REFINE SLIP RATES AND SEGMENTATION OF THE NORTHERN SANGRE DE CRISTO FAULT, COLORADO'S LARGEST ACTIVE FAULT

Program Element II: Evaluate Urban Hazard and Risk.

Final Technical Report
Contract 03HQGR0076
National Earthquake Hazards Reduction Program
U.S. Geological Survey

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20 August 2006

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1. ABSTRACT

We excavated a 25 m-long trench on the northern part of the Crestone section of the Northern Sangre de Cristo fault zone, to see whether the crestone section might be composed of more than one (independent) rupture segments. The Carr Gulch trench exposed evidence for 3 paleoearthquake displacements in the past 27.4 ka. The existence of 3 colluvial deposits (units 2, 3, 4) indicates that the ca. 4.5 m of surface offset was formed during 3 surface-faulting events with an average displacement of about 1.5 m each. The events occurred at about 8 ka, 20 ka, and between 22.5 and 27.5 ka.

In contrast, at the Major Creek site on the southern part of the Crestone section, there has been 8.9 m of displacement in a similar time period (since early Pinedale time). The displacement-per-event, reconstructed from trenches at the Carr Gulch and major Creek sites, is similar (1.5 m at Carr Gulch; 1.4-2.2 m at Major Creek). Therefore, the difference in net displacement implies that fewer events have occurred at Carr Gulch than at Major Creek.

The latest event at both sites occurred at nearly the same time, and may represent a 90 lm-long rupture of the entire crestone section. The penultimate event at Major Creek, however, occurred between about 11 ka and 15 ka, much younger than the penultimate event at Carr Gulch (ca. 20 ka). At Major Creek we have no direct dating control on the earlier events, but the youngest of these 3 events could conceivably correlate with the penultimate event at Carr Gulch. The oldest event at Carr Gulch could correlate with one of 2 (but not both) early events at Major Creek.

Despite the ambiguities of event-matching with such fragmentary dating control, it is clear that there have been 5 inferred faulting events at Major Creek since early Pinedale time, but only 3 events at Carr Gulch. Only the latest event appears to be a possible simultaneous rupture at both sites. The penultimate events at Carr Gulch and Major Creek cannot be the same event, if the age constraints at each site are correct. Some of the earlier events may have ruptured at both sites, but all of them could not have.

This pattern of fault behavior suggests that there is a nonpersistent segment boundary between the Major Creek and Carr Gulch sites. We propose that this segment boundary lies at the junction of the Villa Grove fault zone and the NCSF. Based on the record at Carr Gulch, less than half of the range-front ruptures south of the VGFZ have continued north past the segment boundary. The other half of the ruptures have been deflected out onto the VGFZ, and are responsible for the late Quaternary fault scarps there.

Therefore, we propose to subdivide the Crestone section (as defined by Widmann et al, 1998) into 2 rupture segments, with a segment boundary where the VGFZ joins the NCSF. This subdivision is identical to the suggestion of Jack Benjamin and Associates and Geomatrix Consultants (1996), that the Crestone section should be subdivided into a 38-km-long segment north of the Major Creek/Kerber Creek thrust fault zone, and a 52-km-long segment south of it. We propose the name Hayden Segment for the northern segment and Major Segment for the southern segment.

The Major segment is 52 km long, but most of the time it probably ruptures with the VGFZ, which is an additional 19 km long. According to Wells and Coppersmith (1994), a rupture length of 71 km implies an earthquake of M7.3, whereas the average displacement of 2.15 m

implies an earthquake of M7.0, and the maximum displacement of 2.9 m implies an earthquake of M6.9

The Hayden Segment is 38 km long and has average per-event displacements of 1.5 m (latest 3 events) at Carr Gulch. The only other displacement estimate is the MRE surface offset at Rock Creek (1.7 m; McCalpin, 1982). We use these values as Davg and Dmax, respectively. According to Wells and Coppersmith (1994), a rupture length of 38 km implies an earthquake of M6.9, the average displacement of 1.5 m implies an earthquake of M6.9, and the maximum displacement of 1.7 m implies an earthquake of M6.8. These values yield an estimate of M6.9 for Mchar. The average recurrence interval over the latest 2 closed seismic cycles (5 ka and 12 ka) is 8.5 ka.

During 2-segment ruptures, the combined length of the Major and Hayden segments ruptures for a total rupture length of 90 km. According to Wells and Coppersmith (1994), a rupture length of 90 km implies an earthquake of M7.4. For the 2-event rupture we use the same $M_{char\text{-}D}$ values as for the Major segment. Therefore, we compute a preferred value of the magnitude of the characteristic 2-segment earthquake (M_{char}) as 7.3. The space-time diagram suggests that only about 2 out of 5 (40%) of events that rupture at Major Creek also rupture at Carr Gulch. Thus, if only about 40% of ruptures are 2-event ruptures, the recurrence period of such ruptures should be approximated by dividing the recurrence interval of the individual segments by 40%. This yields a recurrence for 2-segment ruptures of ca. 12-30 ka.

At present the National Seismic Hazard Map assumes a slip rate of 0.18 mm/yr for the entire Sangre de Cristo fault. We propose that, in the next iteration of the map, the NCSF be modeled as being composed of 2 rupture segments, each with a different Mmax and recurrence time, and including the occurrence of occasional 2-segment ruptures with an Mchar of 7.3 and a return period of 12-30 ka.

2. INTRODUCTION

2.1 Purpose and Scope of Study

The Northern Sangre de Cristo fault zone (NSCF) is the largest fault with Holocene movement in Colorado (Widmann et al., 1998), and the largest seismic source (163.6 km long) in Colorado included in the USGS National Seismic Hazard Map. The NSCF is the dominant source of ground motion, along with the newly-discovered Cheraw fault, for Denver and the Front Range Urban Corridor (Fig. 1). In the current model, the fault is considered a 164 km-long source on which the characteristic (M7.5) earthquake is allowed to "float" along the entire fault trace (USGS, 2002). A single value for M_{char} and recurrence (or slip rate) is used for the entire fault.

