# PALEOSEISMOLOGY OF THE SANGRE DE CRISTO AND VILLA GROVE FAULT ZONES, SAN LUIS VALLEY, COLORADO

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

Manual logging of teaching trench across the Villa Grove Fault Zone

**Edited by J.P. McCalpin**
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# PALEOSEISMOLOGY OF THE SANGRE DE CRISTO AND VILLA GROVE FAULT ZONES, SAN LUIS VALLEY, COLORADO

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TABLE OF CONTENTS

# INTRODUCTION

The Intra-Meeting Field Trip (Wednesday afternoon, June 1) travels from Crestone to the Valley View Hot Springs area, a 80-mile (130 km) loop (Fig. 1). The trip will visit several sites of Holocene faulting on the range-front Sangre de Cristo normal fault, and the Villa Grove splay fault on the valley floor. From Crestone, we will drive north to the paleoseismic teaching trench on the Villa Grove Fault Zone. From there we will drive east to the range front of the Sangre de Cristo Mountains, and south along the range front to Major Creek, a site of multiple-event normal fault scarps. From Major Creek we will continue south on the valley floor to the mouth of San Isabel Creek to visit the complex fault scarps there. Returning to Crestone, we will drive south into the Baca Grande subdivision to view the high peaks of the Crestone Group (>4000 m). On the way back to the Baca Campus venue, our last stop will be at a Tibetan-style stupa built by one of the 22 spiritual centers at Crestone.

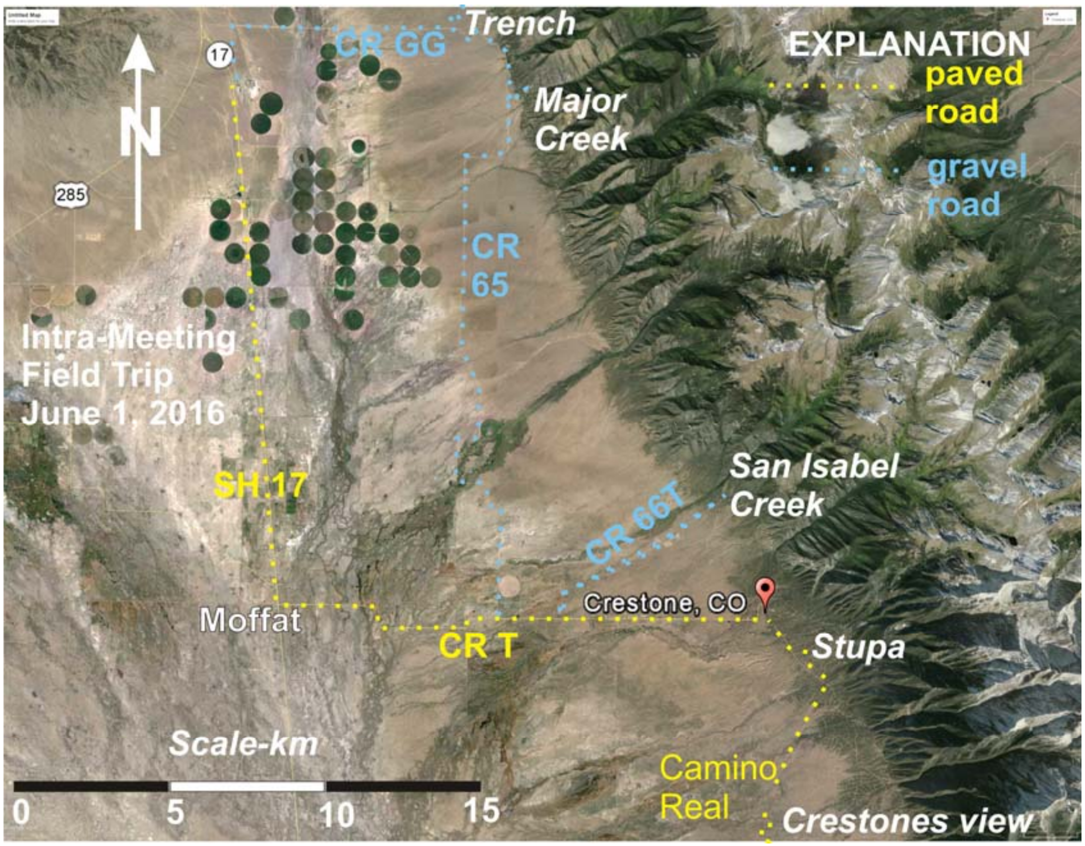



Fig. 1. The route of Intra-Meeting field trip utilizes paved roads (yellow dotted lines) and unpaved roads (blue dotted lines) in the northern San Luis Valley of the Rio Grande rift.

Acknowledgments: We thank the Orient Land Trust for permitting access to the paleoseismic teaching trench, and to John Eiseman for access to the scarps at Major Creek. Deborah Easley of the Pundarika Foundation facilitated access to the Stupa of Enlightenment

# ROAD LOG

Mileage

***START*** ***-Depart 1 pm from Desert Sage Restaurant*** *and drive NE on Townhouse Entrance Road*

*0.2 turn L (W) onto County Road T and drive west 12.0 miles to Moffat, Colorado*

*12.2 turn R (N) onto Colorado Highway 17; proceed north for 12.2 mi to Joyful Journey Hot Springs*

*24.4 turn R (E) on County Road 58EE; road bends to N and passes entrance to Joyful Journey; continue N 1.4 mi to junction with County Road GG*

*25.8 turn R (E) onto County Road GG and drive 4.95 mi E*

*30.8 just past cattle guard, turn L (N) onto an unimproved dirt road; this road curves to R and then straightens; follow it to end (0.6 mi)*

## STOP 1- VILLA GROVE FAULT ZONE AND THE PALEOSEISMIC TEACHING TRENCH (1:45 pm; 31.4 mi; 1 hour stop)

From Grauch and Ruleman, 2013:
The northern half of the San Luis Basin, in the northern Rio Grande rift, forms an asymmetric, east-tilted half graben, with 6-7 km of total displacement [12, 15]. The Sangre de Cristo fault zone (Figure 2) is commonly cited as the eastern margin of this half graben, extending in length from 79 to 104 km, depending on whether it is defined by orientations of the range front, slip rates, or geomorphic expression…. Sediments that filled the Miocene-Pliocene basins consist of poorly consolidated sands, silts, and gravels of the Santa Fe Group. Deposits of this age are found at high elevations to the east and north of the study area, suggesting that early rifting had a different orientation and locus of deposition in this region before Pliocene time…. Our study area is located where the basin narrows dramatically (Figure 2 inset) and marks the southern end of a poorly understood zone of transition from the strongly east-tilted half-graben of the central San Luis Basin on the south, to a strongly west-tilted half-graben in the next basin to the north.

Several periods of Pleistocene glaciation in the region are recorded by deposits of stream and fan alluvium, till, and outwash, which are mainly preserved near the mountain fronts. The relative ages of these deposits are determined from geomorphology and degree of weathering and soil development. From the youngest to the oldest, these deposits are Qfy, Qfi, and Qfo (Figure 2) and are associated with Pinedale, Bull Lake, and pre-Bull Lake glaciations, respectively. Based on regional correlations from previous and recent work, the glaciations in this area correspond to the following age ranges:
**Pinedale (12–30 ka),**
**Bull Lake (about 120–170 ka),**
**pre- Bull Lake (170–640 ka)**
The most recent (<10 ka) deposits in the area are Holocene stream and fan alluvium deposits, unit Qh (Figure 2).

Precipitous, faceted spurs aligned along the range front mark the steeply west-dipping northern Sangre de Cristo fault zone on the east side of the valley (Figure 2). The northwest –trending Villa Grove fault zone, composed of multiple, mainly southwest-facing scarps developed in fan deposits, diverges from the northern Sangre de Cristo fault zone near the southeastern corner of the study area. The zone extends northwestward across the valley for about 10 km, in apparent connection with easterly facing scarps on the west side of the valley near Villa Grove (Figure 2] suggests that much of Rio Grande rift structure is inherited from preexisting Laramide thrust fault geometry, but with reversed sense of motion.

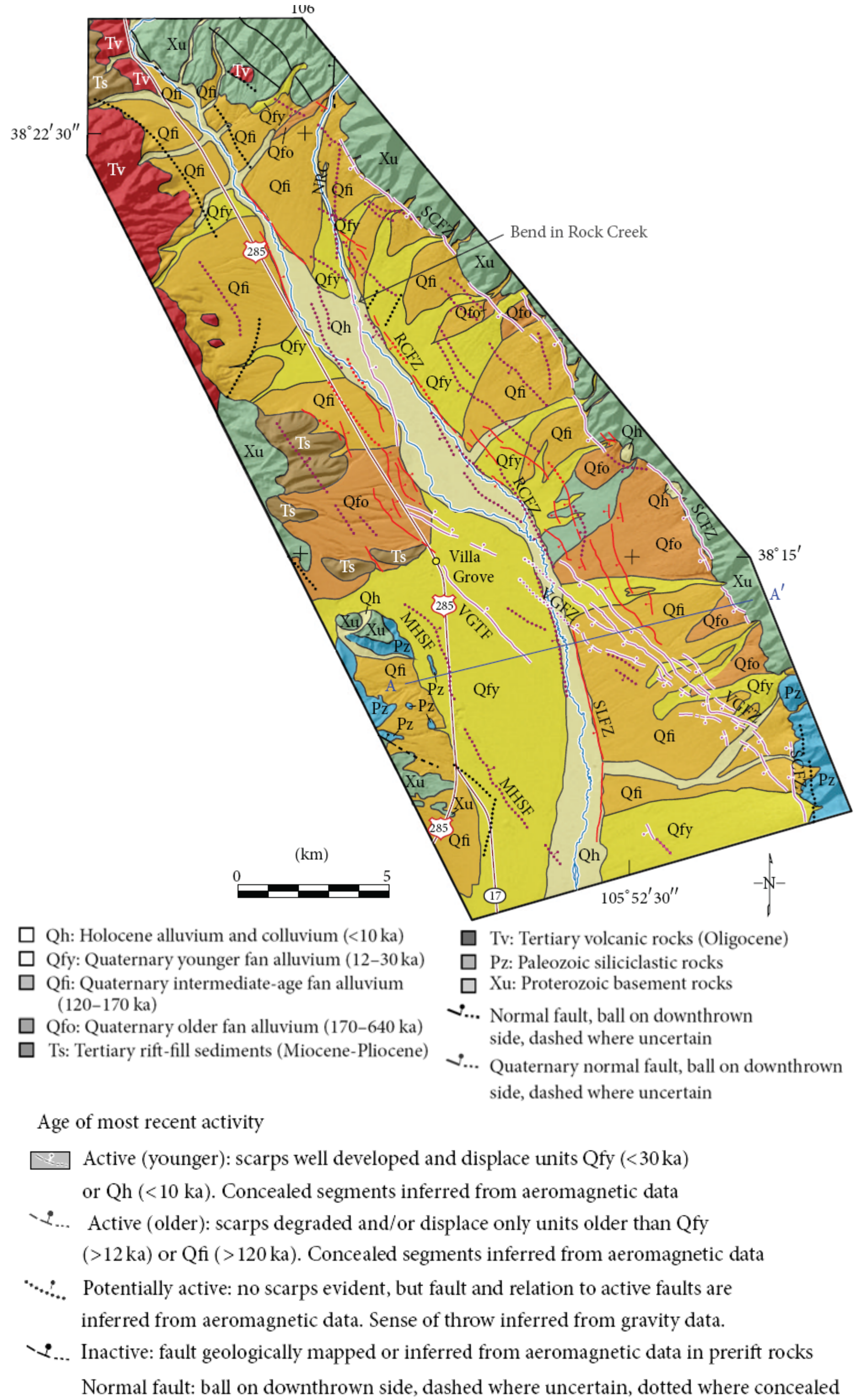



Fig. 2. Surficial geology and inferred active faults and buried fault segments resulting from combined interpretation of the aeromagnetic and LiDAR data for the study area. MHSF: Mineral Hot Springs fault (revised), NRC: Northern Rock Creek; RCFZ: Rock Creek fault zone, SCFZ: Sangre de Cristo fault zone, SLFZ: San Luis Creek fault zone, VGFZ: Villa Grove fault zone, and VGTF: Villa Grove town fault. Model for A-A′ is shown in Figure 16.From Grauch and Ruleman, 2013.

Generalized faults identified by combined interpretation of the aeromagnetic and LiDAR data are presented in Figure 2. Faults were classified by the age of their most recent rupture and relations to other active faults. Younger active faults show LiDAR evidence of displacement of the younger Quaternary units, so they ruptured <10 ka (post-Qh) or <30 ka (post-Qfy). Older active faults displace the older units, so they ruptured between 120 ka and 170 ka (post-Qfi) or between 170 ka and 640 ka (post-Qfo) or are cross-cut by younger active faults. Faults identified by the aeromagnetic data only are considered potentially active if (1) they are buried by any of the Quaternary deposits; (2) they align with trends of active faults nearby, or (3) a combination of these. If faults identified solely by aeromagnetic data do not meet the criteria of a potentially active fault, they are considered inactive and concealed (Figure 2). The sense of displacement of normal faults was determined primarily from the orientation of scarp faces apparent from the LiDAR data. They were inferred from gravity data where scarps were not present and the inferred faults followed gravity gradients, although local structures violating this assumption are possible. Modifications to the mapping of Quaternary deposits were recognized while determining the age of faulting. These modifications are depicted generally on Figure 2 as well. Both the LiDAR and aeromagnetic data (where they cover the range front) suggest the Sangre de Cristo fault is segmented along the northwest strike of the range front and can have multiple discontinuous strands parallel to each other, some of which may be represented by potentially active faults.

