the abandoned valley of early Pleistocene or late Tertiary age.

30.5 Entering Shawnee

37.1 Entering Grant; County Road 62 to right (N) leads to Guanella Pass and eventually to the Clear Creek valley and the town of Georgetown

37.4 Spoil from the excavation of the Harold D. Roberts Tunnel at left across river

37.9 East Portal of the Harold D. Roberts Tunnel. This 37 km-long tunnel extends northwest from this point, beneath the Continental Divide, ending at Dillon Reservoir in the Blue River Valley. Completed in 1962, the tunnel was the 2nd large trans-mountain water diversion tunnel, bringing Western Slope surface water to the thirsty cities of the Front Range, which lie in the rain shadow of the Rocky Mountains. On its northwestern end the tunnel was driven for several km below a low angle, west-verging thrust fault that bounds the western side of the Front Range. This is an unusual and highly important data point for understanding Laramide tectonics.

40.4 Highway leaves the fault-controlled, low-gradient river valley and begins ascending a steep tributary to the SW, toward Kenosha Pass

44.8 Summit of Kenosha Pass, elevation 3048 m. This is one of Colorado's lowest passes, ranking 41st (there are 40 higher passes). As the road descends you get your first glimpse of South Park.

STRUCTURE AND NEOGENE DEVELOPMENT OF THE FRONT RANGE (From Dickson, 1986)

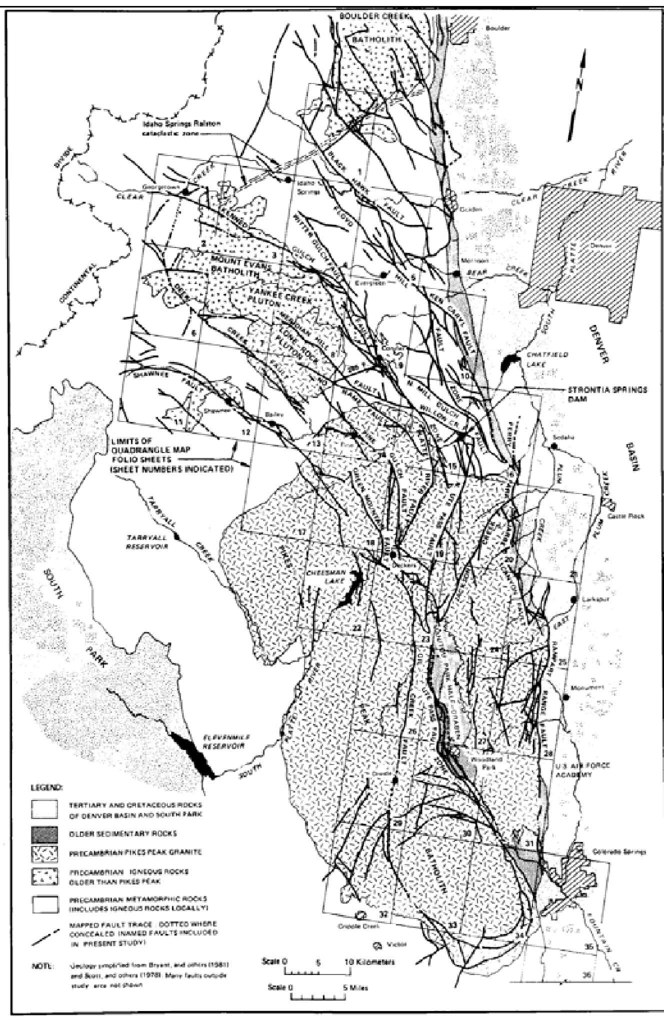


Fig. 2-4. Sketch map of the major named bedrock faults in the Front Range SW of Denver. This map, from Dickson, 1986b, was made for the seismic hazard studies related to the proposed Two Forks Dam in the early-middle 1980s.

<u>*The Tertiary Period*</u>

Active geomorphic development of the region began in late Cretaceous time, about 67 m.y. ago, with Laramide uplift, erosion of the Rockies and deposition in the Denver Basin. Erosion continued through the Eocene, but uplift appears to have nearly ceased early in that period. Prolonged stability through Oligocene time, about 25 m.y. ago, led to the development of the late Eocene erosion surface (Epis and Chapin, 1975), remnants of which can be recognized in many parts of the Front Range, even where subsequently modified by erosion or disrupted by faulting (Scott, 1975). Displacement of the erosion surface, and of associated Oligocene rock units, often is cited as evidence of Neogene fault activity in the study area (e.g. Kirkham and Rogers, 1981).

Greatly accelerated uplift in Pliocene time resulted in erosion of the deep canyons that presently characterize the mountain flanks (Scott, 1975).

THE LATE EOCENE EROSION SURFACE (from Scott et al., 1986)
Development of the modern southern Rocky Mountains began in Late Cretaceous time about 67 Ma. Gradual uplift resulted In erosion of the sedimentary rocks that covered the Proterozoic Basement, and the eroded materials were deposited in adjoining basins during latest Cretaceous and Paleocene time….Continuing early Tertiary erosion gradually uncovered large parts of the much older surfaces on which the Paleozoic and Mesozoic rocks had been deposited…. However, Tertiary erosion generally destroyed the erosion surface and cut Into the Proterozoic rocks below. Some of these exhumed surfaces, such as in the Cripple Creek area, became part of the late Eocene erosion surface, and Oligocene deposits locally covered the surface.

Continued Eocene erosion, during a time of tectonic stability and relatively constant base level, produced a well-formed, widespread montane pediment, the only widespread Cenozoic surface of low relief in the mountains.. …Where the truncated rocks were easily eroded, the surface became broad and flat, such as that represented by the even crestline of the Rampart Range; there, thick grus, a weathering product of Pikes Peak Granite, was easily carved by the ancient streams. On layered rocks of variable resistance to weathering, such as the metamorphic rocks of the Front Range, early Tertiary erosion carved broad channels bordered by resistant ridges or monadnocks as high as several hundred meters..

The Eocene erosion surface is still preserved beneath Oligocene and Miocene volcanic and sedimentary rocks in the Thirtynine Mile, San Juan, and West Elk volcanic fields. In this map area, the oldest rock overlying the Eocene erosion surface is the Wall Mountain Tuff of early Oligocene age (35 Ma) …**Less than 10 percent of the inferred original extent of the Eocene buried erosion surface Is preserved in the Pueblo, Denver, and Greeley quadrangles. Close 90 percent of the surface has been modified or destroyed. It is least modified where it has been protected from erosion on the upstream side of mountain blocks that were faulted up in Oligocene and Neogene time.**

Starting about 28 Ma the late Eocene erosion surface and overlying Oligocene deposits were severely disturbed by block faulting, and some major paleovalleys were segmented. **Up-faulted mountain blocks and intervening grabens have as much as 6,000 m of relative offset.** From late Oligocene tlme on, drainage emptying into these grabens deposited the thick basin fills that characterize the Oligocene and Miocene deposits of the San Luis Valley, Upper Arkansas VaIIey, Wet Mountain Valley, South Park, Middle Park, and North Park.
The Miocelle paleovalleys range in depth below the Eocene surface from about 60 m in the Divide paleovalley to 240 m in the Clear Creek paleovalley; other paleovalleys probably were cut to similar depths.

Uplift apparently accelerated in Pliocene time, and the resulting erosion deepened the canyons to 135 to 170 m below the bottoms of their Miocene channels; the larger streams cut deeper and longer canyons. Some canyons were cut downward from the late Eocene surface, whereas others were deepened from Miocene Channels. The positions of many canyons were inherited from courses established as early as Paleocene or Eocene time, but others were newly created during the Pliocene. Faults control some reaches, but most canyon locations seem to have been established by superposition.

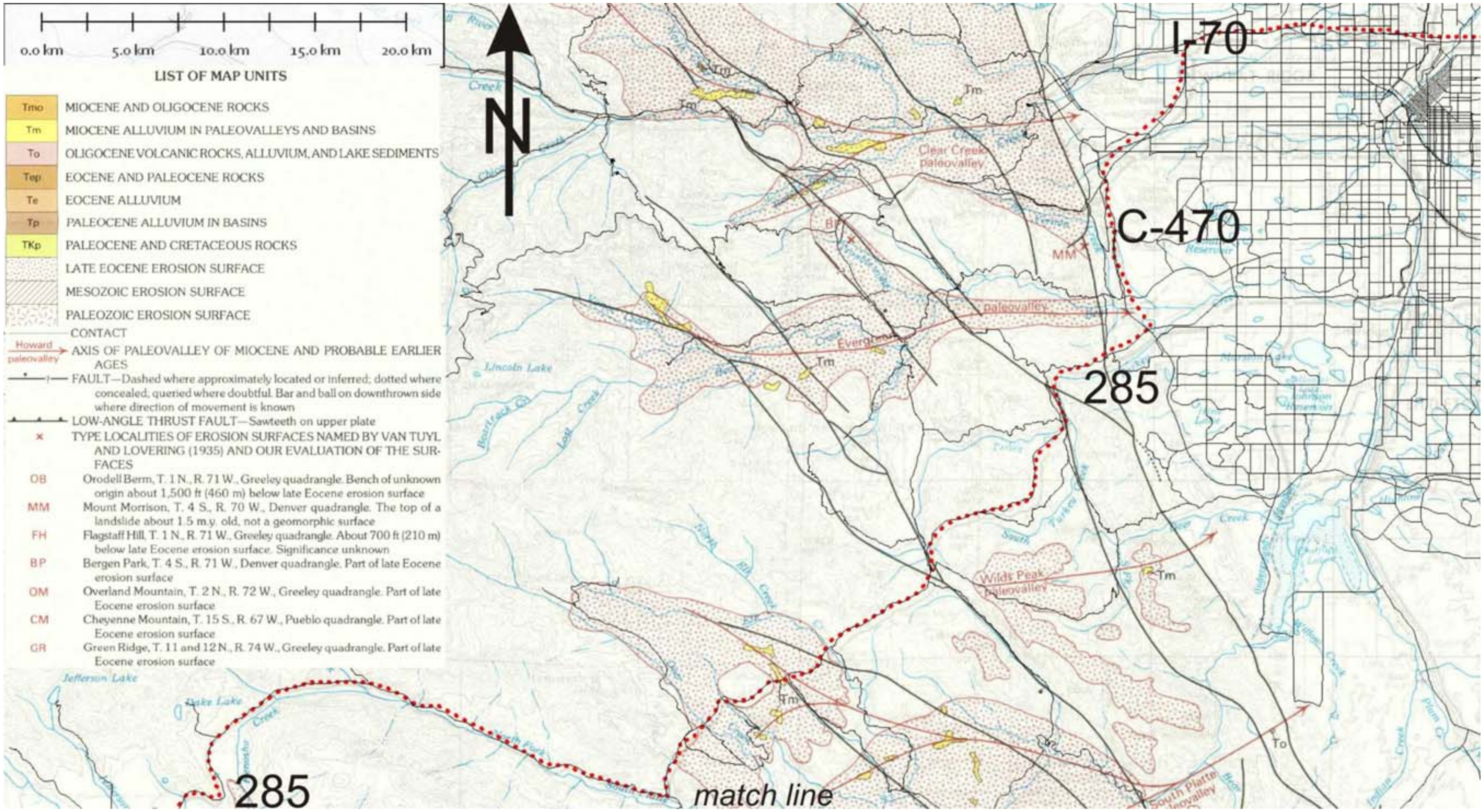


Fig. 2-5a. Map of the late Eocene erosion surface (stippled areas) along the northern half of the field trip route (thick dotted line). After turning off C-470 and ascending into the mountains on US285, the highway crosses numerous NW-trending faults. Only the major faults are shown here. Most fault zones are expressed as linear valleys eroded along the sheared fault rocks; in other words, an erosional signature. However, some faults apparently displace the late Eocene erosion surface up to 600 m vertically.