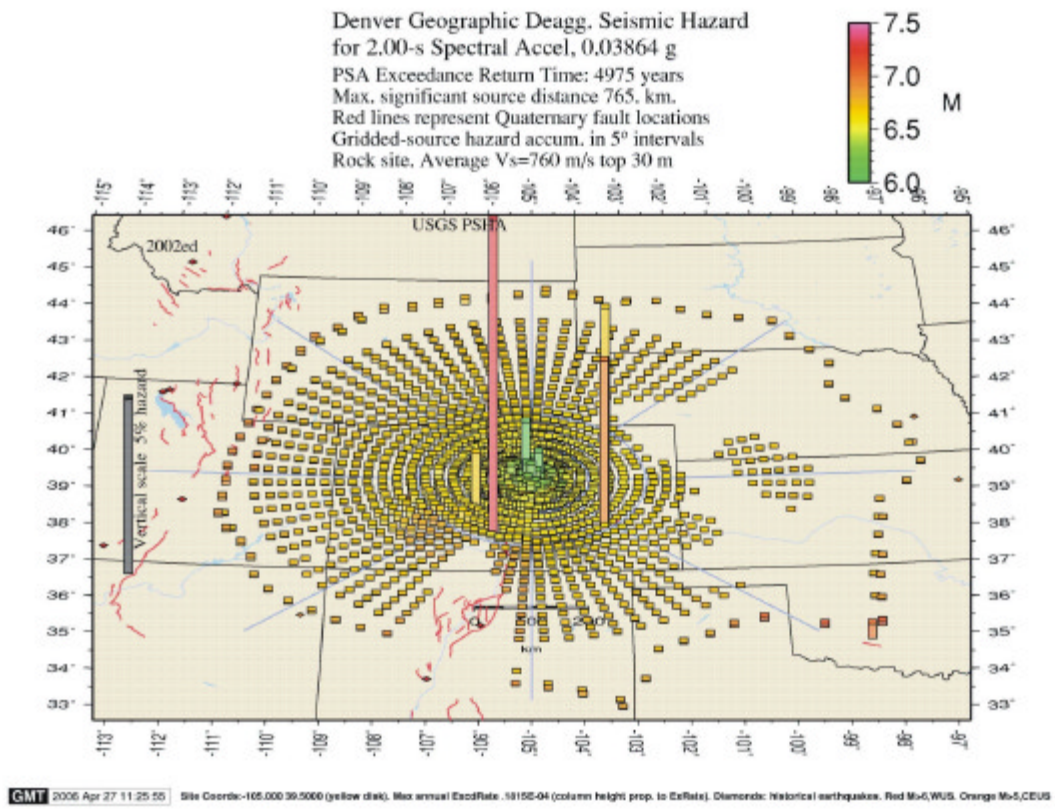


Fig. 1. Deaggregation of predicted seismic ground motion at Denver, Colorado, for 2-second spectral acceleration for a return period of 4975 years. The main source of ground motion comes from the Northern Sangre de Cristo fault (pink bar at left center), with a secondary contribution from the Cheraw fault (tan bar at right center). Source: USGS website.

However, past and ongoing mapping suggests that the Northern Sangre de Cristo fault may be composed of as many as 6 independent rupture segments, each of which has a different M_{char} and recurrence. In particular, the end segments probably have lower M_{char} and longer

recurrence than the central segments. If that change was made to the National Map, it would probably decrease the hazard off the ends of the fault (e.g., Denver, Colorado Springs) and increase the hazard toward the center of the fault (e.g., Alamosa and the San Luis Valley). The San Luis Valley is currently a Project Impact community, encompassing the 6 counties of Alamosa, Conejos, Costilla, Mineral, Rio Grande, and Saguache. It is the first multi-county Project Impact site in the US. New fault information generated by our proposed project is sought by the local Project Impact coordinator for inclusion in their HAZUS loss-estimation model.

However, a fault segmentation scheme cannot be input into the National Map or the HAZUS model unless we can confirm that past earthquake ruptures have stopped at segment boundaries (i.e., they are at least partly persistent), and we can derive a slip rate for each segment. The proposed tasks all aim at this goal, to use existing and new data to segment the fault and to provide USGS personnel with viable slip rates for each segment.

2.2 Significance of the project

The NSCF was segmented by McCalpin (1981) into 3 segments that stretched from Poncha Pass southward to nearly Fort Garland, Colorado (Fig. 2). However, the U.S. Geological Survey changed the nomenclature sometime after 1981 (not fully explained in the Quaternary Fault and Fold Database; see Appendices 1, 2, 3). They defined the NSCF as extending all the way from Poncha Pass to the New Mexico State line and segmented this “expanded” NSCF into 4 “sections” that are currently inferred (but not known) to be earthquake rupture segments (Fig. 3). The lengths of these sections are very different. The majority of the 163.9 km fault length is composed of the Crestone section (79.1 km; identical to segment A of McCalpin, 1981) and the San Luis section (59.1 km; south of McCalpin’s area). The other two sections are much shorter (Zapata section, 25.8 km; identical to segment B of McCalpin, 1981) and the Blanca section (6.7 km; identical to section C of McCalpin, 1981).