The Villa Grove fault zone is similar in character as mapped previously, but the aeromagnetic data indicate which of the multiple faults may have experienced the most displacement. The Villa Grove town fault, named herein, suggests that poorly defined faults mapped previously extend for 5–7 km and pass through the town of Villa Grove. The Mineral Hot Springs fault is revised to apply to an inferred fault in the aeromagnetic data underneath Holocene deposits that parallels the previously inferred fault at the stream bank but passes on the east rather than west side of the hot springs. Faults are evident along both San Luis Creek and Rock Creek, supporting a tectonic or fluvially modified tectonic origin for steep scarps located at stream banks. The aeromagnetic data provide additional information about their extents in between discontinuous scarps and suggest several totally buried, potentially active faults are present on both sides of the valley.

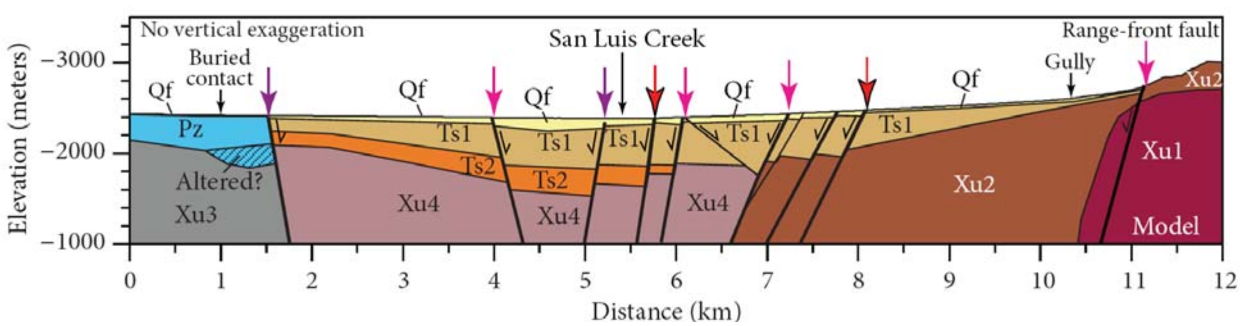



Fig. 3. Interpreted E-W cross-section across the northern SLV just south of Villa Grove (line of section A-A’ shown on Fig. 2).

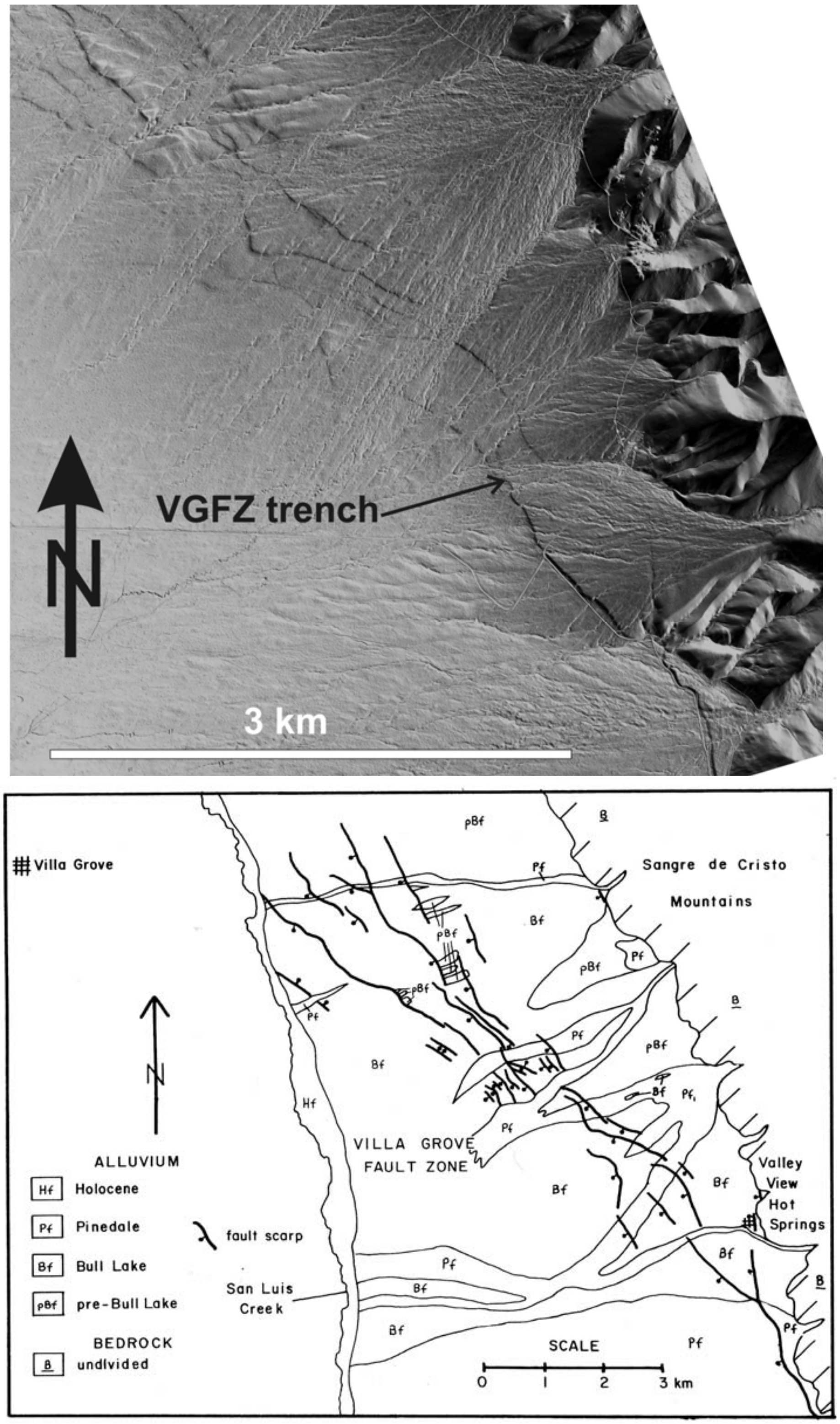



Fig. 4. TOP, Lidar bare earth DEM (1 m pixels) of the SE half of the Villa Grove Fault Zone. Illuminated from the NE. BOTTOM, sketch map of the VGFZ showing scarps and the geomorphic surfaces they offset. Pinedale=MIS2; Bull Lake=MIS6; pre-Bull Lake=MIS 8+.

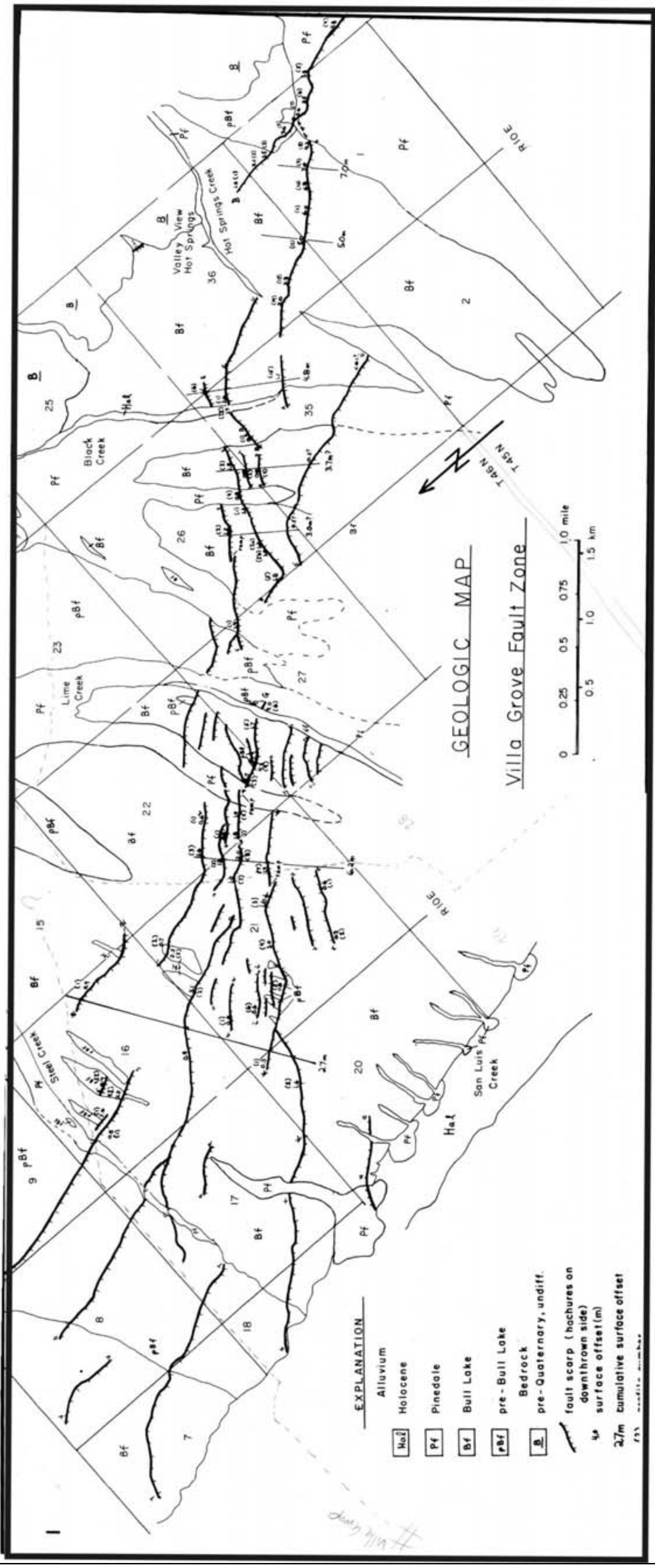



Fig. 5. Detailed map of fault scarps of the VGFZ, made from aerial photographs and field traverses (i.e., pre-Lidar). Map unit abbreviations for alluvial fan age are the same as in Fig. 4, bottom. Every scarp has been assigned a letter designation; heights of fault scarps are shown by small numbers, based on topographic profiles measured in the field.

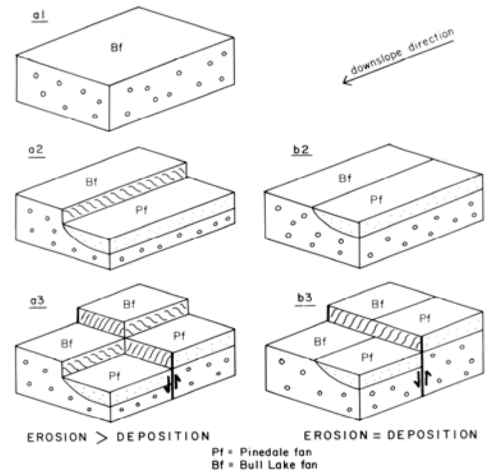



Diagram of single-event fault scarp; LEFT, above intersection point (IP); RIGHT, at IP.