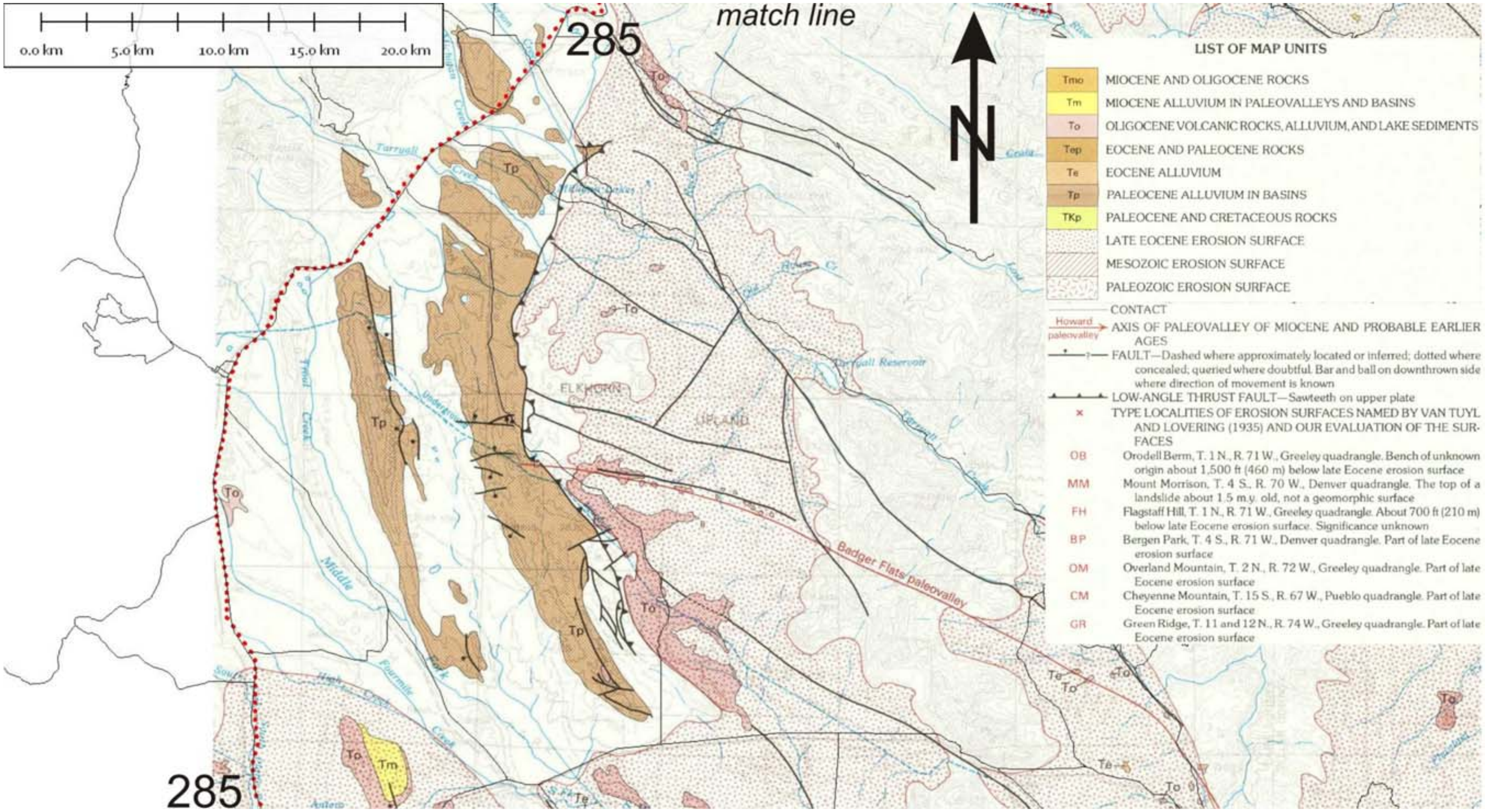


Fig. 2-5b. Map of the late Eocene erosion surface (stippled areas) along the southern half of the field trip route (thick dotted line). The route at the top of the map is shown descending from Kenosha Pass into South Park and then continuing SW into the Park, away from the Front Range and its faults in crystalline basement. Although there are some faults in South Park with documented Neogene displacement, they lie to the east of US285 so we will not see them (see Fig. 2-6).

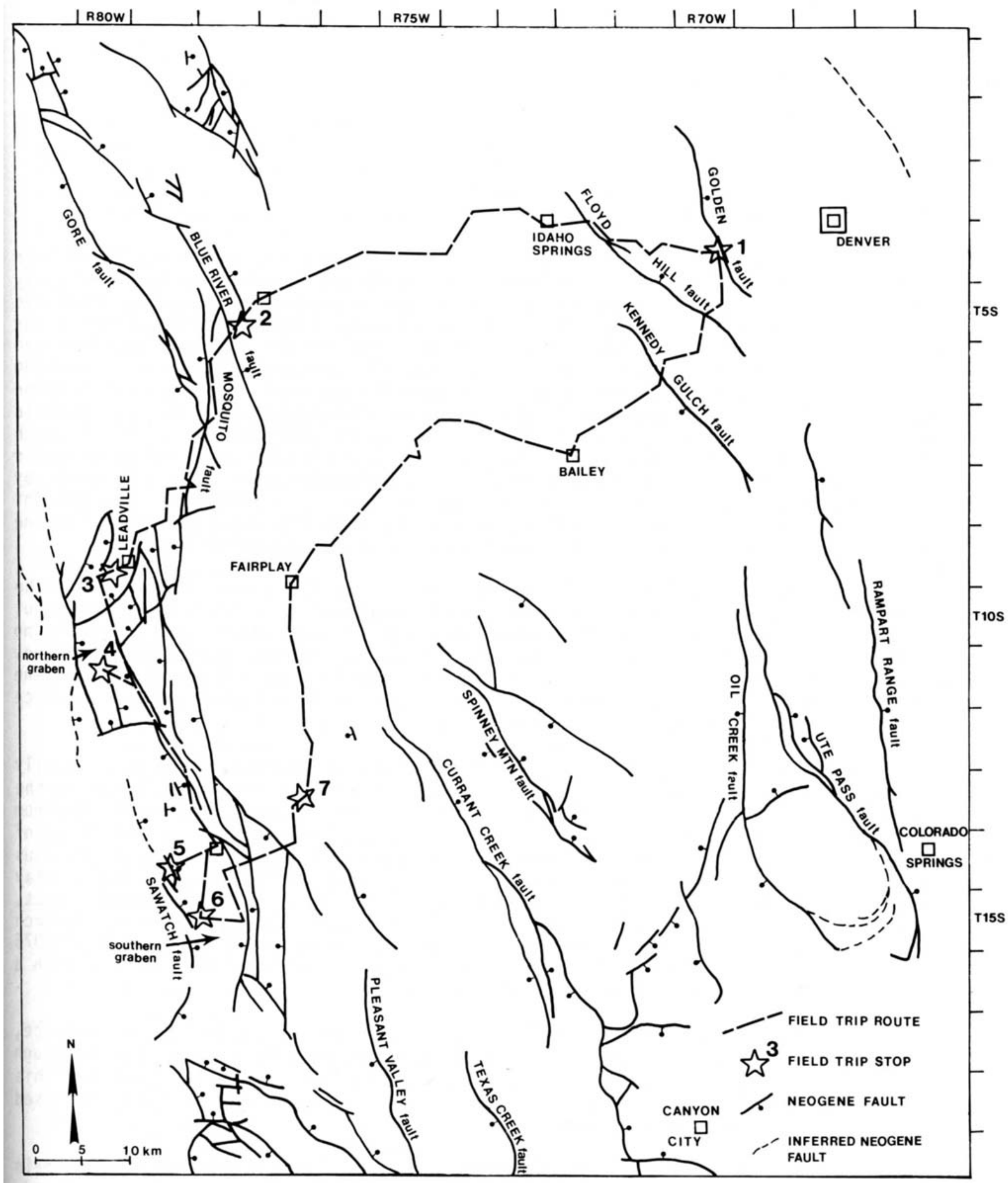


Fig. 2-6. Field trip route (lower part of dashed line) crosses several Neogene faults in the Front Range (between Denver and Bailey), but passes north and west of the Neogene faults in South Park (between Bailey and Fairplay). From Kirkham, 1981.

QUATERNARY DEPOSITS IN THE FRONT RANGE AND THEIR USE IN DATING NEOTECTONIC FAULT MOVEMENTS

The seismotectonic studies for Two Forks Dam were among the first to apply principles of Quaternary stratigraphy and soil stratigraphy to Quaternary deposits along the South Platte and its tributaries SW of Denver.

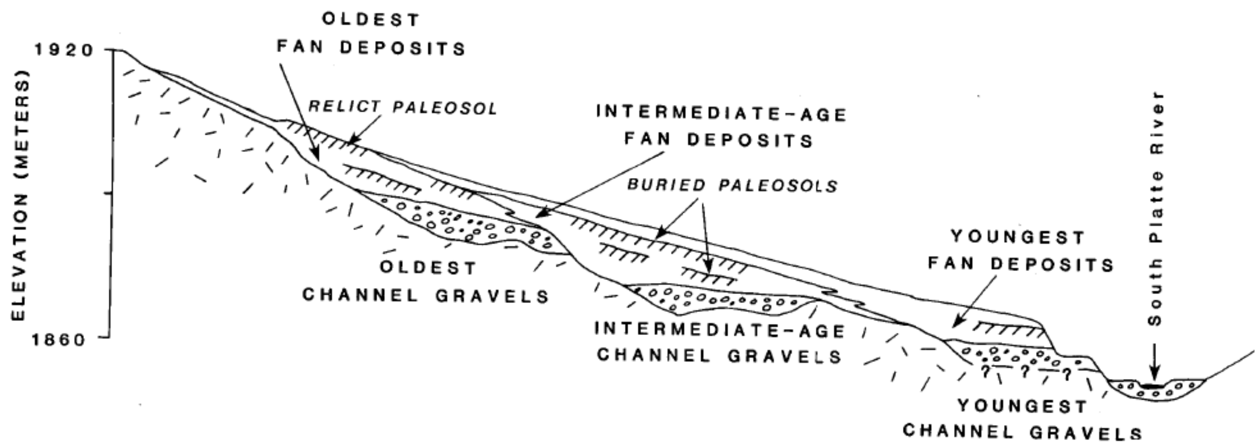


Fig. 2-7a. Schematic cross-section of the Kennedy Gulch fault stratigraphy. Three Quaternary terraces exist above the South Platte River, the oldest of which lies ~30 m above the river. After the abandonment of each terrace, it was buried by alluvial fans sediments from the sideslopes. In the next erosion cycle, the river downcut ~10 m into the two old deposits, deposited some intermediate-age channel gravels, and then alluvial fan sediments buried that terrace. The cycle then repeated for a 3rd time (youngest gravels and fans). From Shlemon, 1986.

A minority interpretation of the 3 terraces is that they were the same terrace, offset vertically by two strands of the Kennedy Gulch fault. If that interpretation would have prevailed with the client, it would have impacted reservoir design, because one major arm of the reservoir was to lie atop the Kennedy Gulch fault zone!