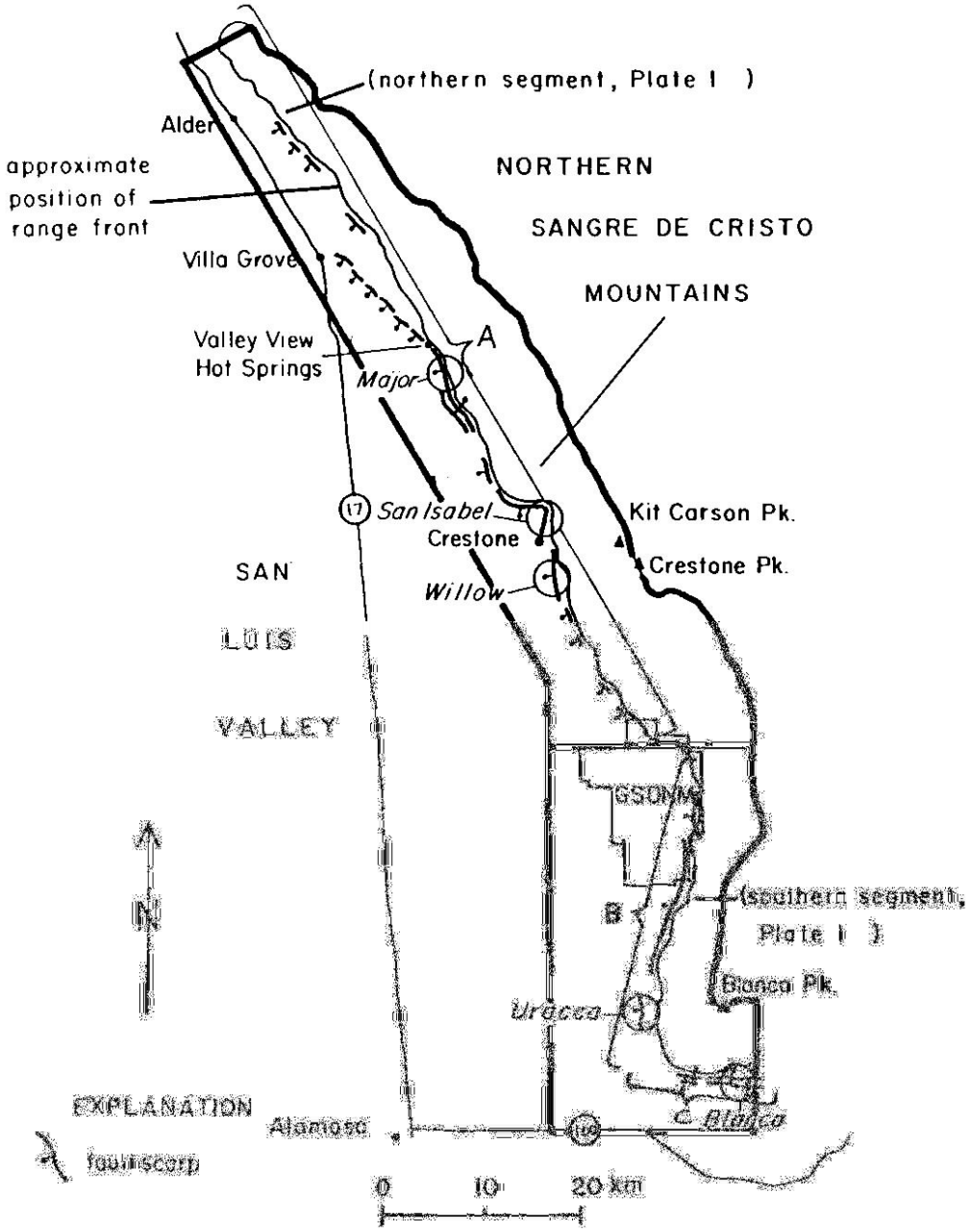


Fig. 2. Map of Quaternary fault scarps along the NSCF, and segments A, B, and C identified by McCalpin (1982). As revised by USGS, segment A is now termed the “Crestone section”, segment B is termed the “Zapata section”, and segment C is termed the “Blanca section.”