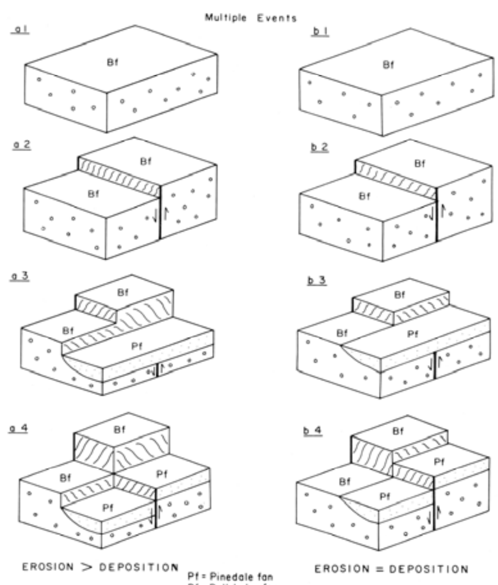



Diagram of 2-event fault scarp; LEFT, above intersection point (IP); RIGHT, at IP.

|  |  |
| --- | --- |
| Fig. 6a. Excavating the paleoseismic teaching trench on the VGFZ in June 2001. | Fig. 6b. Initial logging of the trench, June 2001. |

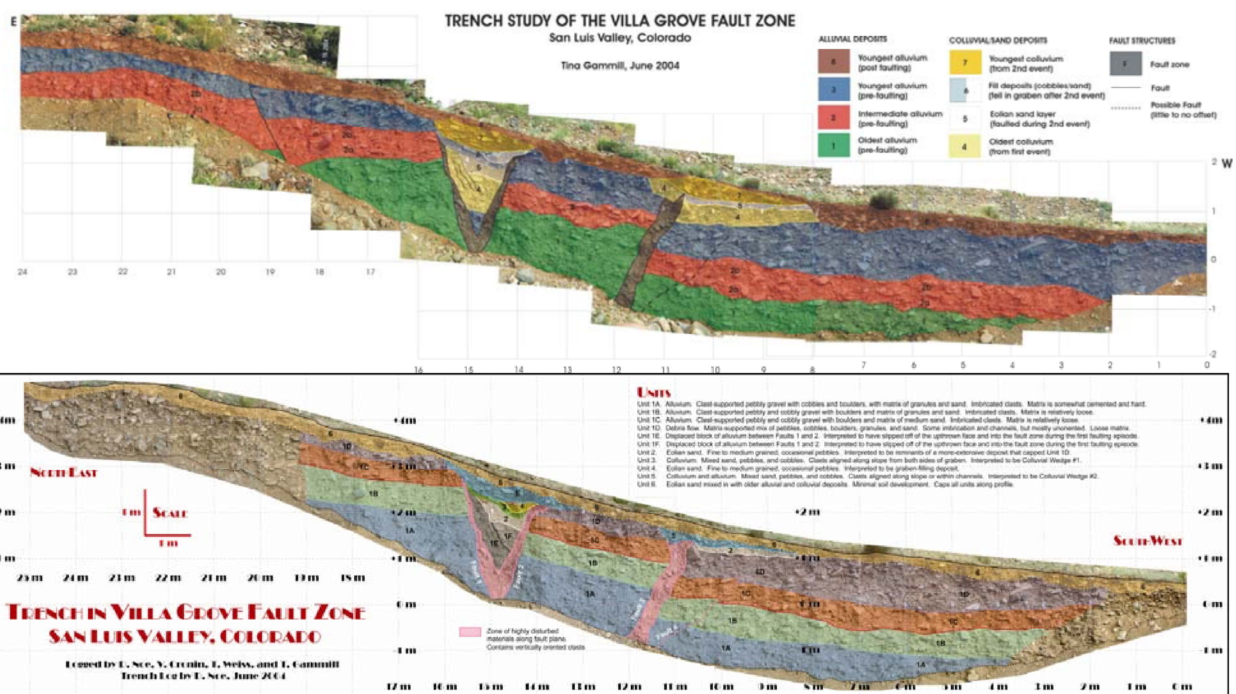
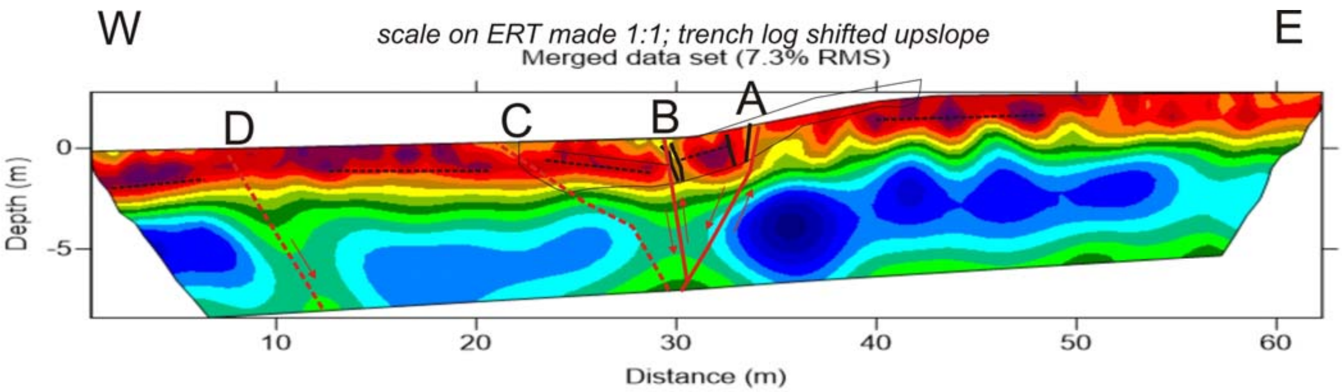


Fig. 7. Photomosiac trench logs by students, June 2004.




INTERPRETATION: 1- on Fault A, refraction that created the graben occurred just below the trench floor; Fault A must flatten downward to avoid penetrating the low-resistivity deposits of the footwall (dark blue); 2- Fault B probably steepens with depth, to stay in the center of the medium-resistivity zone (green); 3- bedding (dashed black lines) on the footwall and hanging wall is essentially horizontal, but in the fault zone is shown to dip. Between Faults A and B the apparent dip is 14 degrees toward the hanging wall, and between Faults B and C is 7 degrees toward the footwall. Both of these tilts are seen in the trench wall, but not as extreme. In other words, the ERT appears to exaggerate the dips. 4- the ERT implies two additional structures (dashed red lines) not exposed by the trench. Fault C is inferred because the dips toward the footwall (between B and C) do not continue farther west, but flatten out. Also, the medium-resistivity zone beneath Fault B seems too wide to just be caused by Faults B and C. This inferred "fault" may be a simple extensional hinge zone, and was not recognized in the far western end of the trench. Fault D is inferred from the existence of another medium-resistivity zone 15 m west of Fault C, and the fact that bedding appears to steepen again west of this zone. Also, west of Fault D the low resistivity strata (dark blue) again reach the same values as seen on the footwall, whereas east of fault D the same beds are less resistive, suggesting they have been affected by faulting. The ERT suggests that the fault zone here actually spans from 10 m to 32 m on the horizontal scale (22 m wide), as opposed to the fault scarp which is only 10 m wide.

Fig. 8. One of several ERT tomograms produced by Andre Revil (Colorado School of Mines) parallel to, but about 3 m south of ,the VGFZ teaching trench.

At 2:45 pm, return on dirt track to County Road GG

*32.0 turn L (E) onto County Road GG and drive uphill for 1.1 mi to junction with County Road 65*

*33.1 turn R (E) onto County Road 65; for the first 0.5 mi the main fault scarp of the Villa Grove Fault Zone is on your left*

*33.6 CR 65 begins to curve in junction area of Villa Grove Fault Zone and Sangre de Cristo Fault; continue for 0.4 mi*

*40.0 CR 65 parallels the main scarp of the Sangre de Cristo Fault, which lies in a dense grove of aspens trees to L (E) of road; grove continues for 0.5 mi*

*40.5 junction with driveway to Garner Creek Ranch; continue south; scarps of Sangre de Cristo fault are to the E*

*41.1 turn L (E) into driveway of Major Creek Ranch; drive 0.37 mi and park by ranch house W of fault scarps (3 pm)*

## STOP 2- MAJOR CREEK, MULTIPLE-EVENT FAULT SCARPS (3:00 pm; 41.5 mi; 45 min stop)

The Major Creek fanhead displays one of the best multiple-event fault scarps within the Rio Grande Rift Zone. Quaternary alluvial fan deposits of five ages are offset by a single strand of the Sangre de Cristo Fault Zone. Detailed scarp profiling, soil description, and scarp trenching yield a coherent picture of multiple surface-faulting earthquakes (as many as 13) in roughly the last 400,000 years, with displacements of 5.2 ft to 7.2 ft (1.6 m to 2.2 m) per event. The last such event occurred about 7,660 ± 140 C-14yr B.P. The timing and style of faulting are important for two reasons:
(I) they indicate the probable way in which the structural relief of the Rio Grande Rift has developed by numerous small-scale earthquake displacements, and (2) they identify the Sangre de Cristo Fault as one of Colorado's few active faults, based on both Holocene activity and recurrent late Pleistocene activity. The significance of this locality in relation to regional tectonics is described in recent reports on Quaternary faulting for Colorado (Kirkham and Rogers, 1981; Colman, 1985) and for the northern Rio Grande Rift Zone (McCalpin, 1983; Colman and others, 1985).

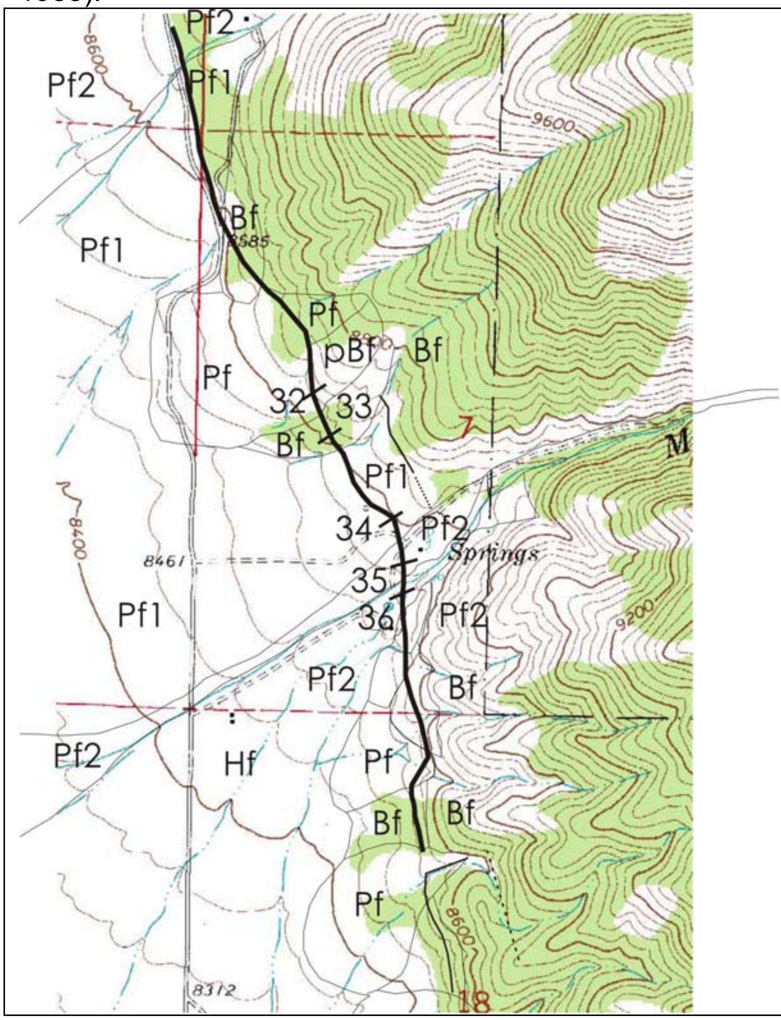



Figure 9. Geologic map ofthe Major· Creek area.
Hi-Holocene fan;
Pfl---early Pinedale fan;
Pf2-mid-late Pinedale fan;
PC-Pinedale fan, undivided;
Bf-Bull Lake fan;
pBf-pre-Bull Lake fan;
Palu-Paleozoic bedrock, undivided.

Fault scarp is a heavy line; subsidiary(?) fault segments to E are dashed lines. The numbered barred lines across the scarp show profile locations of Figure 2-x. Base map: Valley View Hot Springs 7.5' quadrangle: contour interval 40 ft (12.2 m).

See more details in McCalpin, 1987.

SITE INFORMATION

The heads of many alluvial fans on the west side of the Sangre de Cristo Mountains are offset by fault scarps, but the scarps at Major Creek show clearly the geomorphic relations with a sequence of Quaternary terraces. A set of five climatically induced fan terraces is inset into the head of the Major Creek alluvial fan (Fig. 2). Although the range-bounding Sangre de Cristo Fault offsets all five terraces, some terraces are present both above and below the scarp. Such geometry indicates that the terraces are not purely strath terraces cut into the upthrown block (as described by Soule, 1978), because strath terraces would not continue below the scarp. Instead the terraces owe their origin to changes in stream regimen, presumably accompanying climatic change, and resemble non-faulted fanhead terraces common elsewhere along the range front and elsewhere in Colorado.

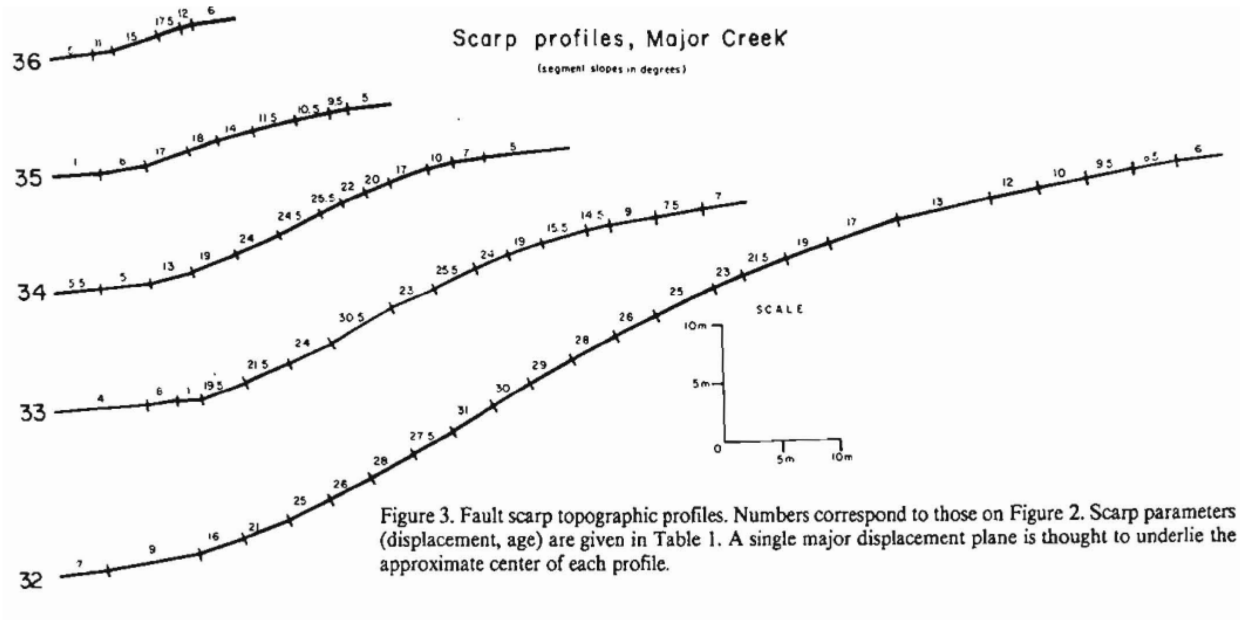



Figure 3. Fault scarp topographic profiles. Numbers correspond to those on Figure 2. Scarp parameters (displacement, age) are given in Table 1. A single major displacement plane is thought to underlie the approximate center of each profile.