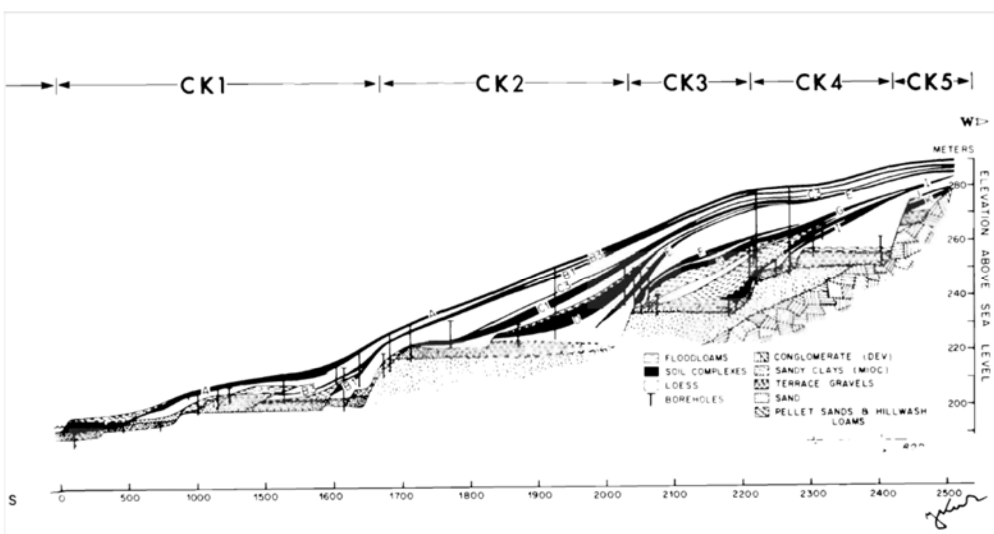


Fig. 2-7b. Where Shlemon got his idea? Cross-section of loess deposits and paleosols progressively burying a sequence of Quaternary terraces at Brno, Czechoslovakia. From the classic paper of the late George Kukla, 1978, The Classical European Glacial Stages: Correlation with Deep-Sea Sediments: Transactions of the Nebraska Academy of Sciences, v. VI, p. 57-93.

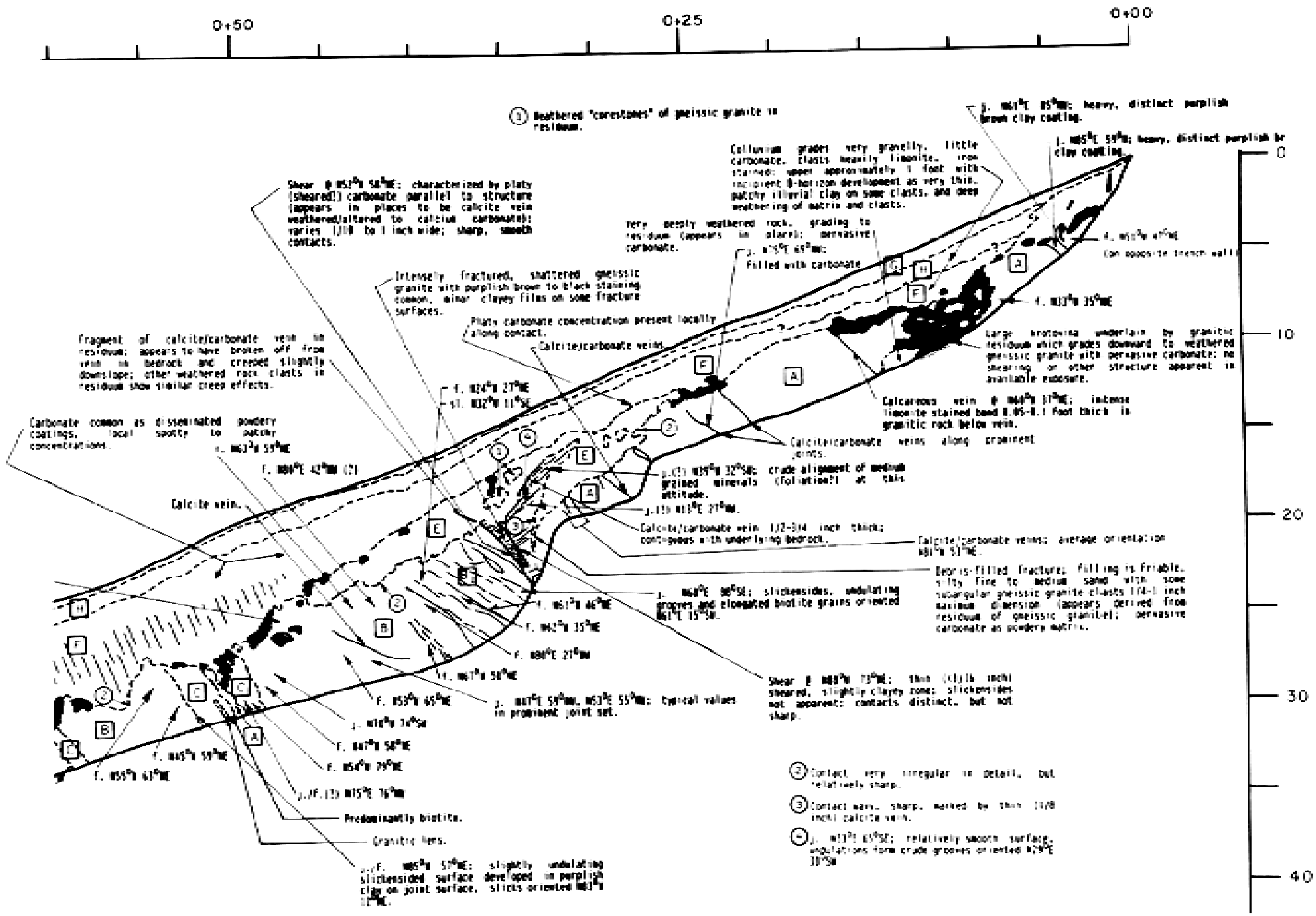


Fig. 2-8.Part of log of Reynolds Ranch trench on the Kennedy Gulch fault, From Yadon, 1986.

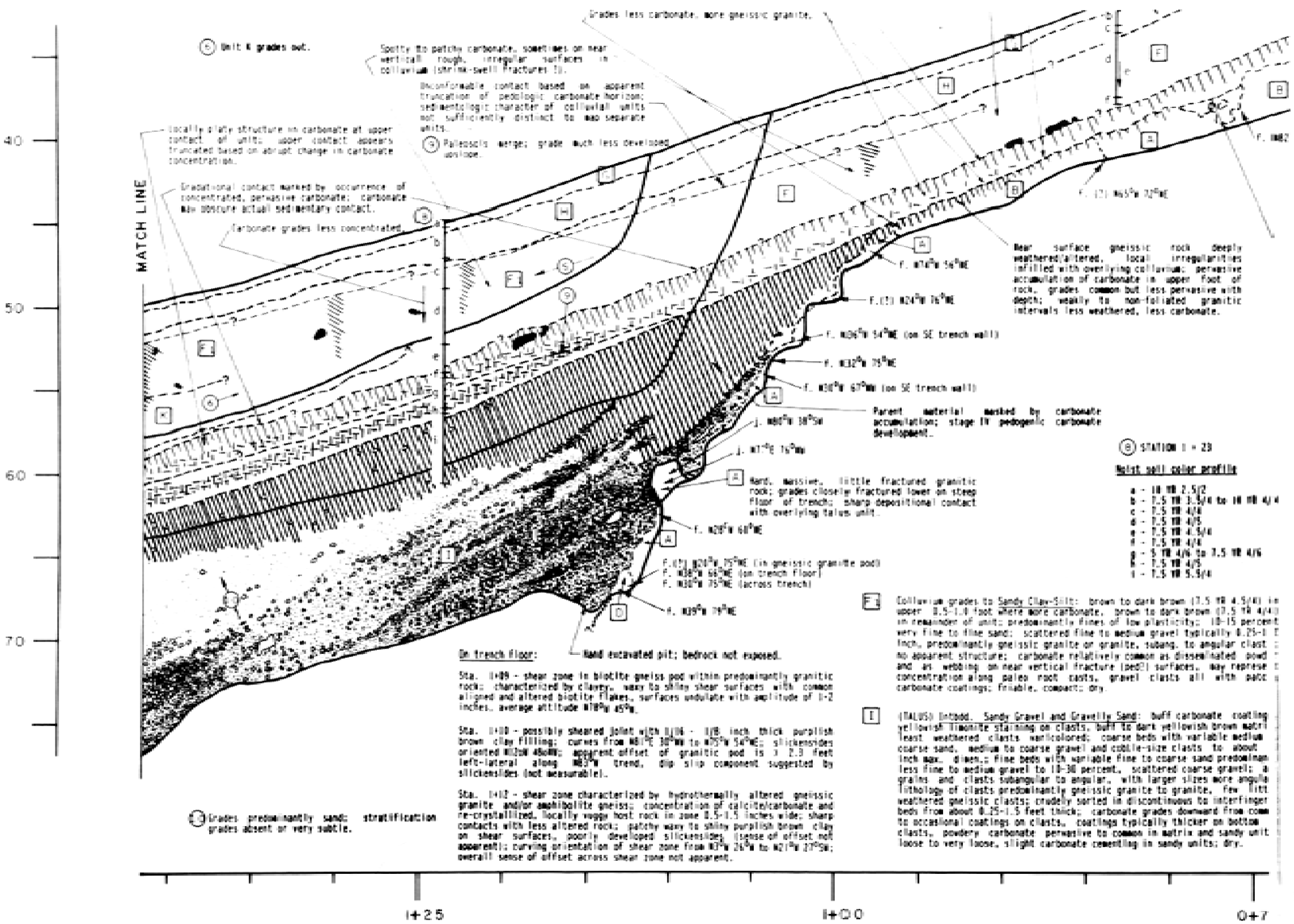


Fig. 2-9. Part of log of Reynolds Ranch trench on the Kennedy Gulch fault, From Yadon, 1986. The sloping dark zones at the bottom of the trench are beds of coarse colluvium derived from the bedrock step in the trench. However, this was not interpreted as a scarp-derived colluvial wedge by the trench loggers.

3-SOUTH PARK

South Park (of American cartoon fame) is a 55 km-wide, 80 km-long, treeless intermontane basin lying at 2700 m elevation, surrounded by mountains up to 4300 m high. Due to the harsh climate and preponderance of fine-grained Paleozoic and Mesozoic rocks, it is a grassland. The buffalo roam there, and the deer and antelope play (Fig. 3).

Fig. 3-1. The most famous residents of South Park, Colorado.

GEOLOGIC SETTING (from Barkmann et al., 2013)

The basin consists of eastward-dipping Paleozoic and Mesozoic sedimentary rocks preserved between uplifts of Precambrian igneous and metamorphic rocks on either side Fig, 3-2). Locally, Cretaceous and Tertiary igneous stocks, sills, and dikes intrude these rocks. Remnants of formally widespread Tertiary volcanic, lacustrine, and fluvial deposits overly the older rocks in many parts of the basin. The high ranges bordering South Park were subject to Quaternary glaciation with moraine and outwash deposits extending well into the basin.

Structurally, the basin is quite complex being dominated by the Laramide Sawatch uplift on the west and Front Range uplift on the east. Internally, the basin contains faulting and folding attributed by many to Late Cretaceous to Eocene Laramide deformation. Deformation styles attributed to the Laramide event include thrust faulting, folding, and possible strike-slip faulting with widespread zones of deformation affecting most of the basin.

The Neogene Rio Grande Rift system follows the upper Arkansas River valley just to the west, where it bisects the Laramide Sawatch uplift into the main Sawatch Range and the Mosquito Range, the latter forming the west boundary of South Park. Evidence of Neogene deformation related to the Rio Grande Rift can be found throughout South Park, as described by Ruleman and others (2011). In addition, there is evidence of ongoing local deformation related to dissolution and possible collapse of Paleozoic evaporite deposits (Kirkham and others, 2012).