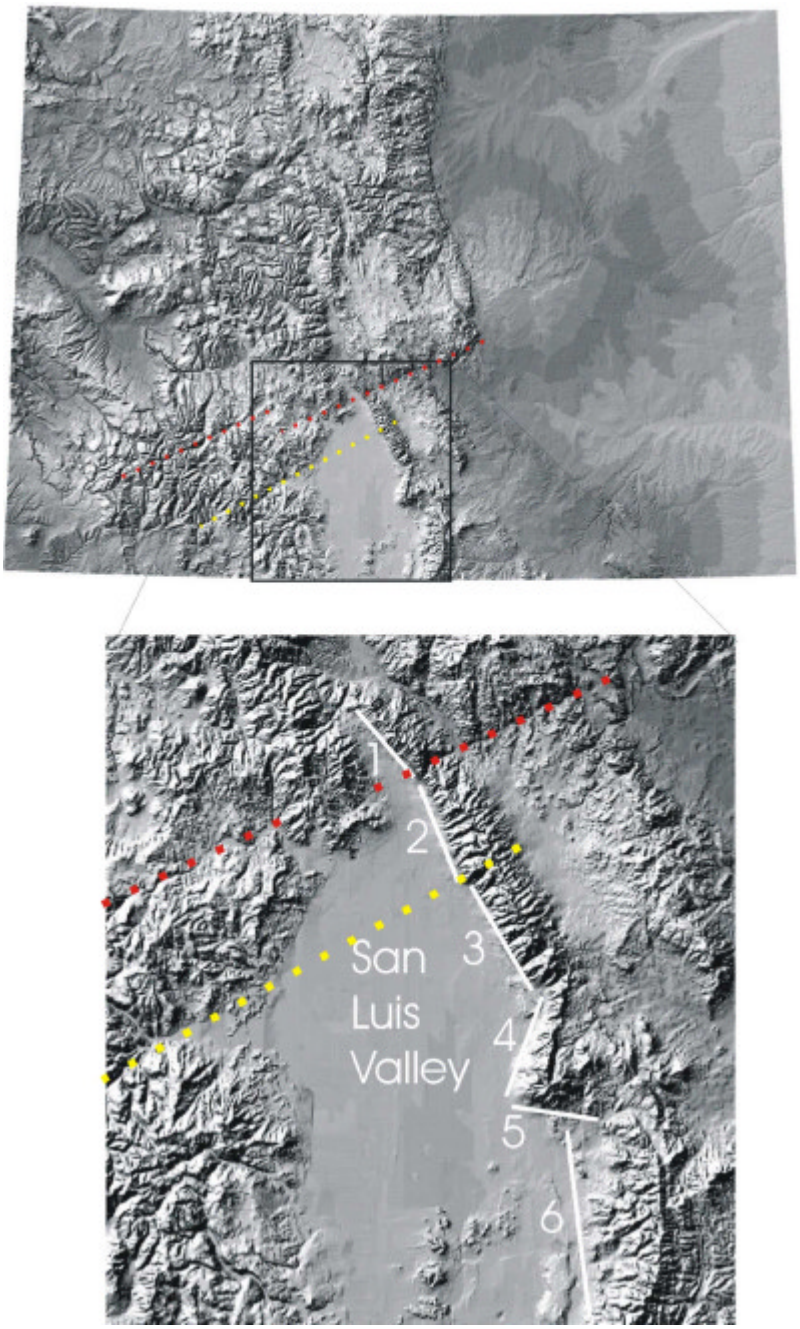


Fig. 3. Map of the study area. Upper part, shaded relief map of Colorado with rectangle centered around San Luis Valley. Lower part, possible rupture segments of the Sangre de Cristo fault are numbered. 1-3 are within the present Crestone section of USGS; 4 is the Zapata section of USGS; 5 is the Blanca section of USGS; 6 is the San Luis section of USGS. Dotted lines show "Arkansas River an unnamed lineament (yellow, N62E) that cross the Sangre de Cristo Mountains and may constitute segment boundaries, possibilities investigated by this study.

2.3 Tectonic Setting

This study concentrates on the northern half of the 79 km-long Crestone section, basically from just south of the junction of the SCFZ with the Villa Grove fault zone (VGFZ), to Poncha Pass. In this region the SCFZ lies at the range front. South of its junction with the VGFZ, the SCFZ displays nearly continuous fault scarps at the base of the range-front faceted spurs (Fig. 3). For example, at Major Creek the scarps displace fanhead terraces of 5 ages (McCalpin, 1987). These fault scarps continue at the range front for less than 1 km past the junction with the VGFZ, and then disappear. Most of the range front east of the VGFZ does not display fault scarps. However, once the VGFZ dies out at about the latitude of Villa Grove, fault scarps begin to reappear at the range front. This occurs north of the Hayden Pass road.

Scarps north of the Hayden Pass road are discontinuous, and in map view mainly bridge across the mouths of embayed alluvial fan heads (Fig. 4). Conversely, scarps are typically absent at the bases of the range-front faceted spurs between the embayed fan heads. This topographic pattern suggests that the latest displacement event on the fault is old, and colluvial processes have obscured the scarps on the relatively steep slopes at the toes of faceted spurs. The only place the scarps are still well-rpeserved is on the low-gradient fan surfaces, where the rate of scarp decline is significantly slower than on steeper slopes.

2.3.1 Previous neotectonic work

Although McCalpin (1982) mapped the NSCF from Poncha Pass to Blanca Peak, he only dug trenches at 4 locations (VGFZ, Major Creek, Willow Creek, Uracca Creek; Fig. 2). These trenches fell on his segments A (Major Creek, Willow Creek) and B (Uracca Creek). No trenches were dug on his segment C (the Blanca section of Widmann et al., 1998).

Subsequently, the PIs have become skeptical that McCalpin's entire 79 km-long segment A (Crestone section of Widmann et al., 1998) is a single rupture segment. In fact, there are several potential segment boundaries on the NSCF within this "segment", as defined by crosscutting structures in the footwall, splay fault junctions, and stopovers in the range front. The northernmost possible segment boundary (between 1 and 2 on Fig. 3) is at Hayden Pass, where a strong N65E-trending lineament exists in the footwall and aligns with a linear reach of the Arkansas River NE of the Sangre de Cristo Mountains. We informally term this lineament the "Arkansas River lineament (ARL)." North of the ARL, range front scarps are common on the NSCF. South of the ARL range front scarps are mainly absent, and instead displacement appears to be shifted to the VGFZ. That part of the NSCF north of the ARL had not previously been trenched, even though fault scarps are abundant and access to BLM land at the range front is possible.

Therefore, this project's main goal was to dig a trench on a 2 or 3-event scarp on the NSCF north of the ARL. The purpose of this trench is to date the MRE and PE on the NSCF north of the ARL, and to determine whether those dates are similar to dates on the MRE and PE from the VGFZ, and from the 1980 trench at Major Creek. If the ages were greatly dissimilar, we would conclude that there is a separate rupture segment north of the ARL. We already know that the northern end of the VGFZ terminates at this latitude, and that scarps in Pinedale and Bull

Lake fans are much smaller north of the ARL than south of it. To calculate the slip rate to use in the National Map for such a new segment, we would use displacement and age data from the trench, as well as fault scarp heights. (see Task 3).

Of the two trenches dug by McCalpin (1982) in the Crestone section, the Major Creek site is north of, and the Willow Creek site south of, a potential segment boundary north of San Isabel Creek (Figs. 2, 3). At that location the range front steps left by about 1 km. This left step is the largest departure of the NSCF from a straight line in the Crestone section, and lines up with a strong N62E-trending topographic lineament in the San Juan Mountains (Fig. 3) that contains the mouth of the Rio Grande. Unfortunately, the Willow Creek trenches did not yield any dating constraints on the age of the MRE and PE. Therefore, unless we dig a future trench somewhere south of the RGL, and obtain good enough dating control to compare with the Major Creek site, we will not know if the RGL is also a segment boundary.