Fig. 10. Topographic profiles measured across the SCF at Major Creek, on deposits of (different age. From top to bottom: Holocene (36),Late Pinedale (35), early Pinedale (34), Bull Lake (33) and pre-Bull lake (32).

The fault scarp is simple in geometry as defined by Slemmons (1957, p. 367), meaning that a single high-angle break offsets surfaces that preserve their original depositional gradient. The scarp becomes progressively higher as it offsets older fan deposits, indicating recurrent movement contemporaneous with episodes of fan formation. Deposits of five ages (Fig. 2) offset at the fanhead are correlated to glacial episodes in the Sangre de Cristo Mountains by McCalpin (1983, p. 9-37), based on relative-dating criteria and by comparison to nearby fans that can be traced directly to late Pleistocene moraines. Figure 3 shows scarp profiles across each faulted unit; the age of the unit and the vertical displacement it has undergone are given in Table 1. The number of faulting events may be estimated by assuming that the smallest scarp (#36, 5.2 ft-1.6 m-throw) represents a single event or alternatively, that the second smallest (#35, 12.5 ft-3.8 m-throw) represents two events. The number of inferred fault events with displacements of 5.25-7.25 ft (1.6-2.2 m) ranges from 5 since Pinedale time to 13 since mid-Pleistocene time (Table 1, column 4). To confirm all assumptions, the scarp at surface profile #35 was trenched; the log is presented as Figure 4.

Study of the trench confirmed that two faulting events had occurred since deposition of unit Pf 2. The first event offset lenticularly bedded, sandy to cobbly late Pinedale alluvium and created a topographic trough in which clayey, organic-rich sag pond deposits had begun accumulating by at least 10,400 ± 240 C-14yr B.P. The base of sag deposits was not exposed. Faulting is therefore roughly bracketed between the formation of the mid-late Pinedale terrace (approximately 15,000 B.P.) and 10,400 ± 240 C-14yr B.P.

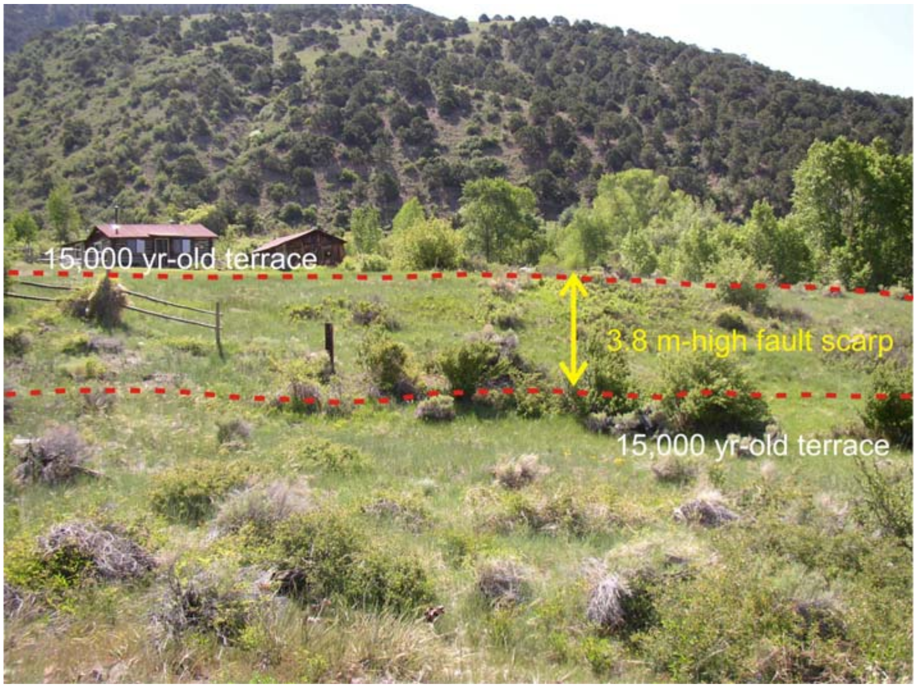



Fig. 11. The 3.8 m-high fault scarp at Major Creek crossing a late Pinedale deposit. This was the site of the 1980 trench.

A second fault event severely deformed this soft muck and created a free face that dumped 5.9 ft (1.8 m) of coarse colluvium onto the sag deposits. The uppermost sag deposit carried an organic A horizon that dated at 7,660 ± 140 B.P.-presumably no younger carbon was added after burial. The mean residence time of organic material in the A horizon may be hundreds or thousands of years, so the date of latest faulting may be somewhat younger than 7,660 D.P. Fault scarp profiling of the younger scarps (#35, #36) does not yield a comparably young date in relation to other published scarp height-slope angle data (e.g., Bucknam and Anderson, (979), because fine sands in which the scarps are developed are highly erodable.

Faulting recurrence intervals for several time periods were calculated based on scarp data. Resulting recurrence intervals seem to be considerably shorter since the Early Pinedale (Table 1,column 6). This conclusion, also reached for most other faulted fanheads along the Sangre de Cristo Fault, has two possible causes: (1) seismicity has rapidly increased within the last 25,000 years on this fault, or (2) not all earlier faulting events resulted in rupture on this fault trace. If (2) is true, as we examine longer pieces of Quaternary history, we may miss more and more fault events that occurred on other less visible traces.

Possible evidence to favor the second hypothesis is found immediately southeast of Profile 33. The base of the range front approximately 425 ft (130 m) east of the scarp here is very steep and linear. A 165-ft (So-m) high outcrop on this face exposes hydrothermally altered Paleozoic carbonate rock now altered to variegated clays (marked AC on Fig. 2). This alteration may be the result of shearing and fluid migration along a second, less active normal fault that parallels the measured scarp. However, no Quaternary deposits are offset by a projection of this suspected fault across the narrow Major Creek valley.

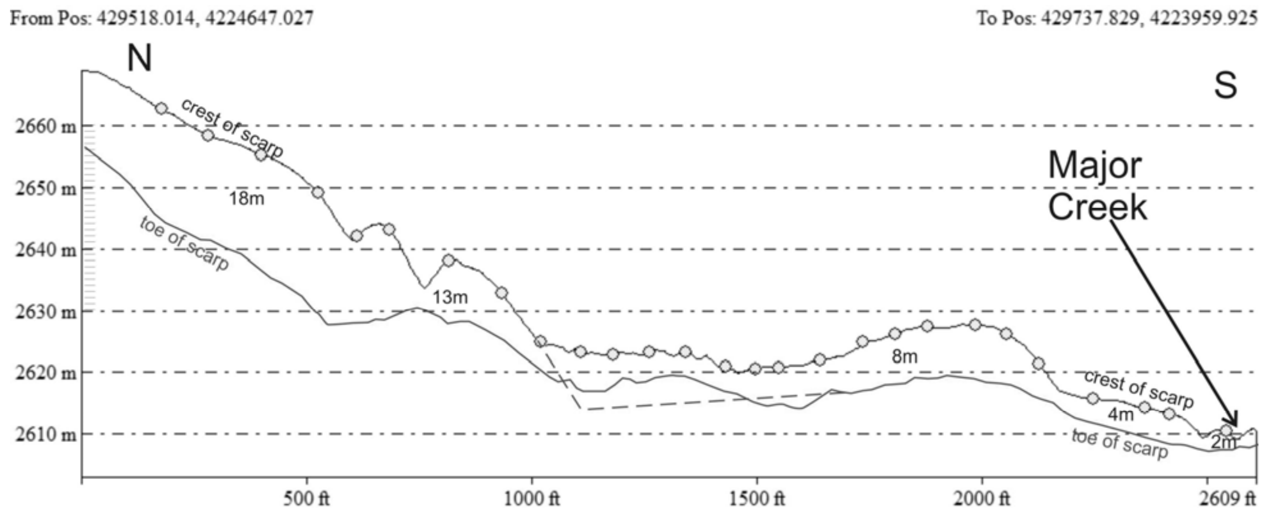



Fig. 12. Fault-parallel topographic profiles drawn along the crest of the fault scarp (black line with circles) and the toe of the fault scarp (lower line). The distance between the lines is the height of the fault scarp. Vertical exaggeration= 4.35. The red dashed line is the estimated scarp toe elevation prior to deposition of post-faulting gully alluvium. For the 2m and 4 m scarp, the upthrown and downthrown surfaces are probably correlative. For the 8, 13, and 23 m-high scarps, the downthrown surface is a younger deposit than the upthrown surface, a result of post-faulting, hanging-wall aggradation. Thus for these scarps, the height is only a minimum estimate for the true vertical displacement of the upthrown surface.

TABLE 1. FAULT SCARP PARAMETERS, MAJOR CREEK SITE

| Profile Number[1] | Deposit[2] | Fault Throw (m)[3] | No. of Faulting Events[4] | Deposit Age (ka)[5] | Recurrence Interval (kyr)[6] |
|---|---|---|---|---|---|
| 36 | Hf1 | 1.4 | 1 | 8 | 8.0 |
| 35 | Pf2 | 3.8 | 2 | 13 | 5.0 |
| 34 | Pf1 | 8.9 | 5 | 25 | 4.0 |
| 33 | Bf | 13.5 | 7 | 150 | 62.5 |
| 32 | pBf | 23.4 | 13 | 400 | 41.6 |

[1] Corresponds to numbers on Figure 3-x.
[2] Hfl, early Holocene; Pf2, mid-late Pinedale; Pfl, early Pinedale: Bf, Bull Lake, pBf, pre-Bull Lake.
[3] Measured by graphical projection of upper over lower surface, assuming a 70-degree fault dip.Yields minimum values for profiles outlined in bold, which are suspected of hanging-wall aggradation.
[4] Calculated by dividing an average 1.6-2.2 m displacement per event into the total vertical fault displacement, rounded to the nearest even number. Yields minimum values for profiles outlined in bold, which are suspected of hanging-wall aggradation.
[5] Ages from local C14 dates, and via correlation to dated glacial deposits elsewhere in the western U.S.
[6] Calculated by dividing the number of fault events (column 4) into the length of time in which they occurred (difference between ages in column 5); Example: 2 events (7 minus 5) occurred between 150 ka and 25 ka, so 125 ka divided by 2 events ~ 62.5 ka per event.

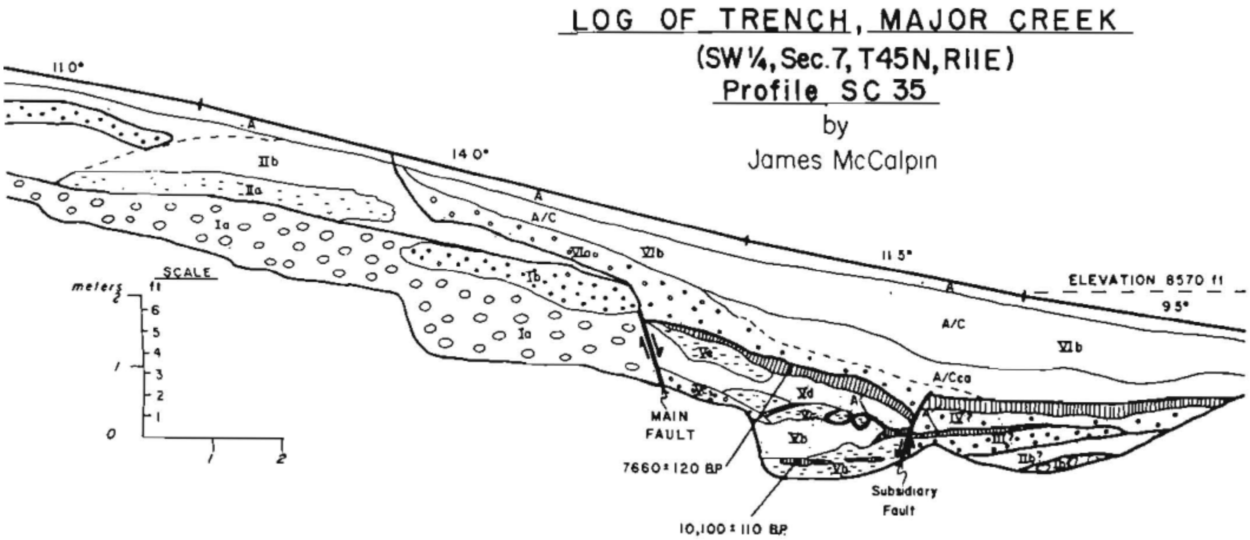



Figure 13. A portion of the log of a trench across profile 35 in mid-late Pinedale alluvium. Heavy lines bound six depositional units: I through IV-mid-late Pinedale alluvium; V---early Holocene tectonic colluvial wedge; VI-mid-Holocene tectonic colluvial wedge. Facies of major units are shown by thinner lines and lower case letters, soil horizons developed on deposits by upper case letters like A/C. Two colluvium-producing fault events are inferred. From McCalpin, 1982.