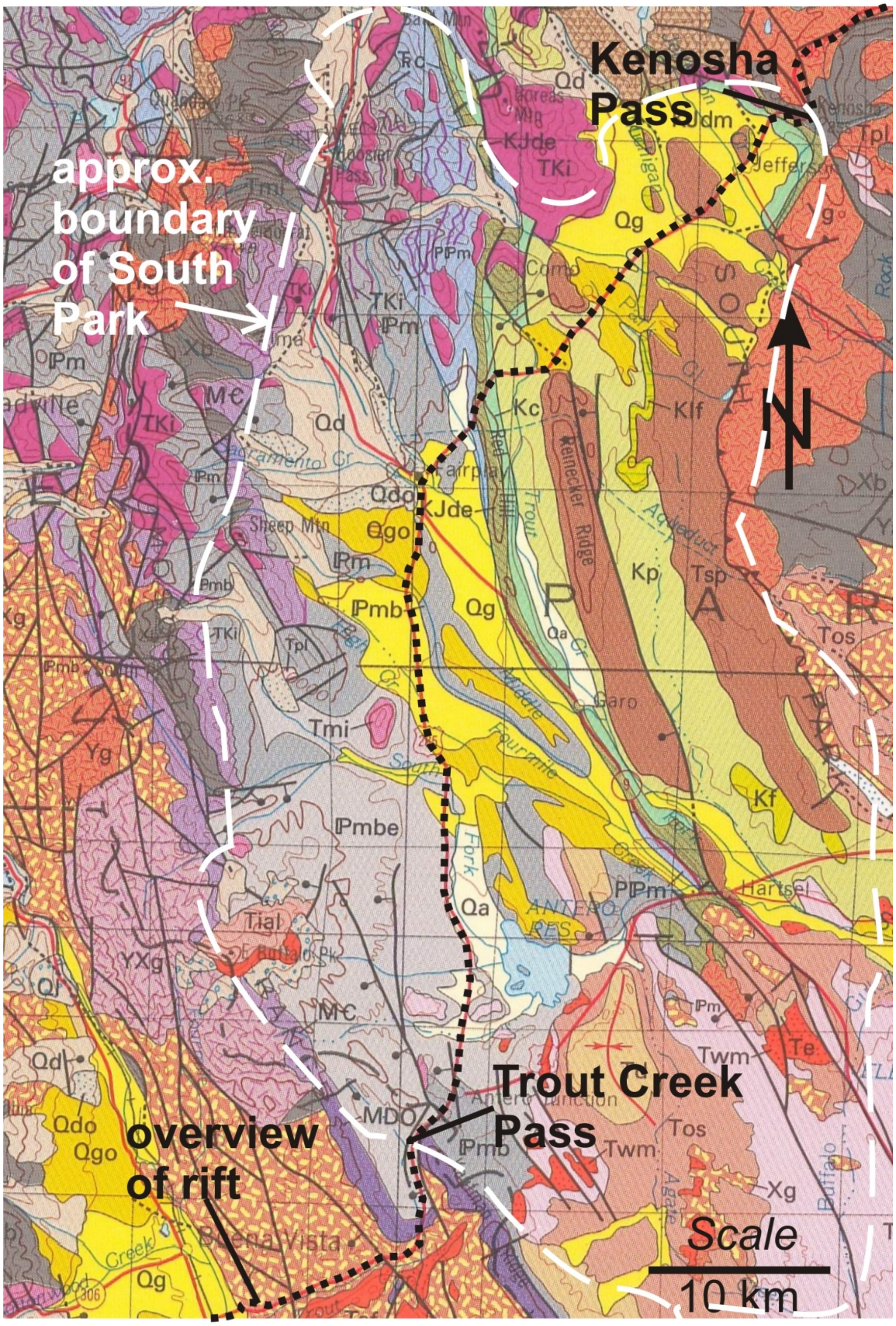


Fig. 3-2. Geologic map of trip route on US 285 (thick dotted line) across South Park, between Kenosha Pass (Front Range) and Trout Creek Pass (Mosquito Range). Geology from the Geologic Map of Colorado, 1:500,000 scale (Tweto, 1979). Our route roughly follows the contact between Paleozoic rocks (to the west) and Mesozoic and early Cenozoic rocks (to the east). This route was chosen to avoid the hilly terrain underlain by Paleozoic rocks to the west, and the swamps and clayey soils of the Mesozoic rocks to the east. It also passes through the historic mining town of Fairplay, the County Seat.

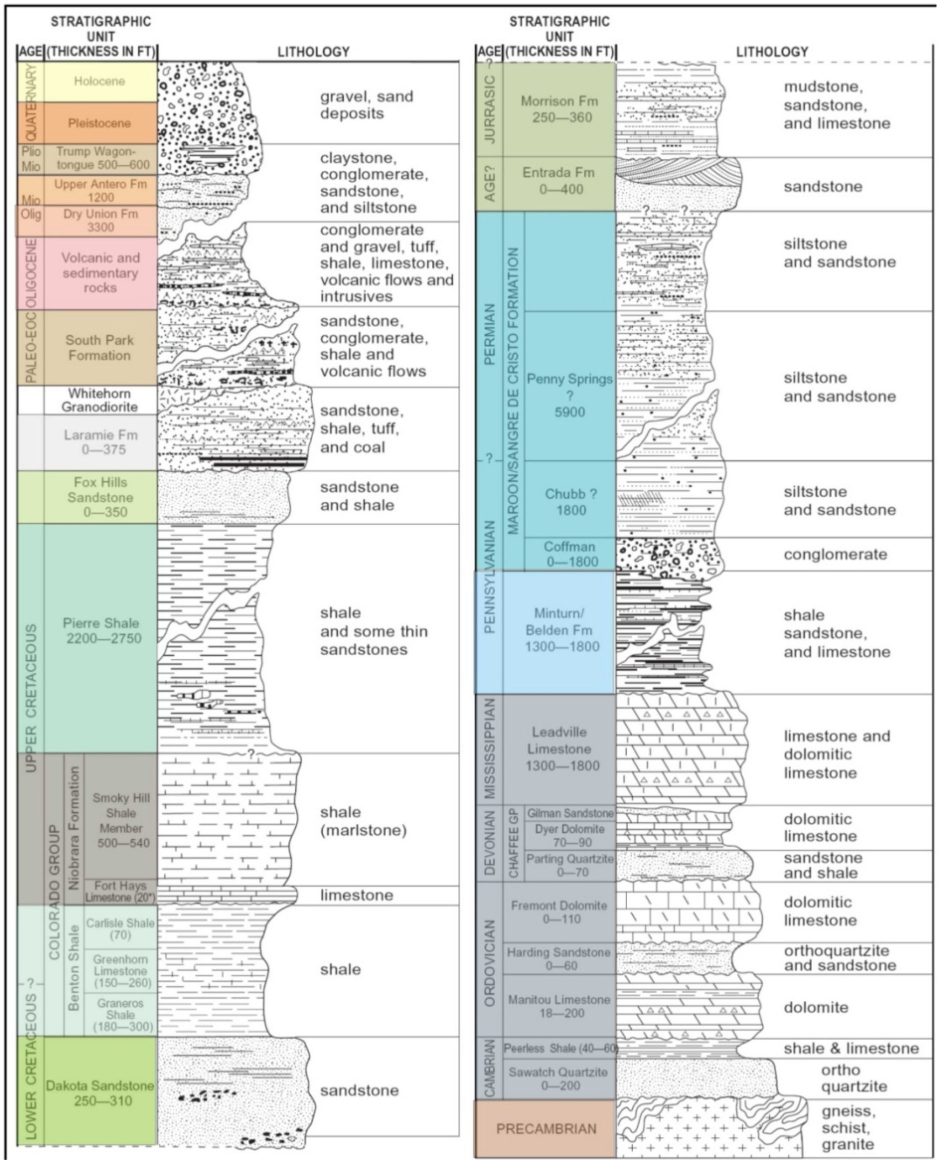


Fig. 3-3.Stratigraphic column of South Park. The harder, redder Paleozoic rocks will dominate to the west of our trip route, such as at Red Hill Pass. To the east of our route, the low topography is underlain by soft Mesozoic shales, whereas the north-south-trending, tree-covered ridges are underlain by Mesozoic or early Cenozoic sandstones and limestones.

Road Log of the South Park stretch of the Field Trip, Kenosha Pass to Johnson Village

Starts at Kenosha Pass (0.0)

4.3 Enter Jefferson (*best fudge in the entire Rocky Mountains*)

16.5 Red Hill Pass

20.0 Enter Fairplay

39.5 Hills at 4 o'clock and 7 o'clock capped by the Oligocene Buffalo Peaks Andesite and underlain by Wall Mountain Tuff. Hill at 9 o'clock formed by Wall Mountain Tuff. The hills mark the position of the Buffalo Peaks paleovalley where it entered South Park.

41.0 Antero Junction. Continue south on US-285.

42.6 Trout Creek Pass

44.8 Buffalo Peaks to west

47.0 Prominent rocky landforms to right are remnants of Oligocene ash-flow tuffs, primarily the Wall Mountain Tuff.

50.9 Elongate ridge to the south that nearly parallels the highway consists of Oligocene Badger Creek Tuff capped by andesitic lava. Note faulting and shearing in Proterozoic rocks exposed along this part of the route.

53.0 OPTIONAL STOP: OVERVIEW OF THE RIFT. Exit US285 to the north and enter the overview picnic area. From top of the ridge you can see the Upper Arkansas Valley of the Rio Grande Rift. On the route just traversed, numerous of step faults have been mapped in the across the granitic landscape, along which the Arkansas graben has been downdropped. However, none of them show evidence for Quaternary movement

54.3 Enter Johnson Village.

54.6 Junction US-24 and US-285. Turn left on US-285. Highway generally parallels the Upper Arkansas River, the axial drainage of this part of the Rift.

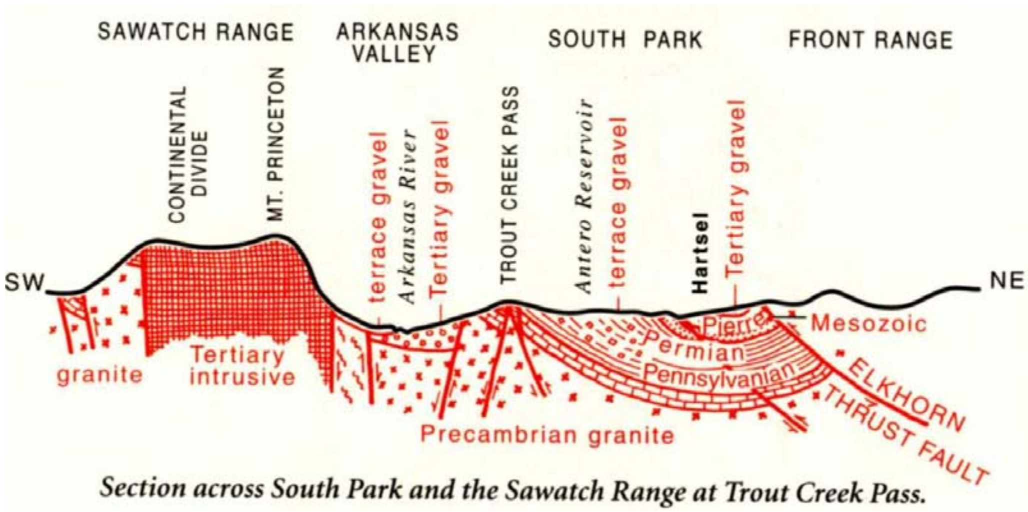


Fig. 3-4. Schematic cross-section from the Sawatch Range and Arkansas Valley (parts of the Neogene Rio Grande rift) and across South Park to the Front Range. From Chronic.

Post-Laramide and Neogene Tectonism (from Barkmann et al., 2013)

Ruleman and others (2011) and Houck and others (2012) have identified many features and relationships within South Park that suggest post-Laramide deformation in the area. Ruleman (personal communication, 2012) believes that much of the topographic relief that defines the South Park physiographic basin may owe its origin to Late Tertiary tectonism. A number of faults in South Park display evidence of movement related to this phase of tectonism (Ruleman and others, 2011)….

The Chase Gulch half-graben east of Spinney Reservoir may also be a feature formed by Neogene extensional tectonism. Evolution of this half-graben deserves further investigation as it may represent one of the only direct rift-related structural feature in the South Park basin. …"Deep drilling in Chase Gulch Valley to assess seismic hazards of the Spinney Mountain Reservoir region identified more than 550 m of what were referred to as "Neogene sediments" filling a half-graben east of Spinney Mountain." (Barkmann et al., 2013).

Similarly, the Oligocene Fairplay Paleovalley sediments just south of Fairplay described by Kirkham and others (2006) appear to be preserved in a fault-bound half-graben. This feature points to significant post-Oligocene faulting and tilting in this area of South Park.