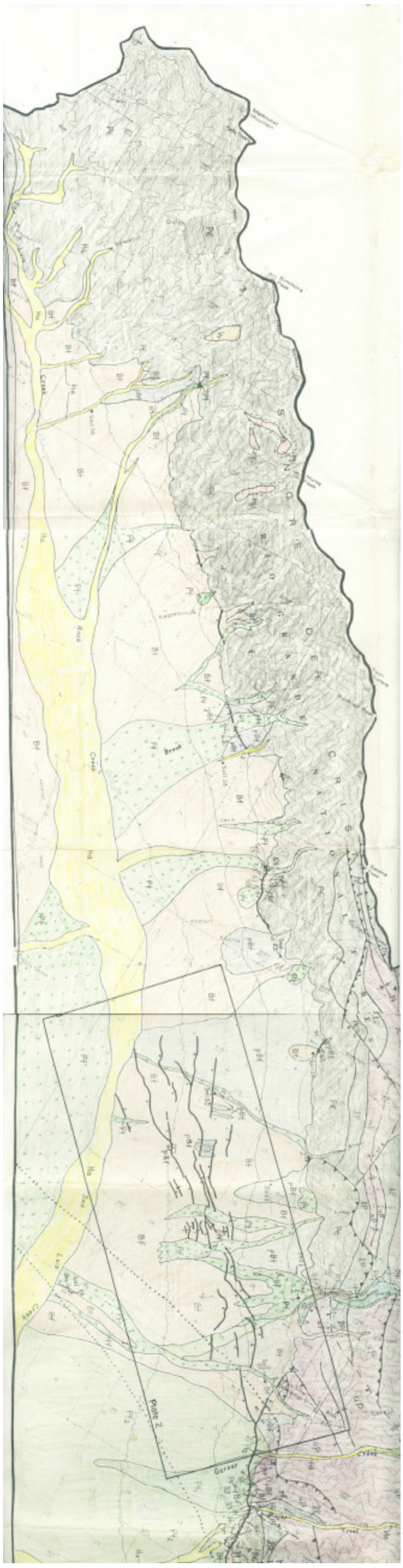


Fig. 4. Geologic map of the northern part of the Crestone section of the NSCFZ, from McCalpin (1981). Original scale 1:50,000. Fault scarps offsetting Quaternary deposits are shown as heavy lines, with bar-and-bar on downthrown side. Numbers on fault scarps of the SCFZ show locations of fault scarp topographic profiles measured by McCalpin (1981, 1983).

Rectangle shows the scarps of the VGFZ. Numerous fault scarp profiles were also measured there, but locations are not shown on this figure (see McCalpin, 1981, Plate 2; or McCalpin, 1983, Fig. x).

Quaternary geologic map units:
Hal—Holocene allluvium
Hf—Holocene alluvial fan
Pf—Pinedale alluvial fan, undivided
Pf2—late Pinedale alluvial fan
Pf1—early Pinedale alluvial fan
Bf—Bull Lake alluvial fan
pBf—pre-Bull Lake alluvial fan

3. METHODS

The trench was excavated by a trackhoe to the width of the 0.9 m-wide bucket (i.e., a narrow slot cross-section), with the addition of a mid-height bench on the north trench wall. The southern wall of the trench was cleaned by manual scraping, then a series of horizontal stringlines were attached to the trench wall, spaced 1 m apart, that served as control for the photomosaic logging. Then obvious geologic contacts were spray-painted. The photomosaic was printed at a scale of 1:20 and then taken into the trench, where final revisions were added. Mapping units were defined either as stratigraphic units or as soil horizons developed on stratigraphic units.

*Mapping conventions***:** The unconsolidated map units defined on trench logs include both parent materials unaffected by soil formation (e.g., unit 25), and parent materials that have been affected by soil formation (e.g., unit 25Ck2). In the latter group the map units are soil horizons defined by changes in soil horizon properties, rather than by a change in parent material sedimentology. Horizons were recognized and named according to the definitions of SCS (1994) and Birkeland (1999). In each map unit abbreviation the parent material number (1=oldest) forms the first part of the unit designation and the soil horizon abbreviation (if applicable) forms the next part of the map unit designation. The final part of the map unit designation indicates whether the soil horizon is part of a buried soil (i.e., not the surface soil) and if so, the number of the buried soil, with “b1” indicating the uppermost (youngest) buried soil. Thus, the map unit designation “10Kb1” indicates that the parent material is unit 10 (sand), the soil horizon is a K horizon (strongly calcified), and the K horizon is part of the 1st buried soil counting down from the ground surface. This same naming convention is used throughout the trench logs.

4. CARR GULCH STUDY SITE

The Carr Gulch trench site lies at the range front north of the Hayden Pass road, at the mouth of Carr Gulch (Figs. 5-7). Previous bedrock mapping shows that the range front faceted spurs are mainly composed of Precambrian high-grade metamorphic rocks that are either overlain by, or have been thrust eastward over, Paleozoic sedimentary rocks.