Larger features of the fault-generated range front are also visible on the approach to Major Creek. Well-developed facets truncate ridge lines above the fault zone, as described for other areas by Wallace (1978). Between narrow faceted ridges, elongate drainage basins extend perpendicularly to the range crest. Faceted spurs exhibiting multiple benches and steps are best displayed in the 12.5-mi (20.km) long range segment stretching from Major Creek south to San Isabel Creek. Steps sloping valleyward at 20° to 34° are separated by lower-angled ridge crests with 7° to 15° slopes. Four persistent facet sets have crests at approximately 10,825 ft (3,300 m), 9,512 ft (2,900 m), 9,180 ft (2,800 m), and 8,760 ft (2,670 m). The higher, larger facets are severely gullied, but the two lower sets are inset within the larger set and exhibit less dissection. The lowest facet set includes numerous small, very steep, ungullied planar facets that rise directly above fault scarps in Quaternary deposits. This geometry suggests that periodic rapid uplift of the mountain block has alternated
with tectonic quiescence and range-front parallel retreat within the late Cenozoic. Recurrence interval data in Table 1 also show that variable activity occurs within shorter time spans and suggest that intervals between individual earthquakes or swarms of earthquakes have varied widely in the late Cenozoic.

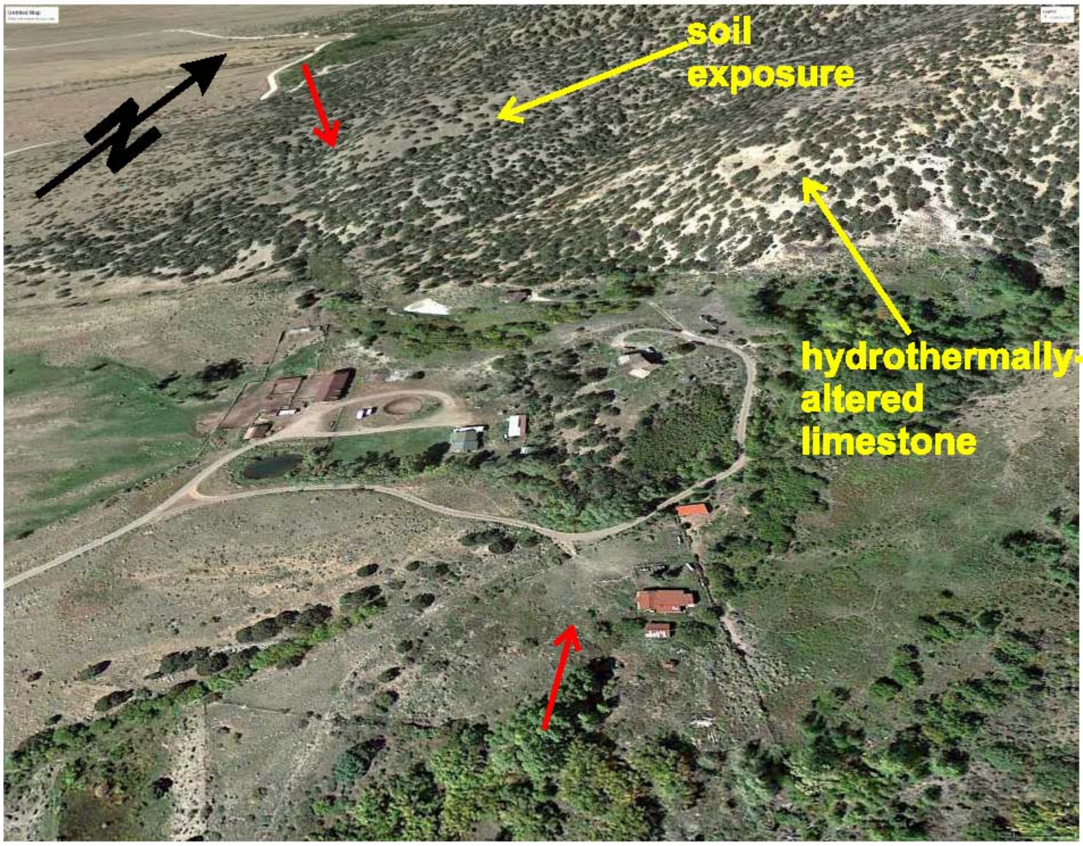



Fig. 14. Google Earth view of the Major Creek site, looking N30W parallel to the range front.

3:45 pm; return to County Road 65

**Road Log**

*41.9 turn L (S) onto County Road 65 and drive South; follow many turns over the next 25 miles turns*
*44.7 road crosses Cotton Creek*
*47.1 junction with County Road AA; turn L (W) and drive 80 m on CR AA, then turn L (S) and continue on CR 65*
*48.9 road crosses Wild Cherry Creek*
*52.5 road crosses Rito Alto Creek*
*56.5 junction with County Road T; turn L (E) and drive toward Crestone*
*58.0 turn L (N) onto County Road 66T; drive N and then ENE on this road for 5.0 mi*
*63.0 jeep road from Crestone enters from South; last place to park for low-clearance vehicles; others can continue; road turns to NE, continue for 0.2 mi*
*63.2 good parking area for smaller vehicles*

## STOP 3- SAN ISABEL CREEK, MULTIPLE-EVENT FAULT SCARPS (4:30 pm; 63.2 mi; 30 min stop)

At the mouth of San Isabel Creek, a prominent 3.2-km long scarp offsets five surfaces, ranging from pre-Bull Lake to mid-late Pinedale age (Fig. 15). Scarps range from 4.4-m high in mid-late Pinedale alluvium to 39.1-m high in pre-Bull Lake alluvium (directly N of the creek). Single-event displacement, based on the calculated throw of the smallest and youngest scarp, is roughly 2.5 m.

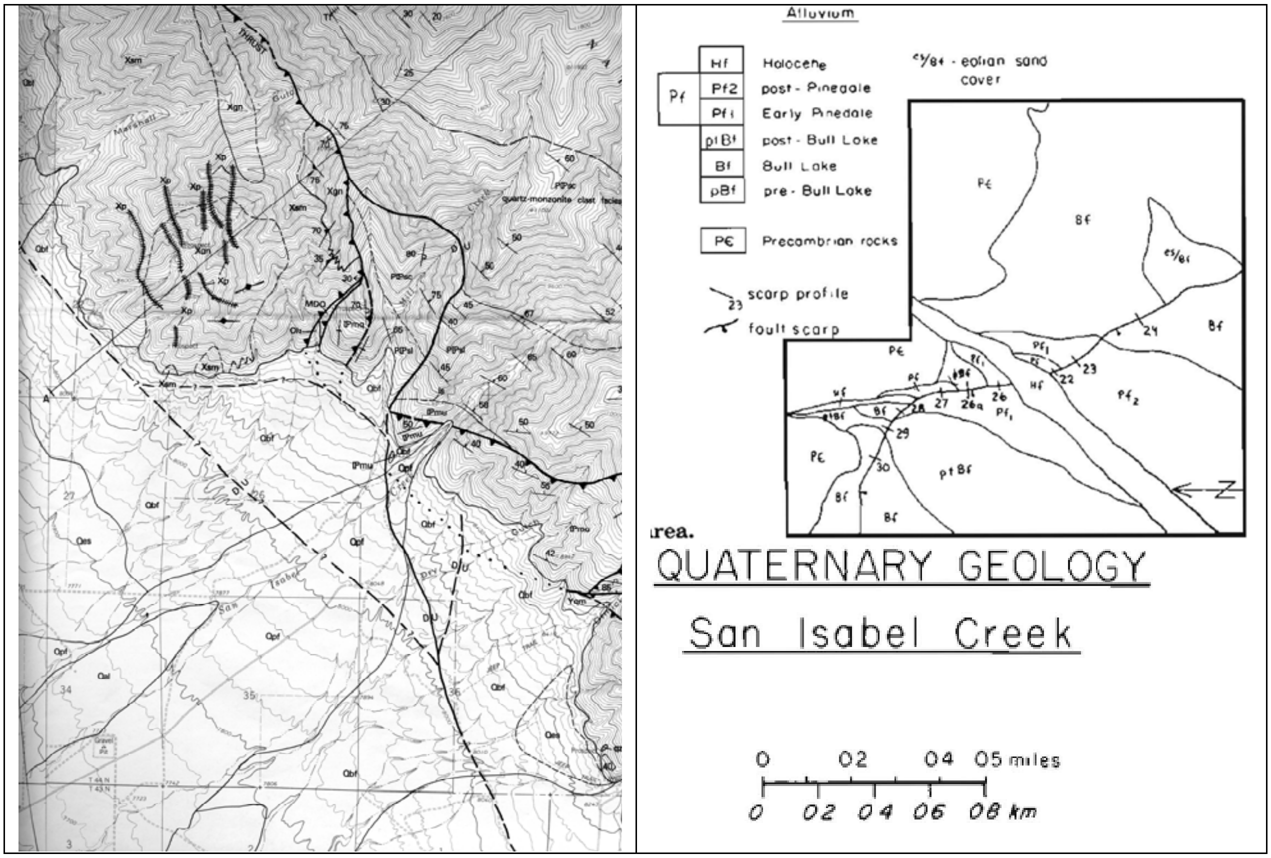
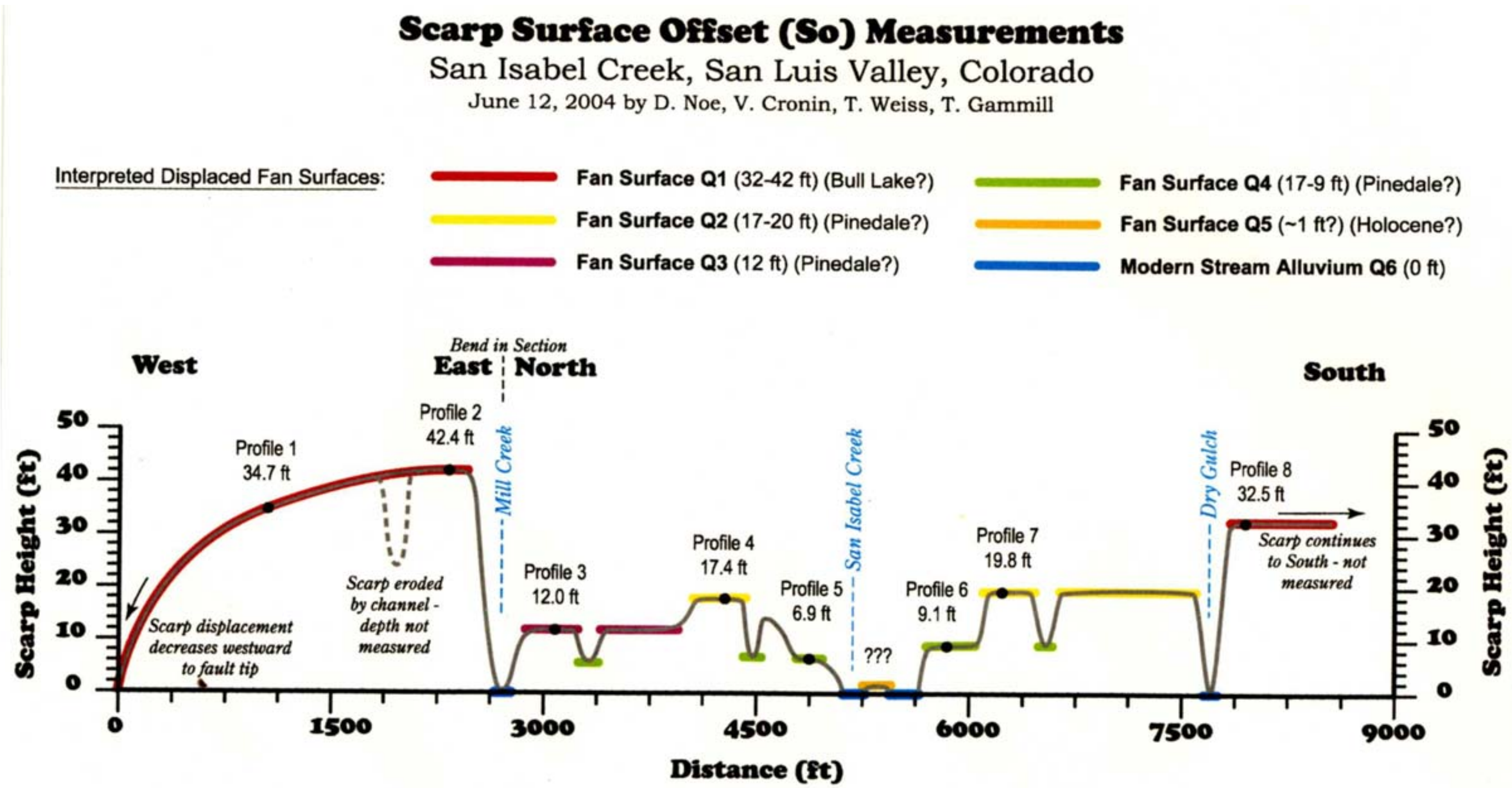



Fig. 15. LEFT, Topographic map of the SCF centered on the mouth of San Isabel Creek; north is at top. Original map scale 1:24,000, contour interval 40 ft (12 m). Mapping of fault traces and geologic units is from Lindsey et al., 1985). RIGHT: Sketch map of a smaller area at the mouth of San Isabel Creek, with North to the left. Numbered lines crossing the fault trace are sites of fault scarp profiles. From McCalpin, 1982.