Evaporitic Tectonism in South Park

Houck and others (2012) and Kirkham and others (2007; 2012) have identified features in the southwest part of South Park that may owe their origin to dissolution and plastic flow of beds of evaporite minerals within the Minturn Formation. Evaporitic tectonism, as this is often referred to, has been recognized in other parts of the state where the similar strata are present (Kirkham and others, 2001). This deformation has played a major role in shaping the geologic landscape in these other areas and this may be another example. While evaporite deposits have long been known to be a part of the Pennsylvanian section, their role in the structural evolution of South Park may not be well understood yet. Differential movement in the evaporitic facies, diapiric flow, and collapse may all modify the Laramide and post-Laramide features where these sediments are present at depth. Much of the apparent discontinuity in structural features in the western part of the basin may be attributable to modification or overprinting by evaporitic tectonism

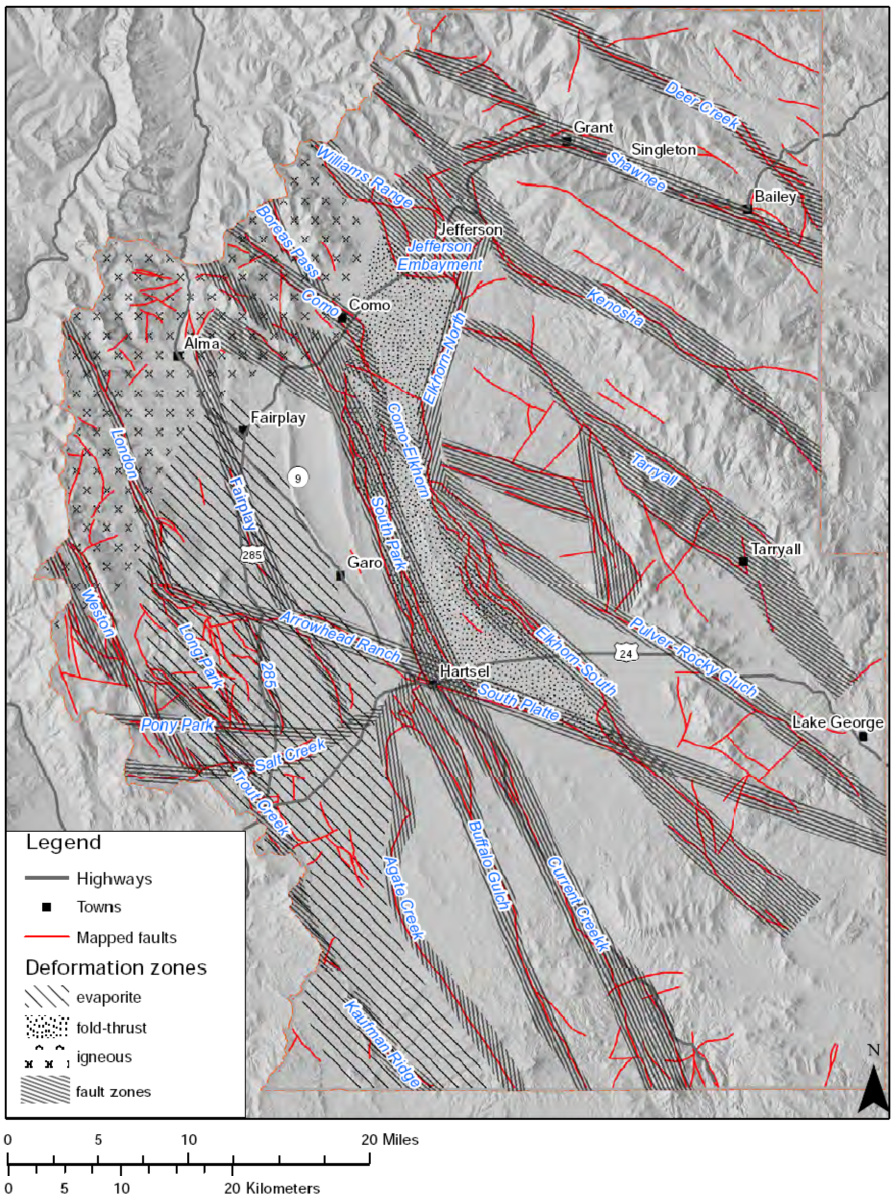


Fig. 3-4. Major structures in South Park. The Elkhorn Thrust is a major east-dipping reverse fault that forms the eastern margin of South Park. It thrusts Proterozoic crystalline rocks of the Front Range over sedimentary rocks of South Park. From Barkmann et al., 2013.

DISRUPTION OF PRE-MIOCENE PALEOVALLEYS IN THE SOUTH PARK AREA, BY NEOGENE RIFT-RELATED BLOCK FAULTING

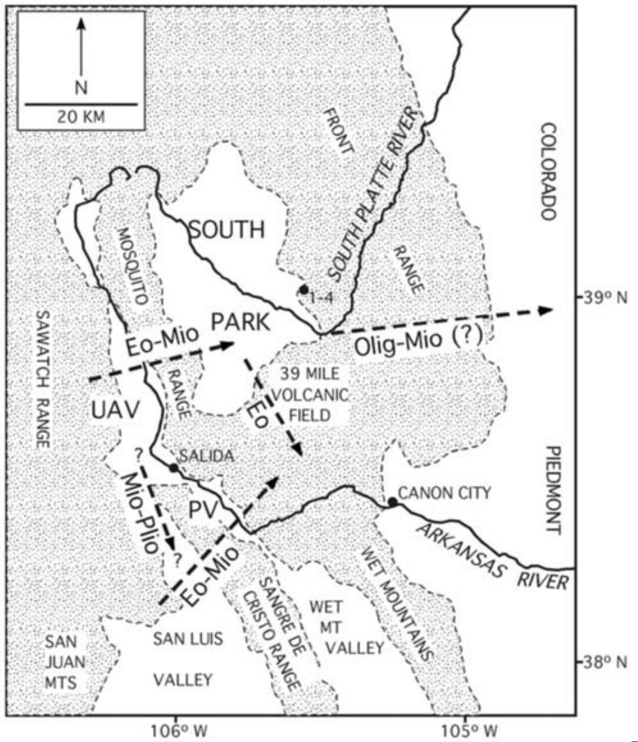


Fig. 3-5. Schematic map of post-Laramide drainage changes in the areas of the modern South Platte and Arkansas drainages, central Colorado. UAV = upper Arkansas valley, PV = Pleasant Valley. Modern river courses are shown with solid lines. Dashed arrows indicate patterns of now-abandoned drainages and are labeled with the approximate period when flow pattern prevailed. Arrows indicate only general patterns and are not intended to portray individual paleovalleys. Miocene and Pliocene north-to-south flow across Poncha Pass from the upper Arkansas valley into the San Luis valley has been proposed by Epis et al. (1976), but is disputed by Knepper (1976). From GSA Field Guide.

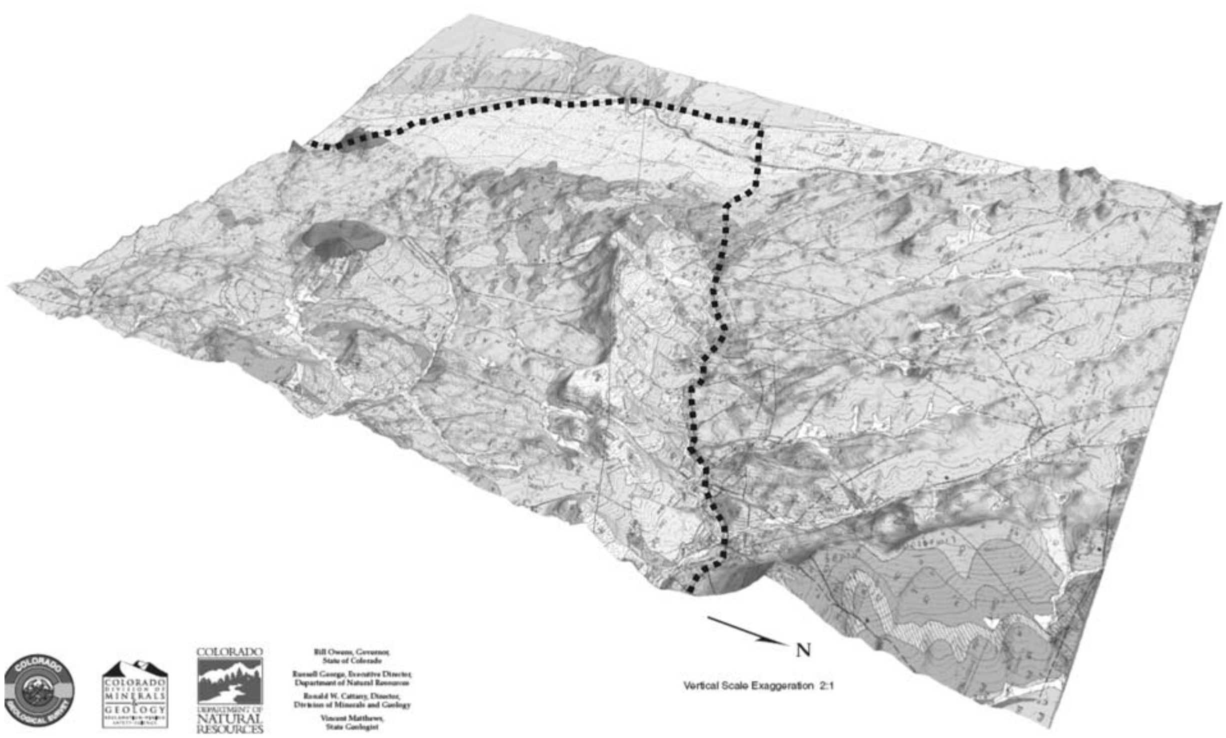


Fig. 3-6. Oblique view of the geologic map of the Buena Vista East quadrangle draped over the USGS 30 m DEM. Look direction is WSW; N is to the lower right. The thick dotted line is the field trip route. Shaded relief topography shows the prominent ridge to the left (South) of our route, composed of Oligocene welded tuffs sourced from the Sawatch Range on the western side of the rift.

4- RIO GRANDE RIFT

The final segment of the Pre-Meeting Field trip travels south down the axis of the *Rio Grande Rift* from Buena Vista to Crestone. Where we enter the rift at Buena Vista in the Upper Arkansas Valley, the rift floor lies at 2400 m and the flanking horsts rise to 4300 m (Fig. 4). Our route takes us south over Poncha Pass (2746 m) and into the San Luis Valley, one of the largest graben of the Rio Grande Rift.

Fig. 4-1. Mount Princeton (top center; elevation 4327 m) rises above the floor of the Rio Grande Rift, and the town of Buena Vista and Upper Arkansas River (elevation 2400 m). Fault scarps lie hidden in the forest at the base of range.

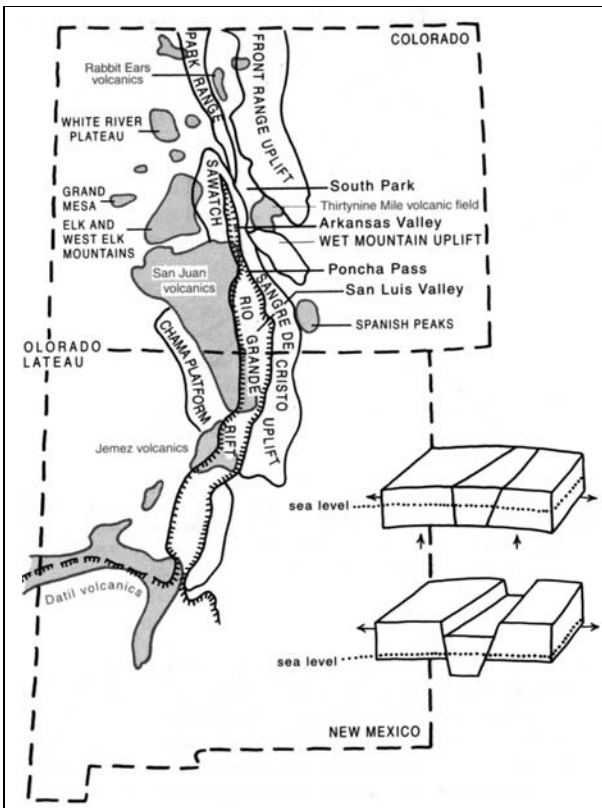


Fig. 4-2. Schematic drawing of the Rio Grande rift zone extending from the northern boundary of Colorado to southern New Mexico. Gray shaded areas are Oligocene (pre-rift) volcanic centers. From Chronic.