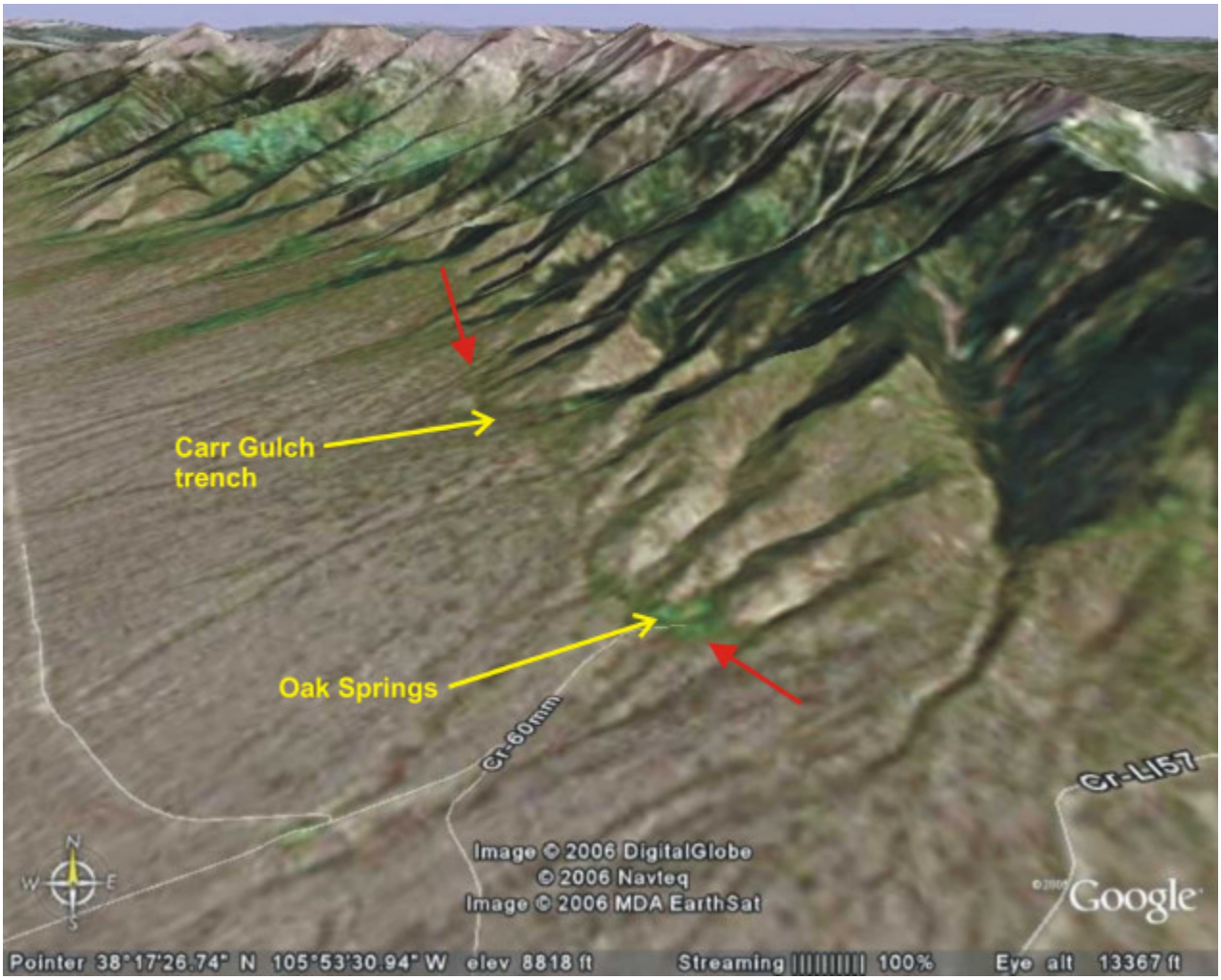


Fig. 5. Satellite perspective view of the Carr Gulch study site, on the western side of the Sangre de Cristo Mountains. View is to the north. The Carr Gulch trench is at the northern end of a 1 mile-long fault scarp (between red arrows) that extends from south of Oak Srpings to just north of Carr Gulch.

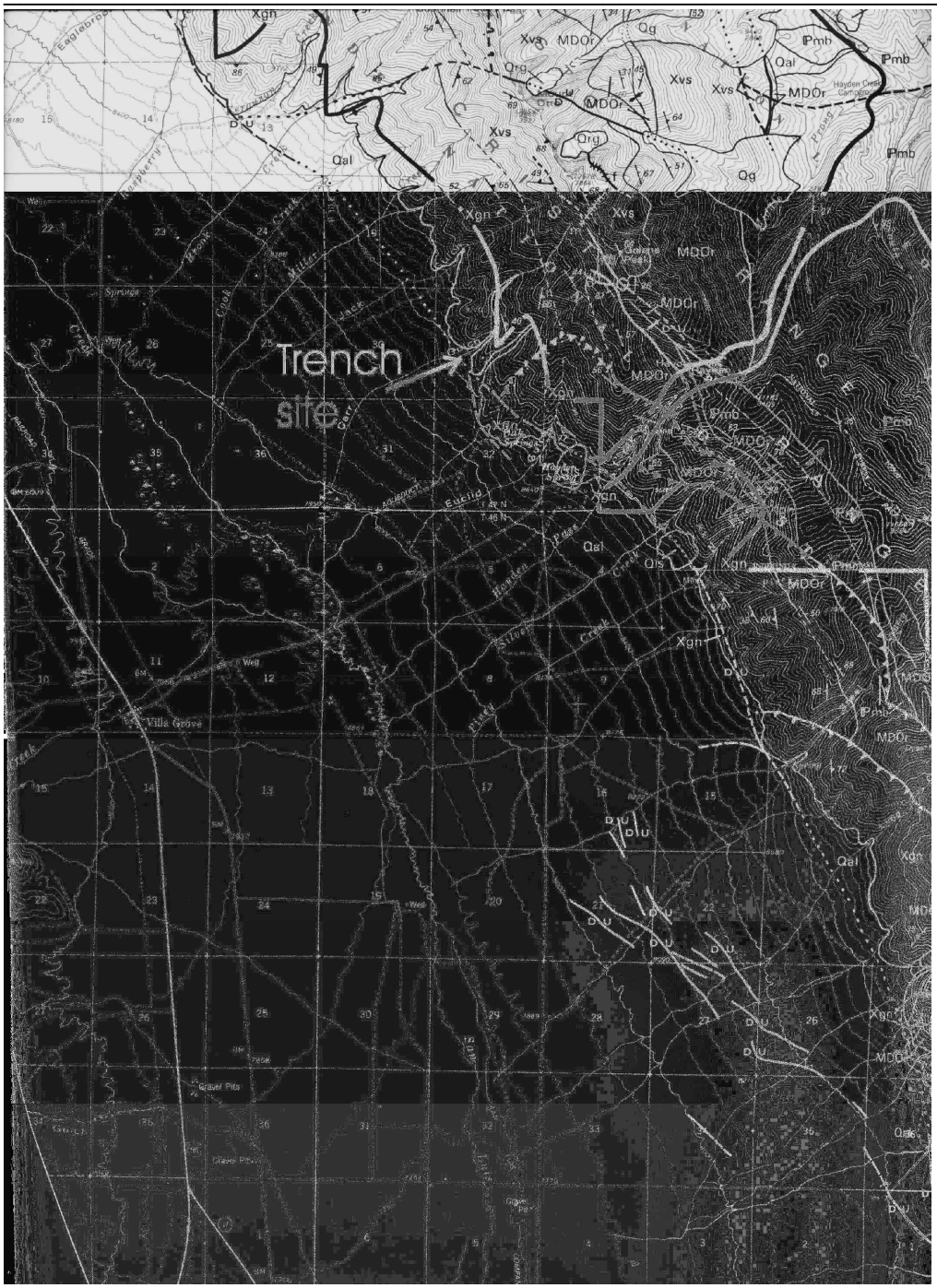


Fig. 6. Location map of the trenching site. Base map is USGS geologic map MF-1635-B, scale 1:63,360. Scarps on valley floor at lower right are the Villa Grove fault zone; town of Villa Grove is at left center.