Pages 19-23 are bare-earth lidar DEMs of the SCF, annotated with the locations of fault scarps and their height in meters. The images are screenshots from Global Mapper v14 GIS, displayed as grayscale slopeshades; the grayscale is stretched between white (slopes of 0°) and black (slopes >20°). These five maps overlap very slightly, with Fig. 17 being the farthest north and Fig. 21 the farthest south. Fig, 17 is roughly centered on the mouth of San Isabel Creek and covers an area similar to that in Fig. 15-right. The vertical surface offsets (vertical separations) shown in Fig.16 TOP are smaller than the scarp heights on Figs. 17-21, because they correct for the effect of scarp decline slowly increasing fault scarp height with time on a sloping alluvial fan surface.



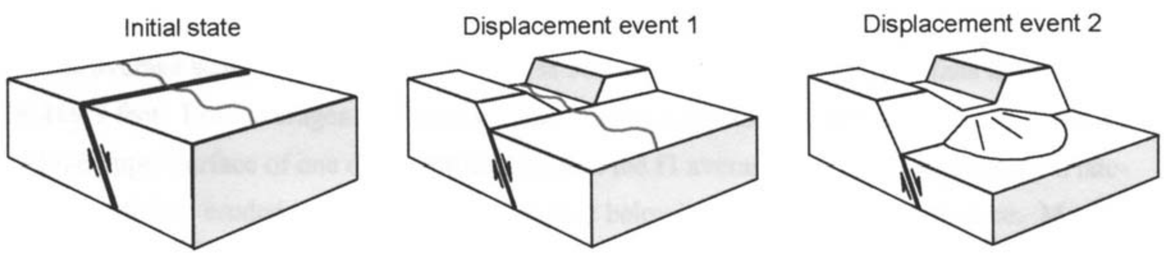




**Figure 3.** Block diagrams showing a possible scenario for development of stranded drainage channels due to two displacement events. Upper surface is the f1 surface.

Fig. 16. TOP, Fault scarp heights measured in 2004 by students at the Paleoseismology Field Camp. The area between Mill Creek and Dry Creek has smaller fault scarps because it was periodically incised between faulting events (as shown in the 3 diagrams at LEFT). Episodic footwall incision after each faulting event is confined to broad channels, so does not completely destroy the fault scarps formed by earlier events.

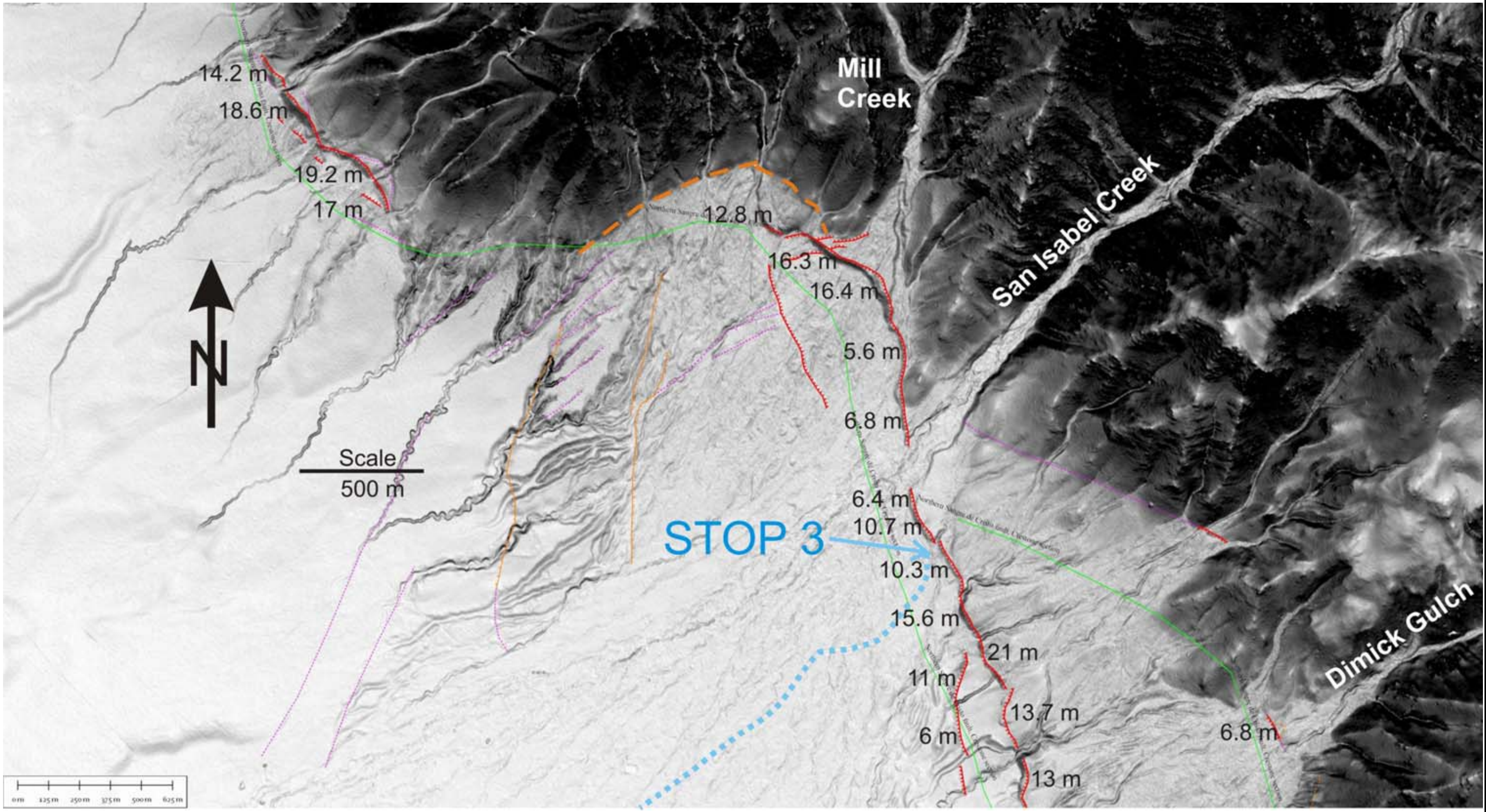



Fig. 17.Grayscale slopeshade of a 1-m bare-earth lidar DEM of the Sangre de Cristo range front; creek names are shown in white. At STOP 3 we will walk along the main scarp from the south bank of San Isabel Creek to about 500 m south, where scarps reach up to 15.6 m high. The "scarp heights" shown on Figs 17-21 represent the elevation difference between the toe and crest of the scarp. The faulted surfaces here slope 4°-8° perpendicular to the scarp, so as the scarp declines and broadens, the crest and toe become farther apart in elevation.

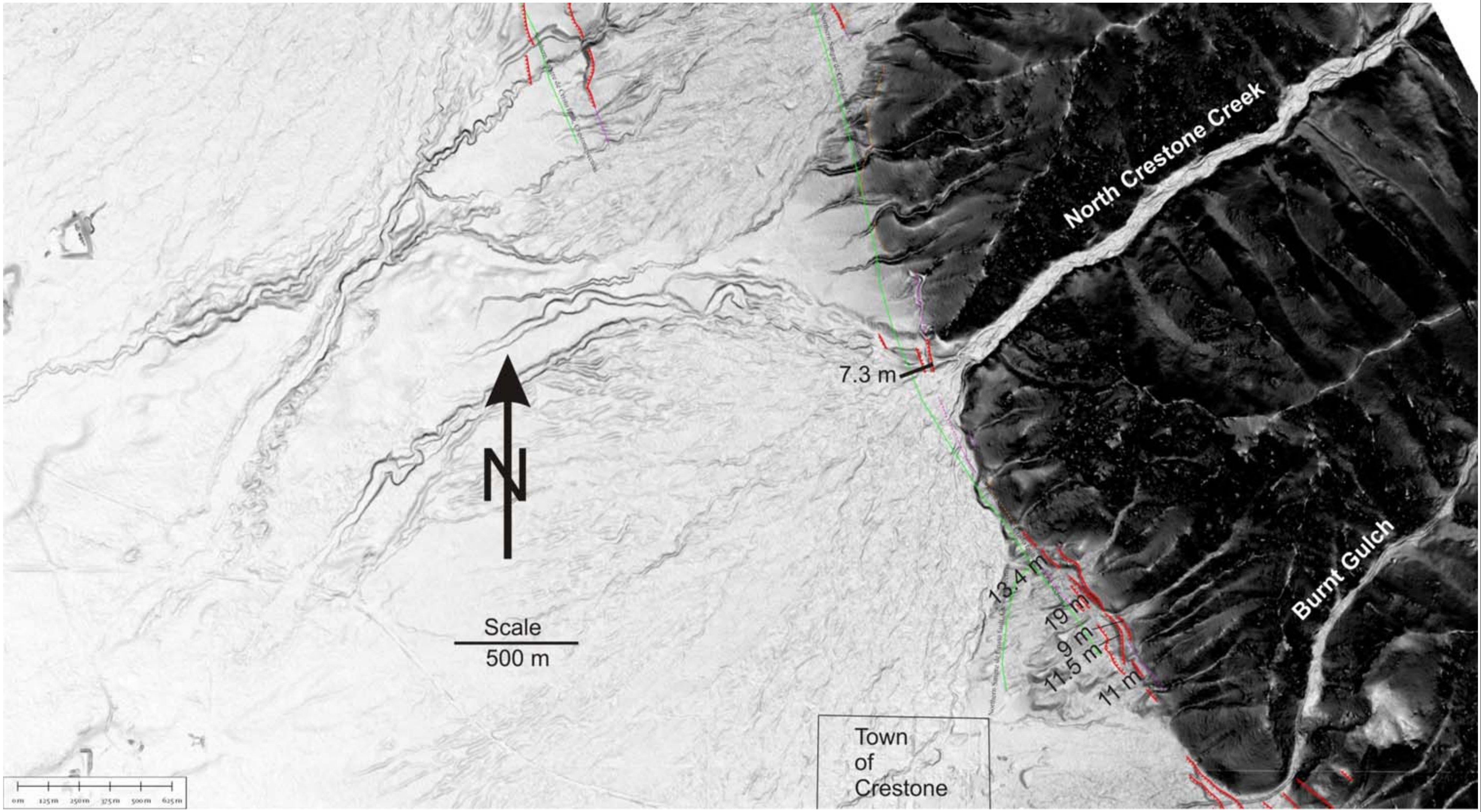



Fig. 18. Scarps between Dimick Gulch (just off image at top) and Burnt Gulch. The northern half of the Town of Crestone is visible at bottom.