This simplistic map shows the rift (bounded by hachured lines) ending just south of the northern end of the Sawatch Range. However, most geologists (including Ogden Tweto) have believed since the 1970s that the rift extends farther north and includes the Blue River Valley (north and south of I-70), the Williams Fork Valley (north of I-70), Middle Park (includes Hot Sulfur Springs, Granby, and Grand Lake), and possibly North Park. Colorado geologists lose interest in finding the rift north of the State Line, and Wyoming geologists seem to have little interest in tracing the rift.

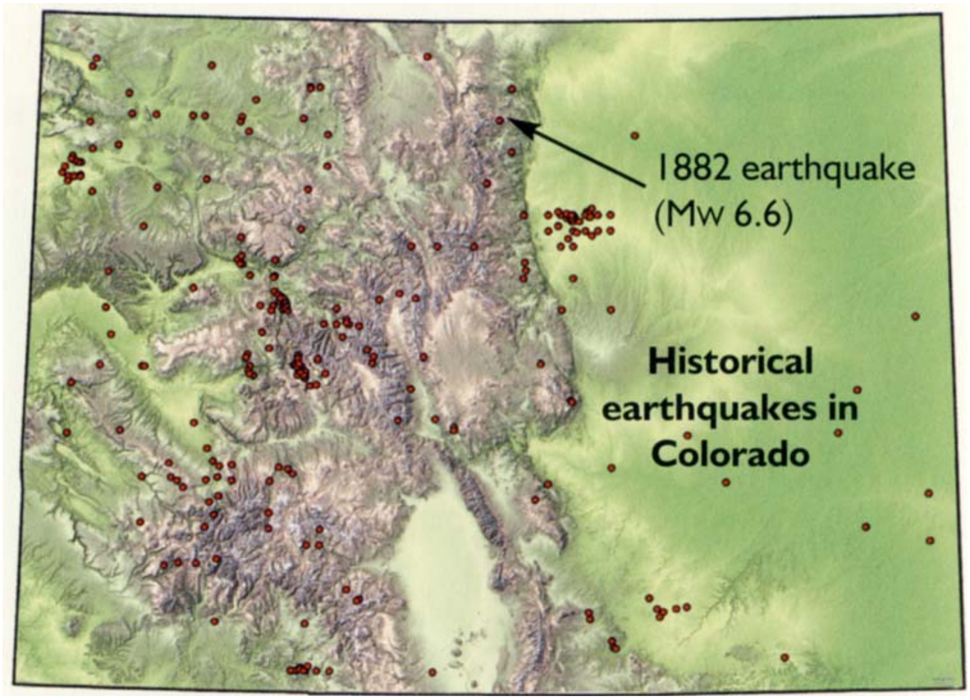


Fig. 4-3. Map of historical earthquakes in Colorado. From Colorado Geological Survey. The Rio Grande rift is defined by the large San Luis Valley at bottom center; by the much narrower Upper Arkansas Valley farther north; and by the less obvious Blue River Valley farther NE (we will traverse this in the Post-Meeting Field Trip). Although these rift valleys have abundant and large Quaternary faults scarps along their eastern and western edges, respectively, they are not associated with any significant historic seismicity. Put another way, based merely on the distribution of historic epicenters, you would not know there was an active Neogene rift in Colorado.

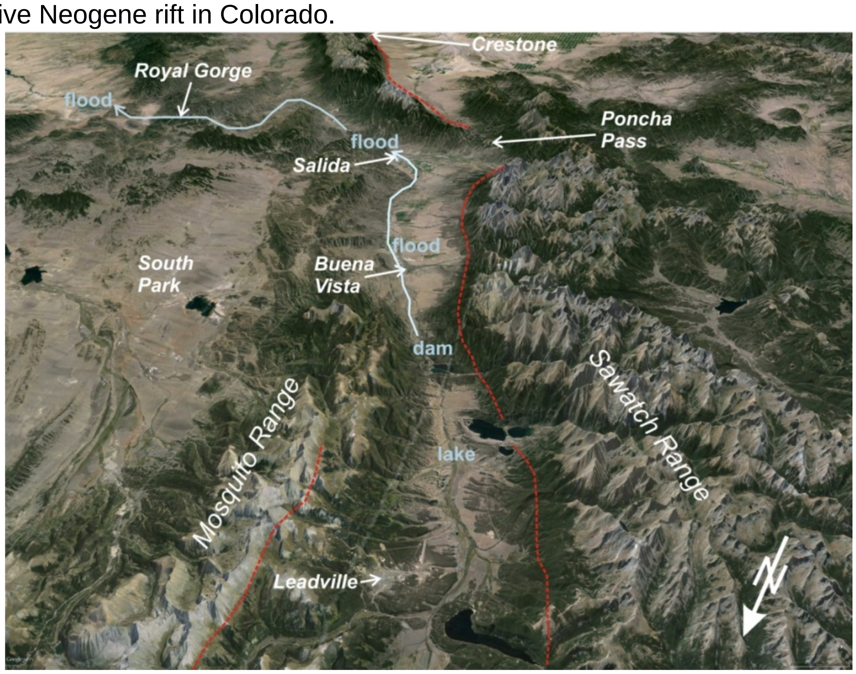


Fig. 4-4. We leave South Park and enter the rift at Buena Vista, then turn south (in the direction of view and drive over Poncha Pass and into the northern San Luis Valley.

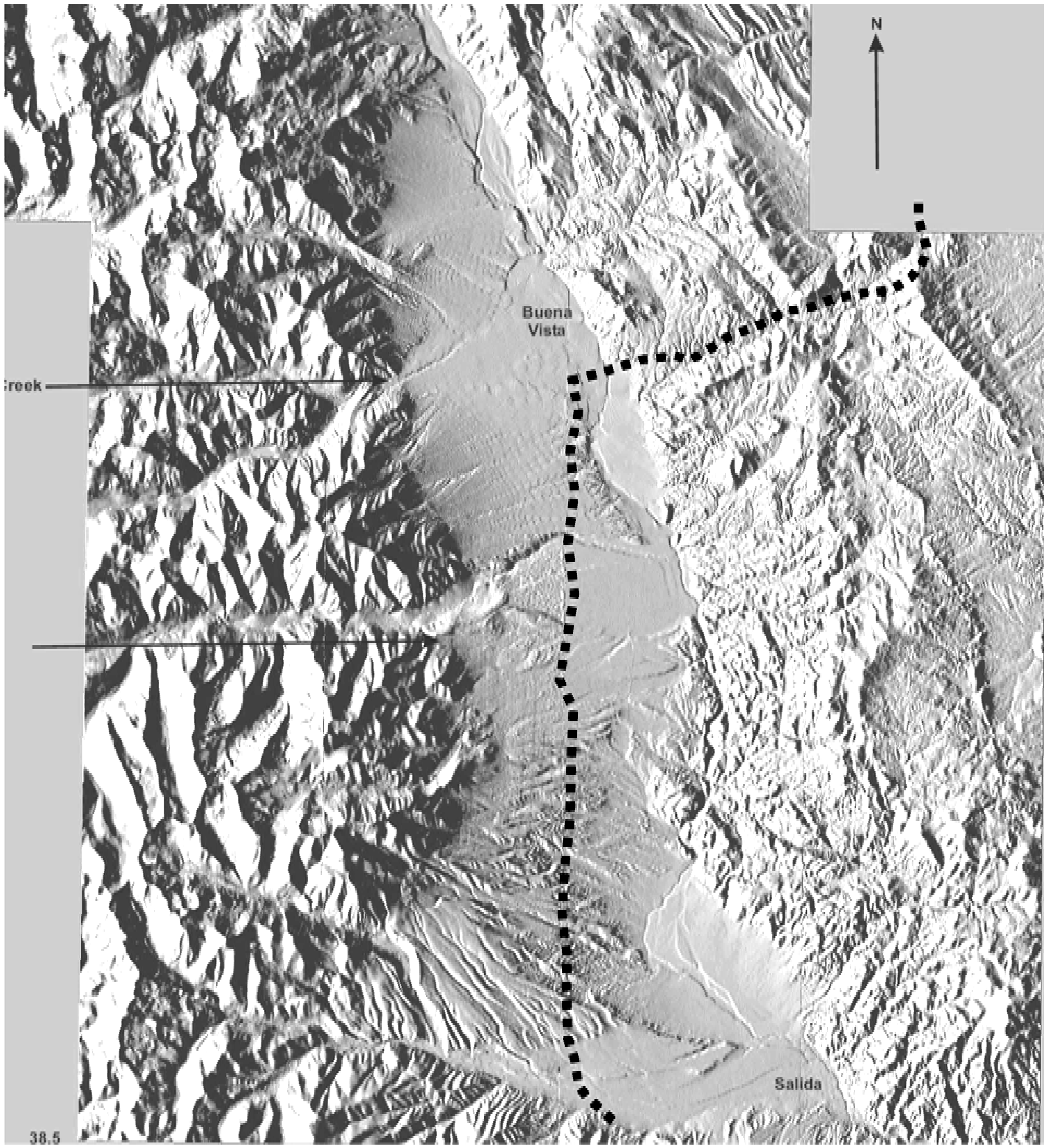
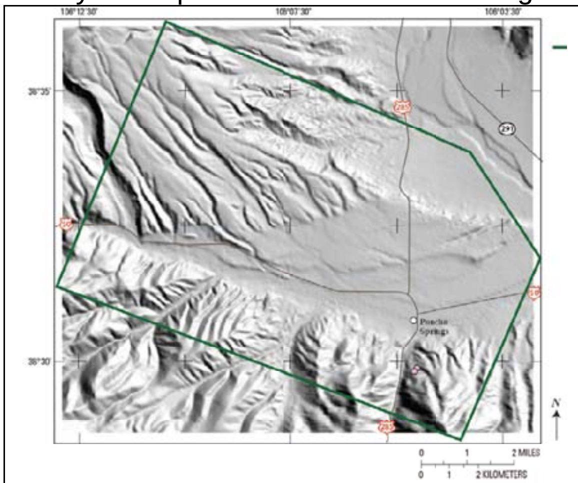


Fig. 4-5.Route of the field trip (thick dotted line) crossing the Arkansas Hills from the east and entering the Upper Arkansas Valley (UAV) just south of Buena Vista. The route then turns southward and traverses alluvial fans derived from the Sawatch Range. The master fault of the UAV (the Sawatch fault) is on the western margin of the valley; it is an east-dipping normal fault..

At its south end the UAV broadens to the east (Salida) and west (Maysville), creating a triangular basin. The south edge of this basin is the horst of the Sangre de Cristo Mountains south of Poncha Springs. Because the master fault of the UAV is on its western side, but the master fault of the San Luis Valley is on its eastern side, a right-lateral accommodation zone is required here. Grauch and Drenth (2009) of USGS-Denver have used aeromagnetic and gravity sureys to explore where such faults might be (Fig. 4-6).