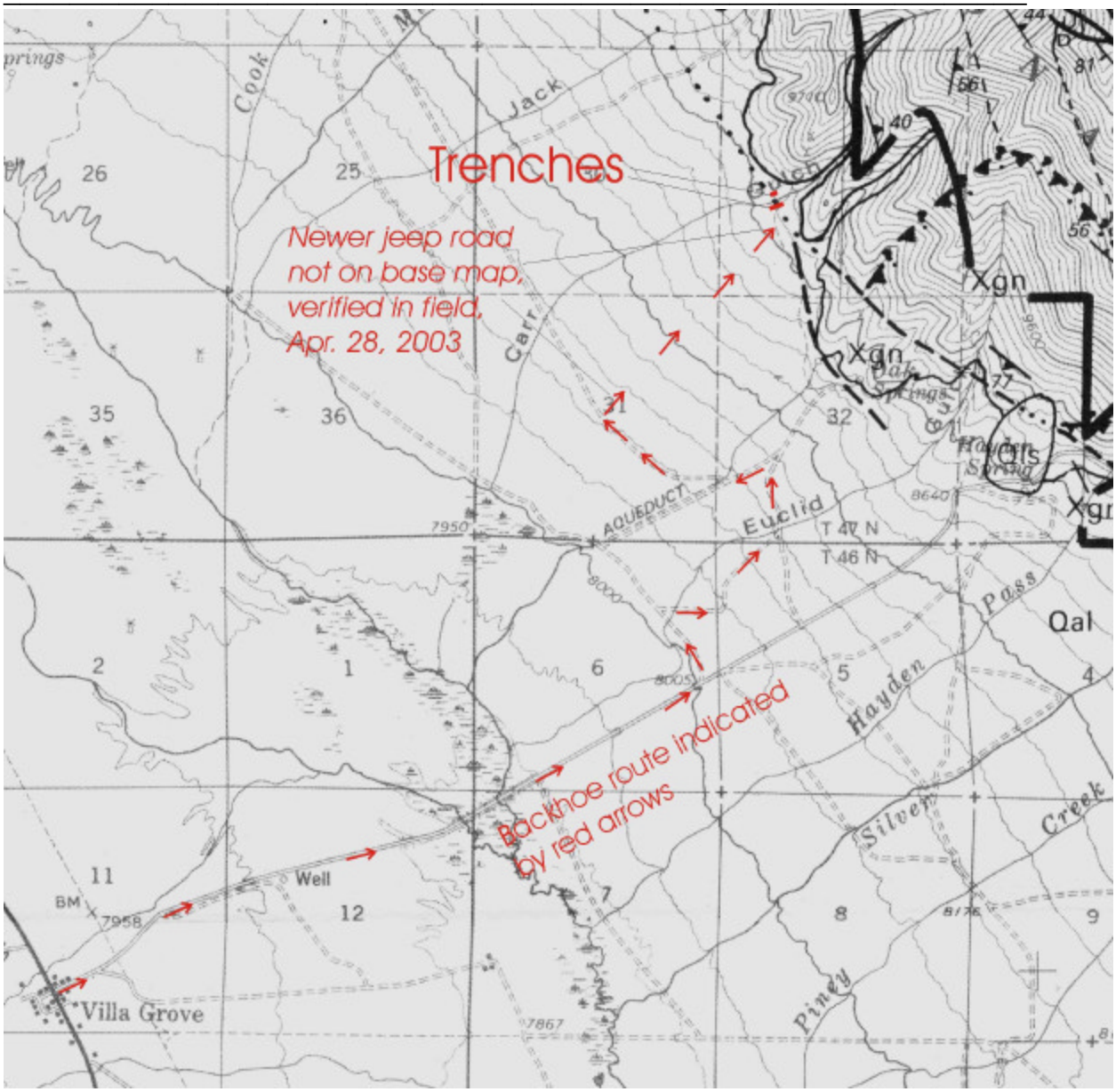


Fig. 7. Close-up of MF-1635-B showing the trenches and the access route.

4.1 Local structural geology and geomorphology

In the vicinity of the Carr Gulch trench, there are many bedrock faults in the upthrown block of the NSCF (Figs. 8, 9). They tend to have a slightly more westerly trend that the overall orientation of the NSCF. Many of these bedrock faults eventually come to the range front, and at those locations the NSCF commonly, but not always, utilizes the older fault trace and changes orientation at these fault intersections. The interelationships between this range front fault and these bedrock faults is very intriguing. Based on the amount of brecciation and iron staining in

Proterozoic rocks along these bedrock faults, we suspect they are pre-rift structures. It would be interesting to know if these faults were reactivated along their entire lengths during rifting, or only if the segments that coincide with the NSCF were reactivated during rifting.

The NSCF almost seems to be a "new" structure that locally in part follows these older faults. The NSCF appears to coincide with an older structure for a distance, then cuts a new trace for a short distance, then soon hooks up with and adopts the trace of another older structure. This may be repeated along the entire length of the fault, as Kirkham (pers. comm.) noted similar relationships in the Culebra Reentrant.