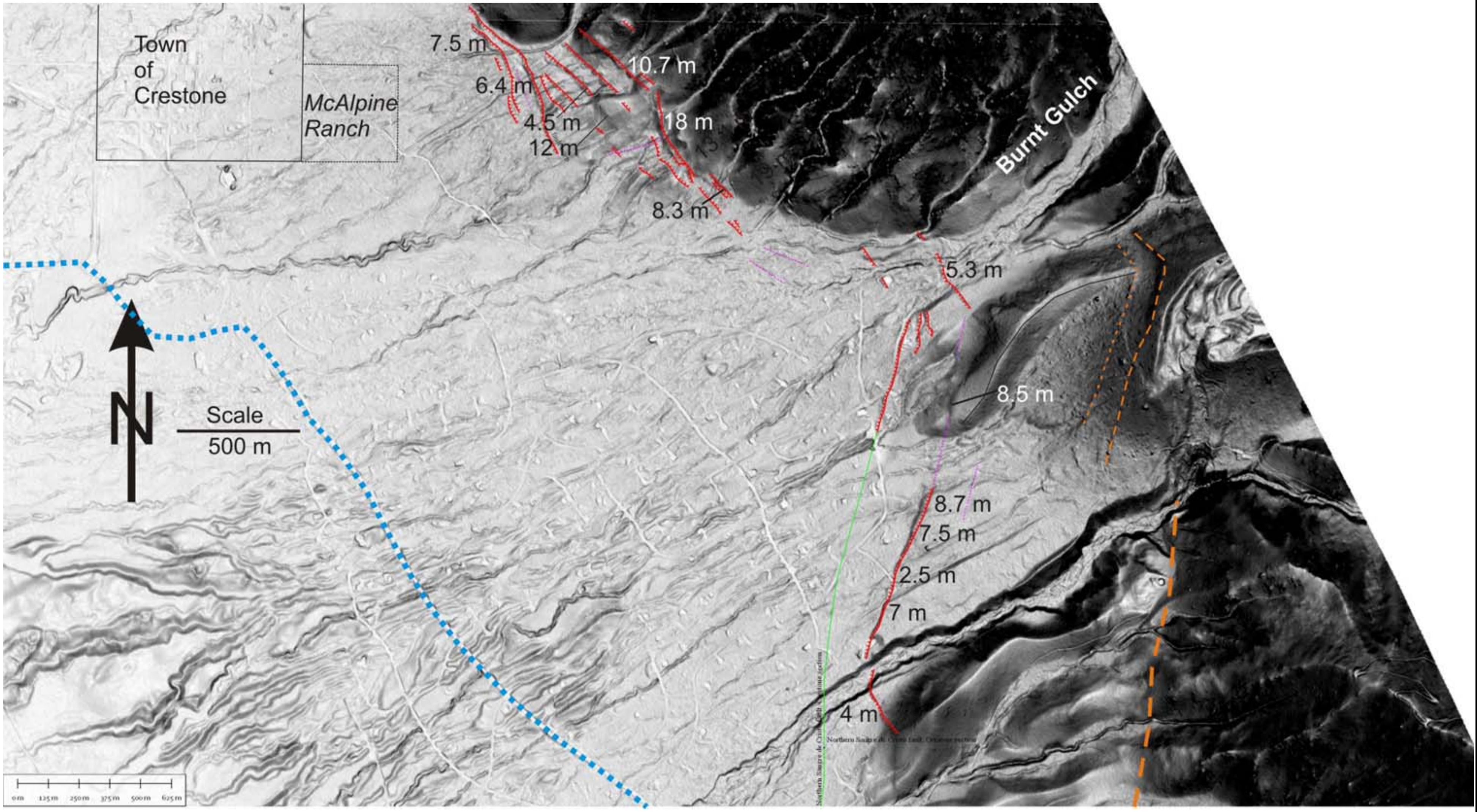



Fig. 19. Scarps between Burnt Gulch (at top center) and Willow Creek (large stream that exits the bottom of the image at center). Willow Creek flows out of the Pinedale (MIS2) terminal moraine complex of Willow Creek, visible as looping ridges on the right center margin of the image. Downslope is a preserved part of the older Bull lake terminal moraine (MIS6), which appears as a gray ridge that intersects the fault scarp where it is 8.5 m high (numbers in white). The remainder of the Bull Lake terminal moraine was eroded away by Pinedale outwash.

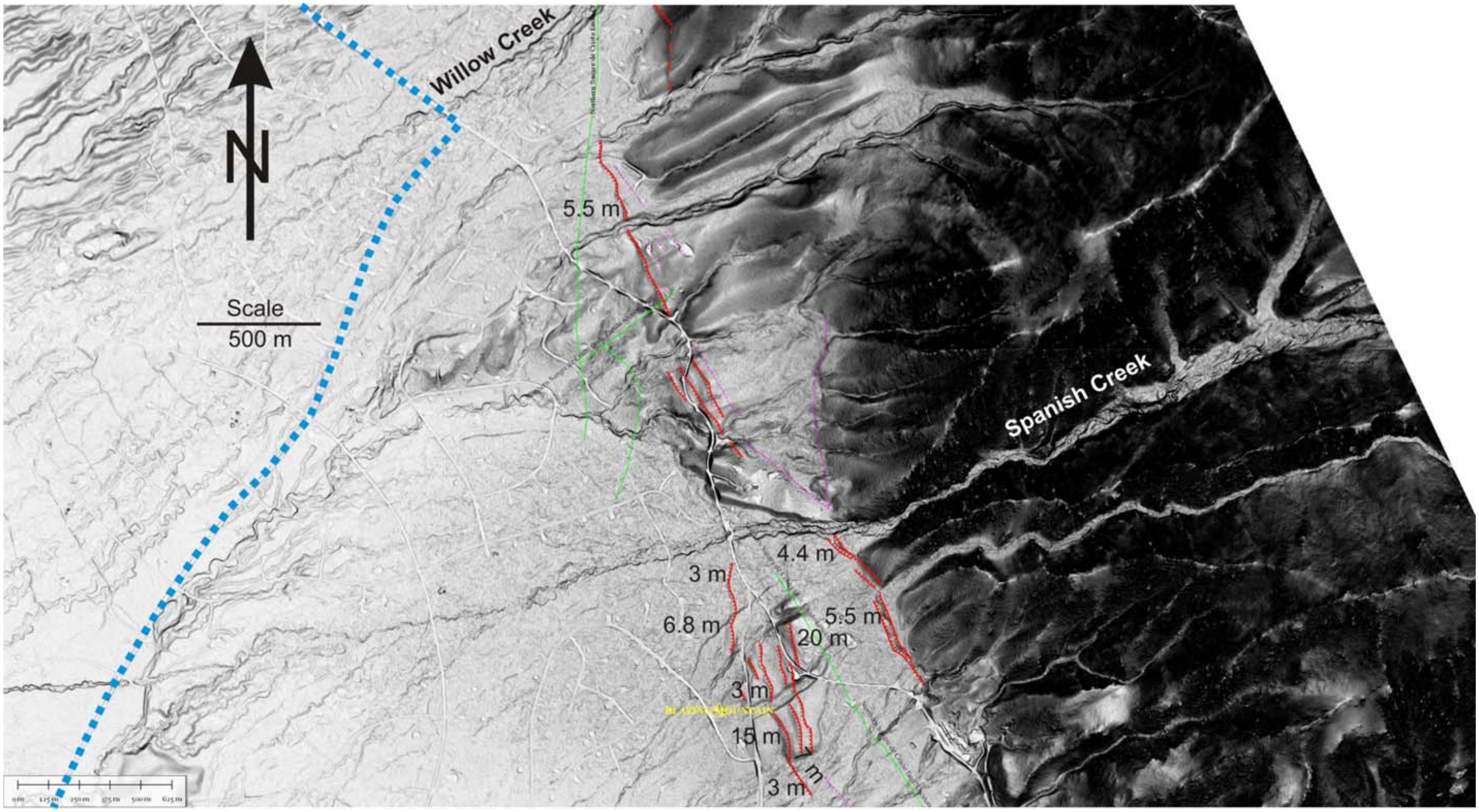



Fig. 20.Scarps between Willow Creek (top) and Spanish Creek. At lower center, south of Spanish Creek, there is an isolated remnant of older fan deposits surrounded by younger outwash. The remnant is riddled with fault scarps that do not extend across the younger outwash surfaces. Some scarps do extend from the remnant into the younger outwash, but with significantly smaller scarp heights. This fortuitous "window" into the pre-latest glacial deposits shows that the fault zone in the past has been wider and more complex than in the Most Recent Event(s).

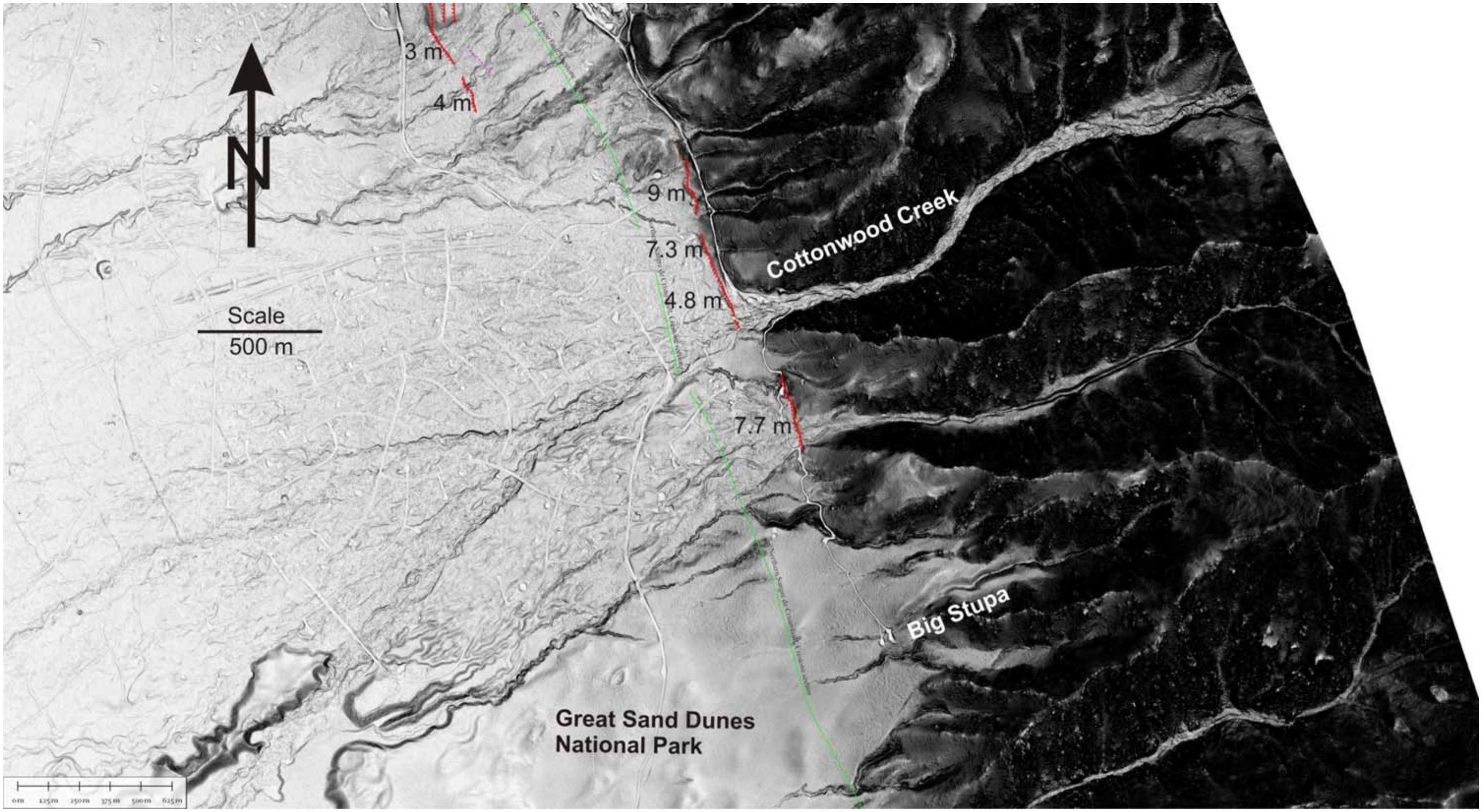



Fig. 21. Scarps between Cottonwood Creek and the Great Sand Dunes National Park. The southern part of the isolated fan remnant in Fig. 19 is just visible at top center. The terrain of this part of Great Sand Dunes National Park is a rolling eolian upland (note elliptical deflation craters) that stands above the latest braided glacial outwash fan of Cottonwood Creek. Few scarps can be traced through the eolian sand.