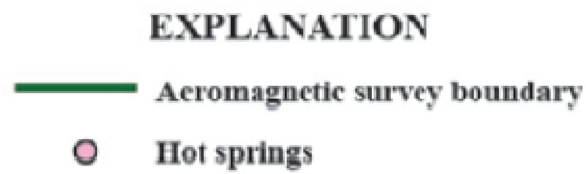
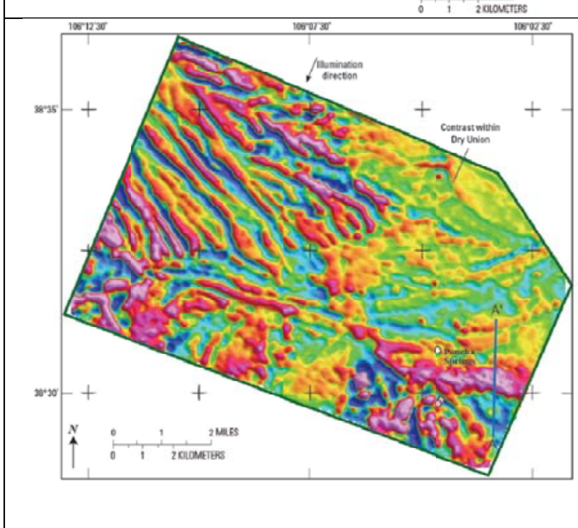
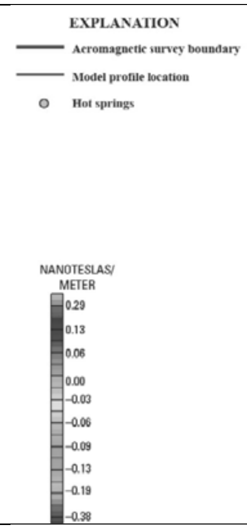
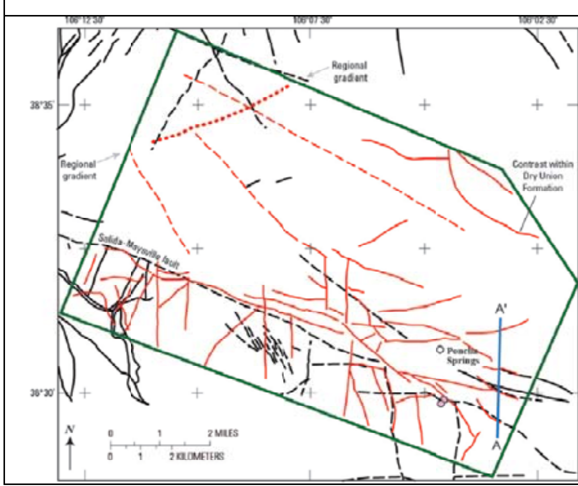


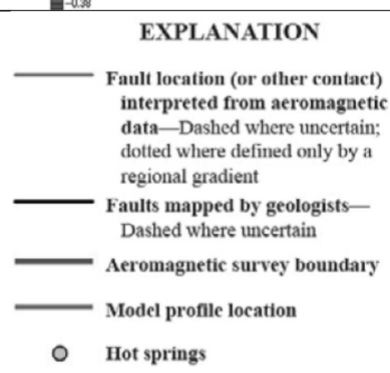
Fig. 4-x. TOP: Shaded relief map of the triangular basin at the south end of the UAV. Airborne geophysical surveys were performed within the area outlines in black. All figures from Grauch and Drenth, 2009.

MIDDLE: Horizontal gradient map of the reduced-to-pole aeromagnetics.









BOTTOM: Interpreted lines inferred as faults or other linear geologic contacts and criteria used for interpretation.

The most likely fault to accommodate the required right-lateral slip is the fault at the southern margin of the triangle, which extends ESE through Poncha Springs, a high-temperature hot springs. Evidence of Quaternary right-lateral slip should in theory be detectable at the mouths of all the drainages crossing the fault from south to north, such as Poncha Creek. To date, nobody has looked for this.

THE SAN LUIS VALLEY

Fig. 4-7.The San Luis Valley and Sangre de Cristo Range as seen from just below Poncha Pass. Photo by Bill Ellzey.

The San Luis Valley (SLV) is one of the largest topographic basins in the Rio Grande rift, measuring 80 km wide and 150 km long. Its valley floor lies at an average elevation of 2300-2500 m, and the flanking mountains (Sangre de Cristo and San Juan ranges) rise to >4000 m. The SLV has been known to be an asymmetrical, complex graben since the 1970s (Fig. 4-x).

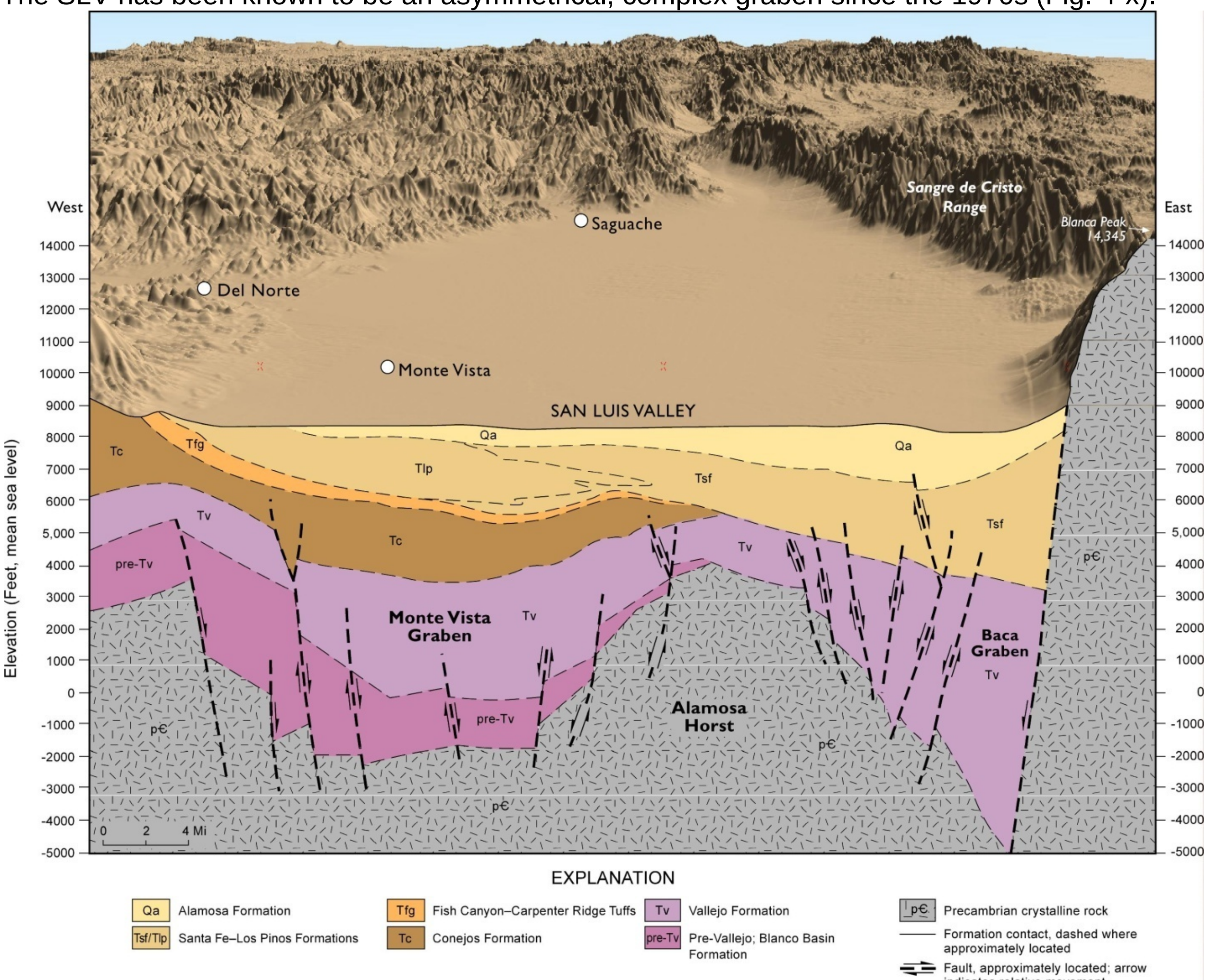


Fig. 4-8. East-west cross-section through the SLV situated south of the Great Sand Dunes National Park (visible at right center margin). From V. Matthews.

The master fault of the SLV graben is the eastern margin fault, the northern Sangre de Cristo fault (NSCF). Fault scarps displace alluvial fans along the entire length of the range, except where covered by eolian sand at Great Sand Dunes National Park (Fig. 4-9). The map below shows generalized scarps that were mapped in 1979 using stereo aerial photography. However, because most of the range-front lies in a forest of pinyon pine and juniper trees, not every scarp could be seen.

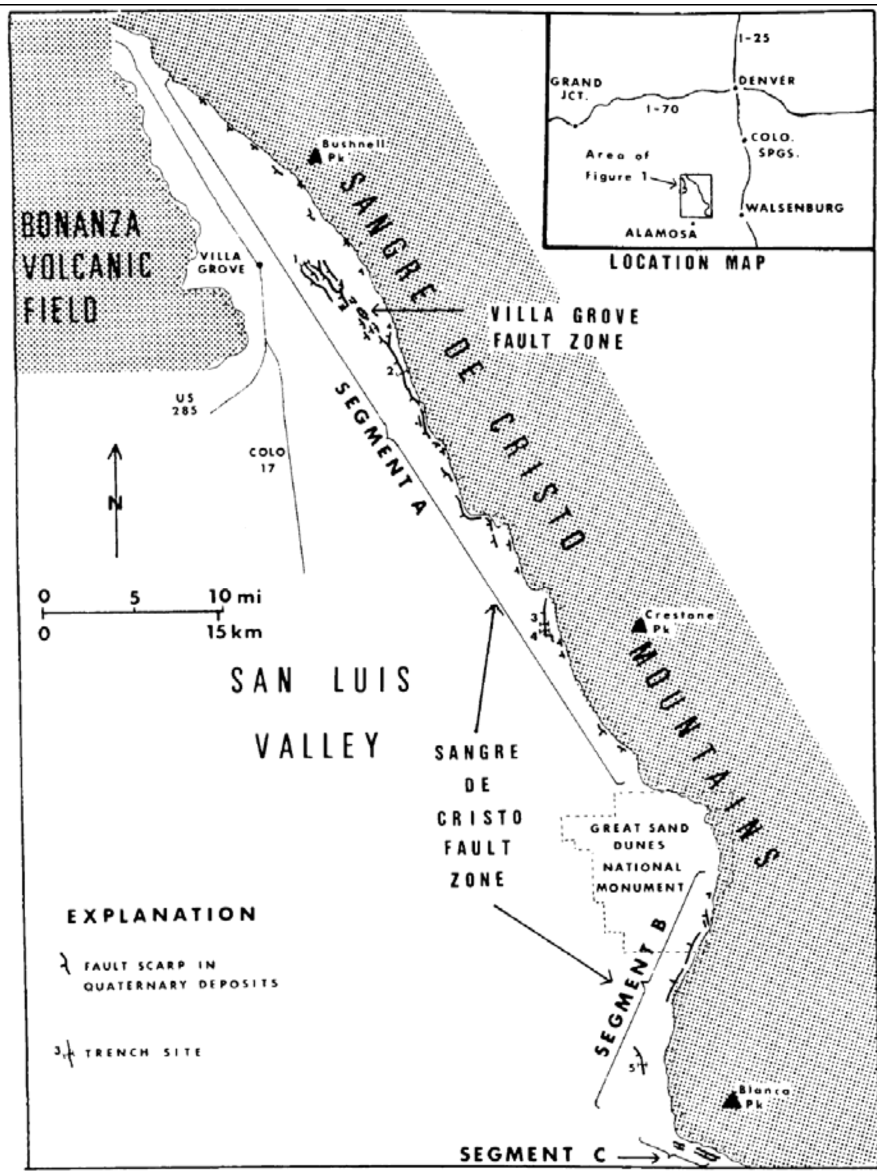


Fig. 4-9. Map showing the location of fault scarps (thick black lines) and interpreted segments of the northern Sangre de Cristo fault, on the east side of the San Luis Valley (from McCalpin, 1986). Shaded areas are mountains. The locations of the 5 trenches dug in 1980 are also shown. The three segments interpreted in 1980 were defined by gross changes in the geometry of the range front , which was probably too simplistic. As a result, the segments have very different lengths, with the longest being Segment A (the Crestone segment of USGS), and the shortest being only a few km long (Segment C, the Blanca segment of USGS). Subsequent trenching studies in 2003 and 2013 were aimed at trying to subdivide the 90 km-long Segment A into shorter segments, more typical of M7-7.5 earthquakes of the Basin and Range Province (e.g., 30-60 km).