From **STOP 3- SAN ISABEL CREEK:**
5:00 pm; retrace route to County Road T (5.2 mi)

**Road Log**

*68.4 turn L (E) onto County Road T; drive E 4.6 mi to entrance to Baca Grande subdivision*

*73.0 turn R (S) into Baca Grande subdivision and onto Camino Baca Grande; continue south*
*73.5 Camino Baca Grande begins to overlie the old railroad bed to the mines at Spanish and Cottonwood Creeks; continue south*
*73.7 road crosses South Crestone Creek*
*74.7 Stupa of Enlightenment on Left*
*75.2 road crosses Willow Creek; road ahead leads to most Spiritual Centers, but we will turn R (W) and descend into valley on Camino Real*
*77.2 road crosses Spanish Creek; continue S*
*79.2 end of Camino Real;*

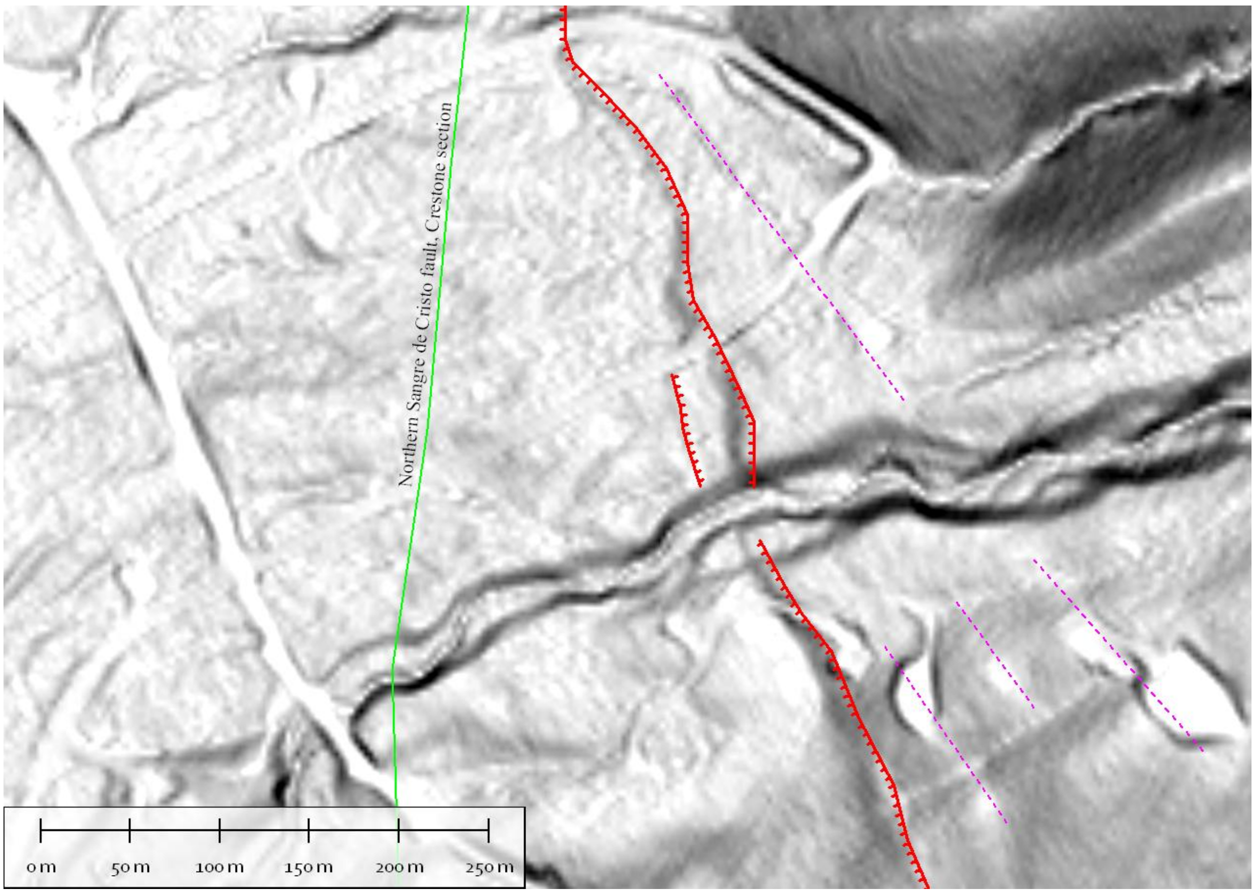



Fig. 22. OPTIONAL STOP (time permitting) at the two Baca Grande trench sites of 1980 at unnamed drainage. Road directly north of drainage crosses the scarp; it is the upslope extension of Rocky View Way. Fault scarps are shown by hachured lines. Dashed line show slope breaks of probable tectonic origin.

## OPTIONAL STOP 3.5 AT 1980 TRENCH SITES SOUTH OF ROCKY VIEW WAY

The small scarp offsetting early Holocene alluvium at Profile 9 (small inset terrace on south side of active channel) shows clear evidence of a single fault movement. Stratigraphic displacement at the fault plane was measured as 1.35 to 1.45 m (figure 74). The upthrown surface was dragged into the fault plane with a vertical drag component of 0.9 m. Thus, of the net 2.3 m of displacement across the fault zone, 0.9 m was contributed by drag and 1.4 m by abrupt offset on the fault plane.

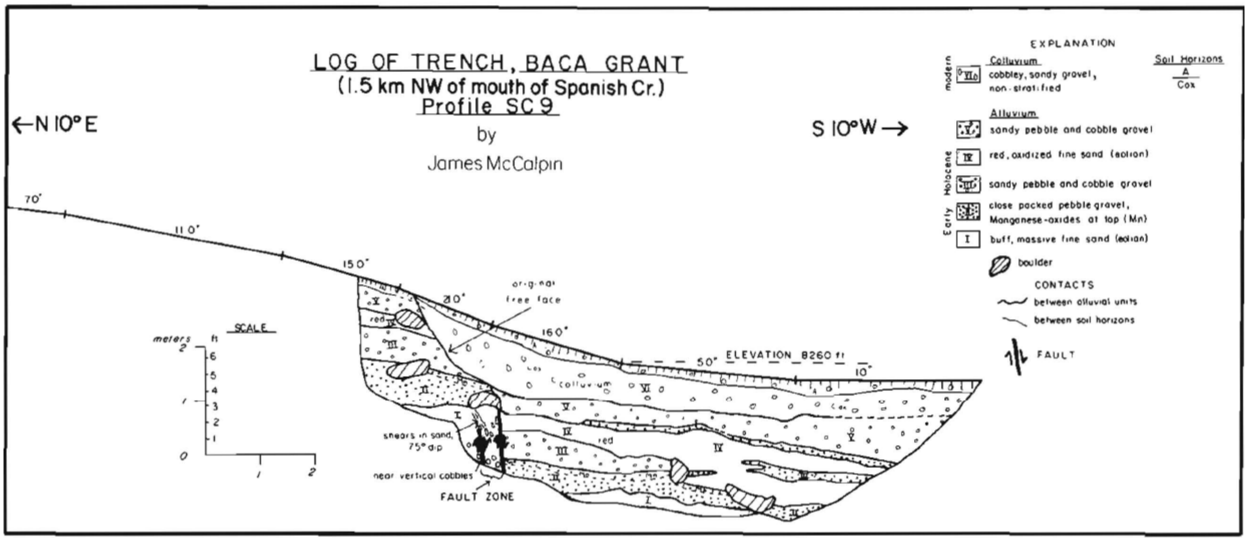



Fig. 23. Log of south wall of trench across a small (1.5 m-high) scarp across an small inset Holocene terrace, south of Rocky View Way. From McCalpin, 1982.

The larger scarp offsetting Bull Lake alluvium was fronted by a complex colluvial wedge containing three colluvial units, each grading to coarse-grained toward its base (figure 75). The colluviums contain soil profiles in their upper parts that can be compared in development to other soils observed throughout the study area. Colluvium I carries a soil with a well-developed textural B horizon and an underlying Ceo horizon; overall the soil is similar to soils developed on relict Bull Lake fan surfaces. The middle colluvium carries no soil, indicating that insufficient time for soil development occurred between its deposition and that of overlying Colluvium III. Colluvium III carries a weakly developed A/C profile which is similar in development to soils on mid-late Pinedale or early Holocene deposits.

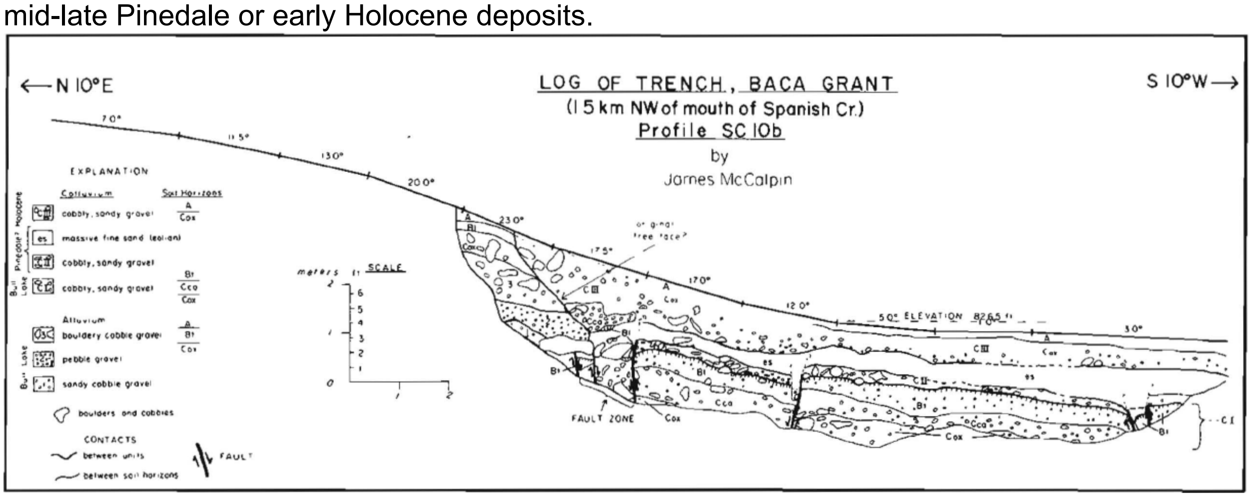
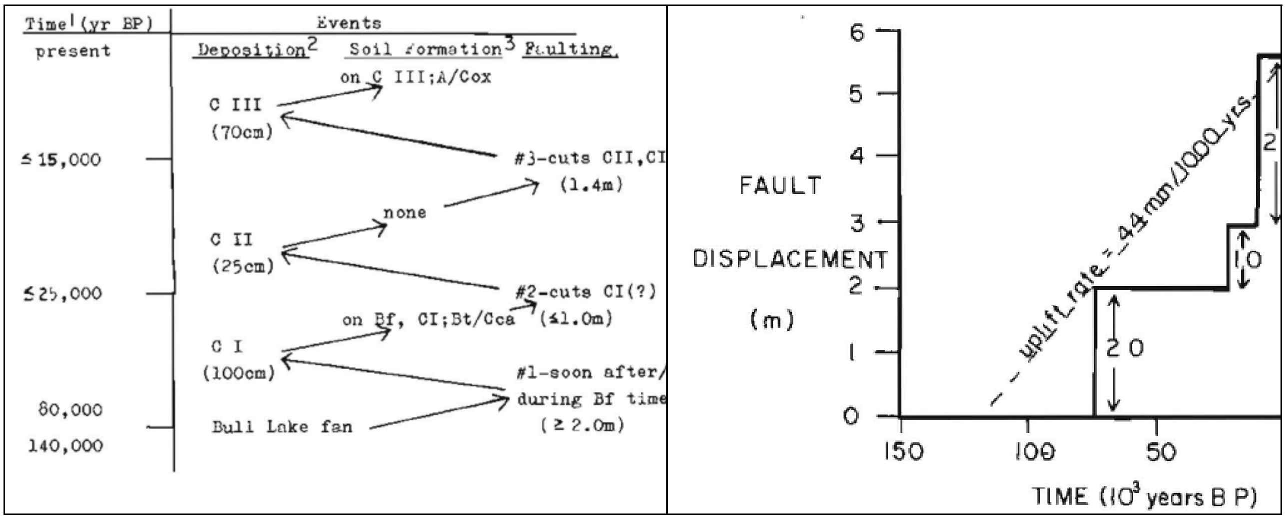



Fig. 24. Log of south wall of trench across a scarp on a Bull Lake (?) fan, south of Rocky View Way. From McCalpin, 1982

Displacements due to individual fault events can also be estimated, using several assumptions: (1) total displacement of all events (probably three) must equal the net displacement of 5.3 m; (2) the latest event had a displacement of about 2.3 m, according to the trench in the single-event scarp directly to the north; and (3) each displacement must have been equal to or greater than the thickness of the colluvial wedge resulting from renewed faulting. The degree of soil formation and deformation in the colluvial units indicates the sequence of fault events diagrammed in figure 76. This sequence is also compatible with geomorphic relations along the scarp north of the trench site (figure 72). A graphical representation of displacement through time suggests that uplift is episodic, with recurrence ranging from approximately 58,000 to 9,000 years (figure 77). Estimated displacements for single events range from less than 1 m to 2.3 m.




***STOP 4- PHOTO STOP AT SOUTH END OF CAMINO REAL( 5:30 pm; 15 min stop)***

Great Sand Dunes National Park lies less than 50 m to the south

5:40 pm; Turn around and drive back North on Camino Real to Camino Baca Grande (4.0 mi)

*83.2 turn L (N) onto Camino Baca Grande; drive 0.5 mi N to Stupa of Enlightenment*

*83.7 turn R (E) into driveway to Stupa and drive to end*

**STOP 5- STUPA OF ENLIGHTENMENT, YESHE RANGSAL RETREAT LAND, PUNDARIKA FOUNDATION (5:50 pm; 83.7 mi; 10 min stop)**

This Tibetan stupa lies on land of the Pundarika Foundation, dedicated to the late Tulku Urgyen Rinpoche, one of the most respected Tibetan Buddhist teachers to escape Tibet. It was consecrated in 2005. Inside the stupa are tens of thousands of small plaster tsa-tsas, miniature replicas of the stupa containing relics of the Buddha and mantra scrolls. A detailed list of the relics can be found at www.tsoknyirinpoche.org/yeshe-rangsal/stupa-and-shrine-hall/

Visitors have the opportunity to accumulate merit by circumambulating the stupa in a clockwise direction. The Pundarika spiritual center is one of 22 centers in Crestone.
Return to Camino Baca Grande and drive back North to Desert Sage Restaurant (1.5 mi).
**END OF TRIP (~ 6 pm)**

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