In 2008 the USGS and Colorado Geological Survey flew 1 m lidar over the Sangre de Cristo fault. This bare-earth imagery shows many more fault scarps and more subtle geomorphic anomalies in the fault zone that were visible on aerial photographs. As a result the zone of fault-related deformation can now be seen as wider and more complex than originally thought. The amount of vertical displacement (see Fig. 4-10), based on field fault scarp measurements is now considered to be an underestimate, by an unknown percentage.

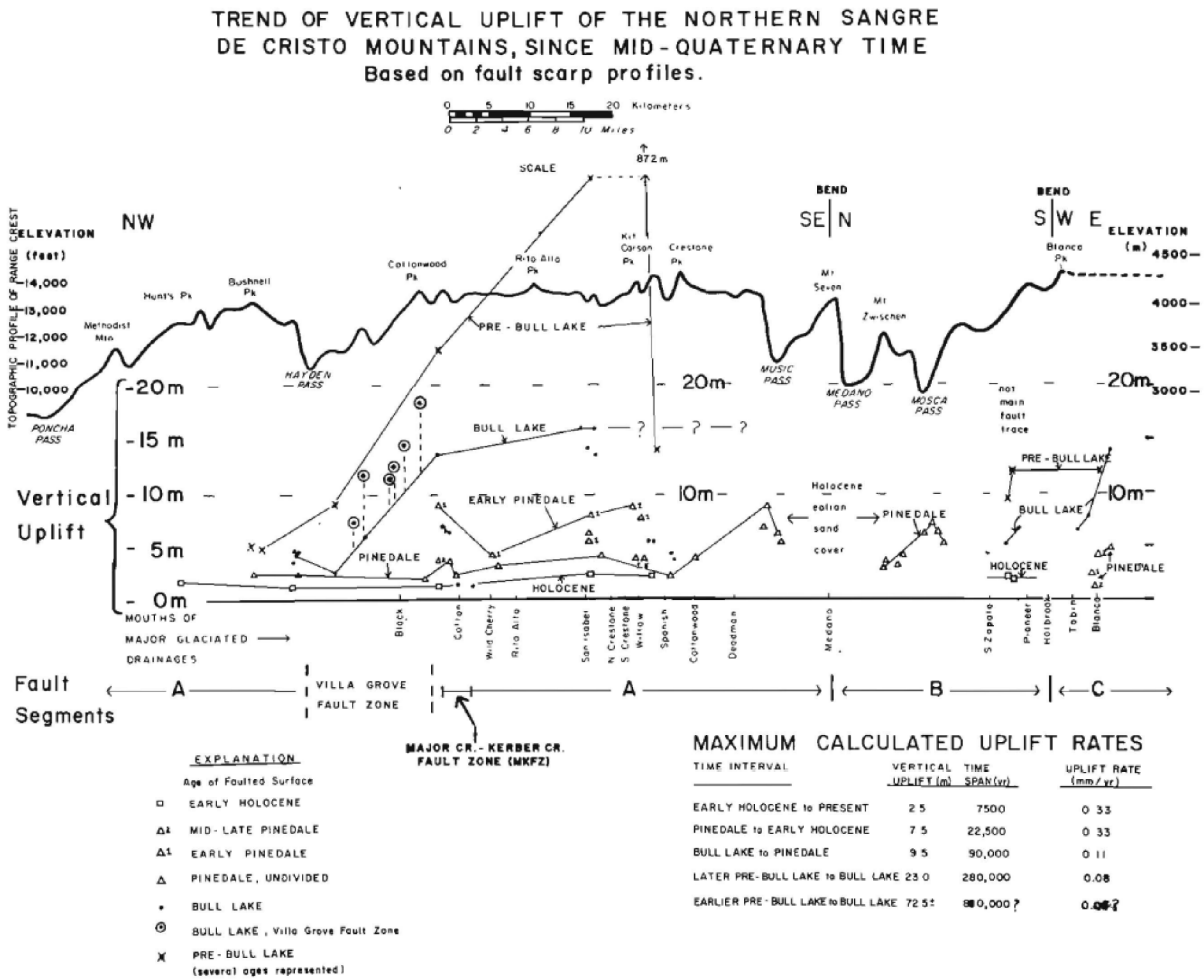


Fig. 4-10. Trend of vertical uplift along the northern Sangre de Cristo fault, based on fault scarp profiles measured in the field during 1979 and 1980 (ca. 77 profiles). Although the general pattern is probably correct, two aspects need updating: (1) the ages of the faulted surfaces, based on direct dating (e.g., cosmogenics) rather than correlation based on soil profile development, and (2) the net vertical displacement across the wider fault zone that can now be seen on lidar.

The vertical displacement per faulting event can be deduced from the heights of the smallest fault scarps across the youngest deposits along the range front, which are assumed to be single-event scarps (Fig. 4-11). Some of these scarps have been trenched, and a 2-event scarp trenched at Major Creek yielded 3.8 m of cumulative vertical displacement in 2 events.

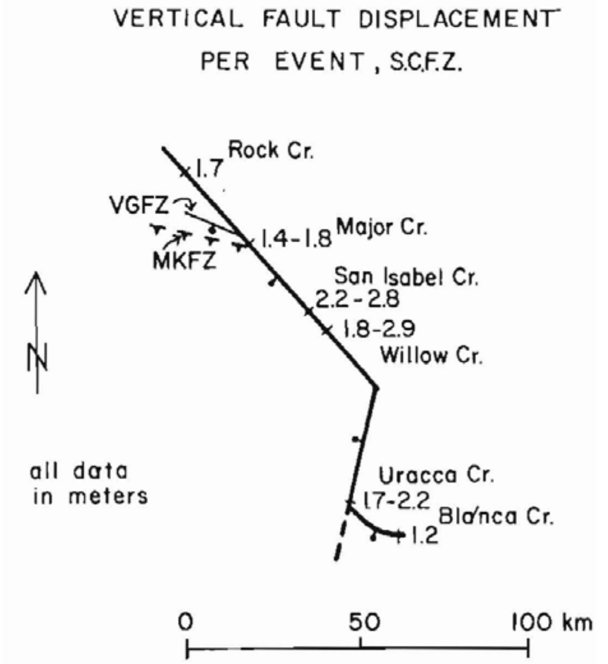


Fig. 4-11. The vertical displacement per event on the northern SCF ranges from 1.2 m to 2.9 m, with the largest values in the center of the fault (San Isabel Creek) and the smallest values on the shortest segment (Blanca segment, 3 km long). For the Crestone segment (Dmax=2.9 m; Davg= 1.6 m), Wells and Coppersmith (1994) estimate M=6.9 and M=6.9, respectively for normal faulting earthquakes. However, M6.9 earthquakes should not rupture the entire length of the Crestone segment (90 km); a 90 km-long normal surface rupture has an associated magnitude of M=7.4. Instead, M6.9 normal surface ruptures tend to be about 28 km long., or about 1/3 of the length of the Crestone segment.
Because of this disparity, USGS currently models the SCF in the National Seismic Hazard Map as having a possible M~7 earthquake that is allowed to "float" randomly along the mapped length of the SCF.

Recurrence intervals between the latest few paleoearthquakes were computed in two ways: (1) from dated samples of multiple events within trenches, but more commonly (2) from dividing the estimated age of the displaced geomorphic surfaces by the inferred number of surface-faulting events. Method 2 yields only average recurrence times over multiple seismic cycles. It also assumes that, at each fault scarp profile, the geomorphic surface above and below the scarp is the same surface. If this is true, then today's measured scarp heights are equal to the vertical displacement since the surface was formed.

Field evidence observed subsequent to 1980 suggests that this simplistic assumption is not true in many locations along the fault, and become less likely as fault scarps become older and higher. In those latter cases, it becomes more likely through time that the geomorphic surface below the scarp is a younger, post-faulting aggradation surface considerably younger than the surface above the scarp. If that is true, then todays measurable fault scarp height is just a minimum estimate of the vertical fault displacement since the formation of the geomorphic surface above the scarp. This, in turn, means that the number of paleoearthquakes estimated from fault scarp heights becomes a progressive underestimate as scarps are higher/older. Put another way, we may be missing displacement events the farther back in time we go. This may be one reason that the apparent recurrence intervals during older time periods (Fig. 4-12) are longer (fewer events) than the recurrence intervals in more recent geologic time. M.N. Machette noticed the same phenomenon on the Wasatch fault in the 1980s.

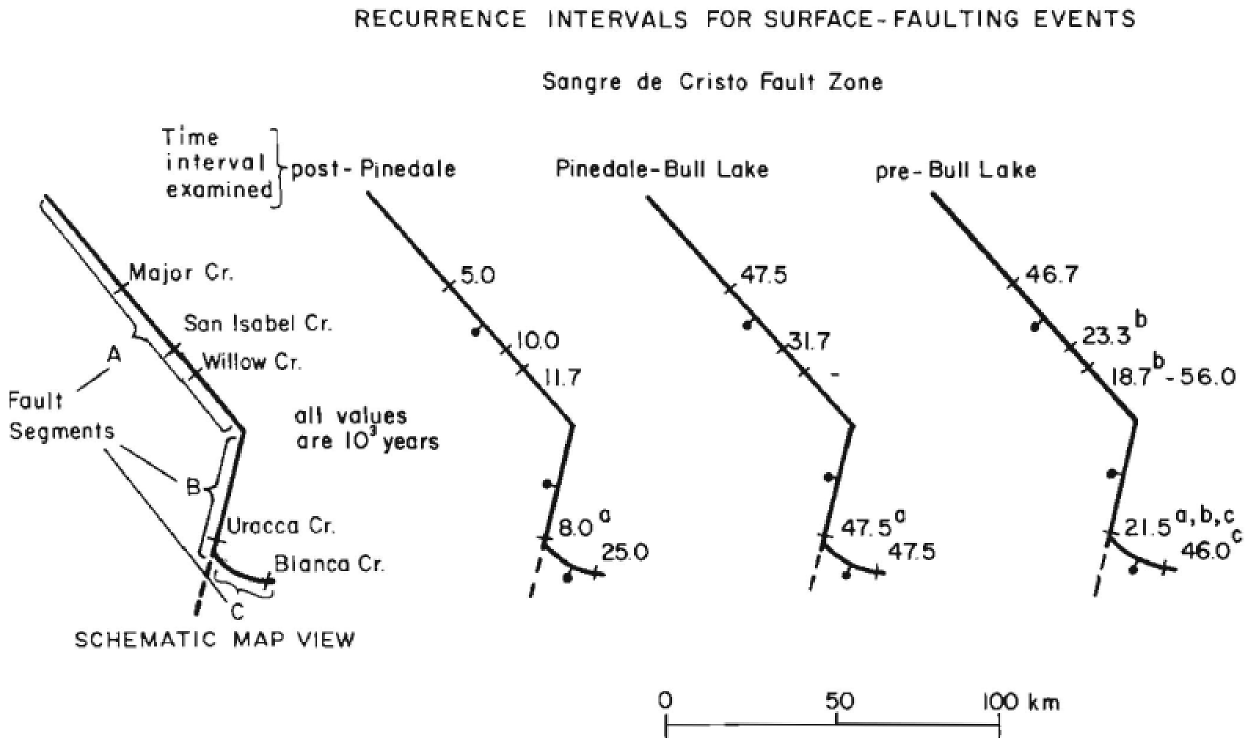


Fig. 4-12. Comparison of estimated recurrence intervals in three time periods along the northern SCF. From McCalpin, 1982.

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