The fault strand that forms the range front fault south of Hayden Pass goes into bedrock about where the Hayden Pass Road crosses the range front fault. This bedrock fault appears to abut against the NSCF at the range front on the north side of Carr Gulch. Since this bedrock fault forms the range front south of the trench site, it is possible that this bedrock fault accomodated some of the Quaternary displacement along the western margin of the Sangre de Cristo Mountains in the vicinity of the trench. That is, the trench might not include all of the late Quaternary displacement. In the valley directly south of the trench, there are valley fill deposits of 2 different ages where this "bedrock" fault crosses the valley. We did not find any conclusive evidence of a tectonic scarp along the "bedrock" fault in these deposits, which are probably Pinedale and Bull Lake in age. The depositional surfaces on these alluvial deposits were a bit irregular where they are preserved in the footwall of the NSCF, and their surfaces are irregular in the vicinity of where the "bedrock" fault crosses the valley, but I do not believe these irregularities are tectonic scarps.

There is another bedrock fault further east and higher up in the range in the vicinity of Carr Gulch. This fault comes to the range front north of Jack Creek. The NSCF is very linear and has the same strike as this bedrock fault north of where the bedrock fault comes to the range front. It is a great example of how the NSCF locally utilizes the trace of a pre-existing fault. We did not field check this bedrock fault for evidence of tectonic scarps in the alluvium of Carr Gulch or the next valley to the south. Fairly wide alluvial deposits fill both of these valleys where this bedrock fault crosses the valley. We examined the aerial photos for evidence of tectonic scarps in the alluvium where these faults cross the valleys, but did not observe any evidence of scarps.

The Pinedale deposits in Carr Gulch, and those in the first drainage south of Carr Gulch, are faulted by the NSCF. We did not profile these scarps, but estimate they have scarp heights of 3-5 ft. McCalpin's (1981) measured profile 59 is across the scarp in the Pinedale alluvium in the first valley south of Carr Gulch, so that gives an idea of the scarp height in Pinedale deposits (Fig. 10). At the trench site, the scarp displaces a fan mapped as Bull Lake alluvium (unit Ba, Fig. 8) with a gradient of 6.5°. The scarp has a vertical surface offset of 4.5 m.

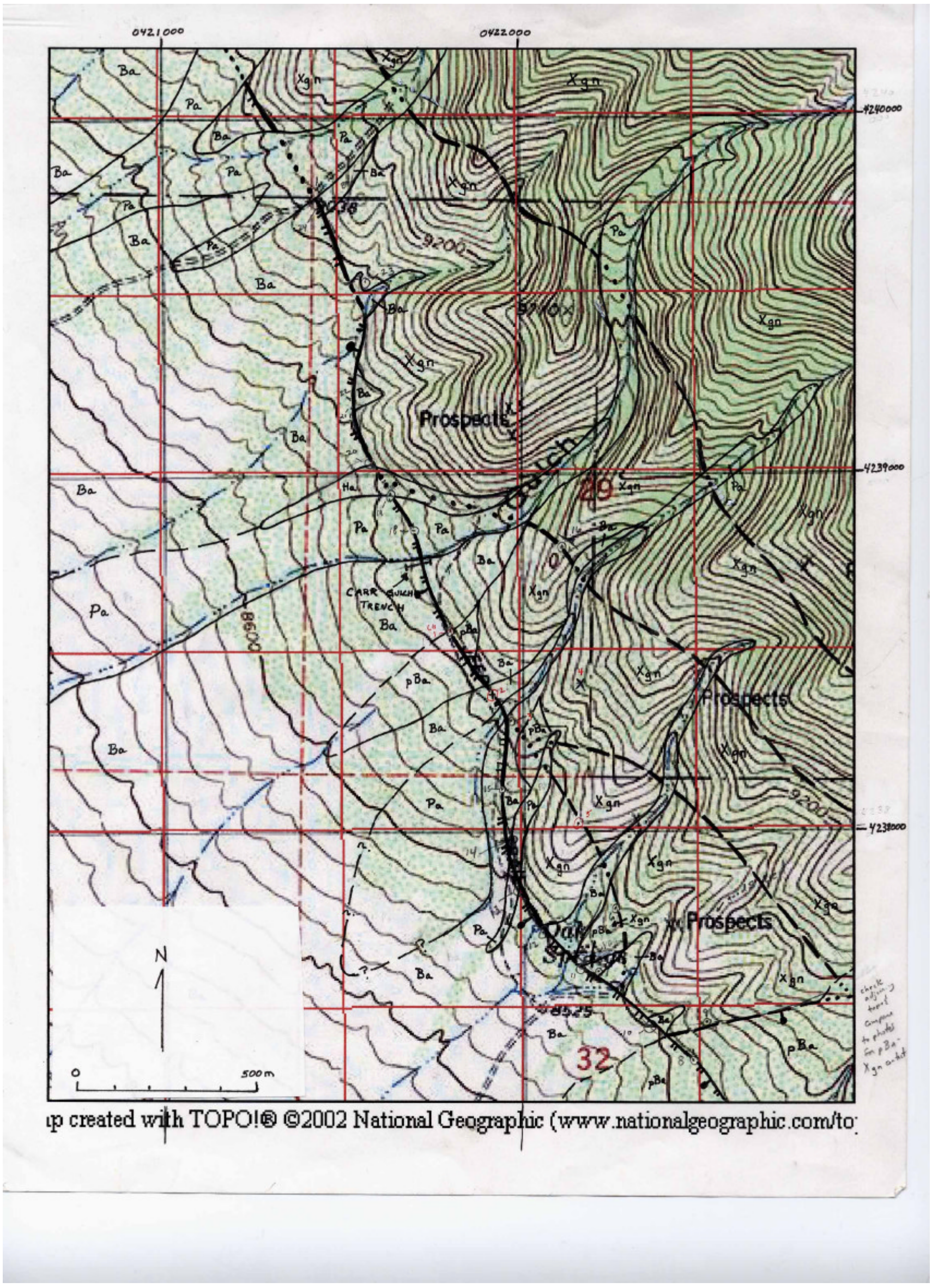


Fig. 8. Geologic map of the Carr Gulch area made for this study. Xgn, Precambrian granitic gneiss; pBa, pre-Bull Lake alluvium; Ba, Bull Lake alluvium; Pa, Pinedale alluvium.

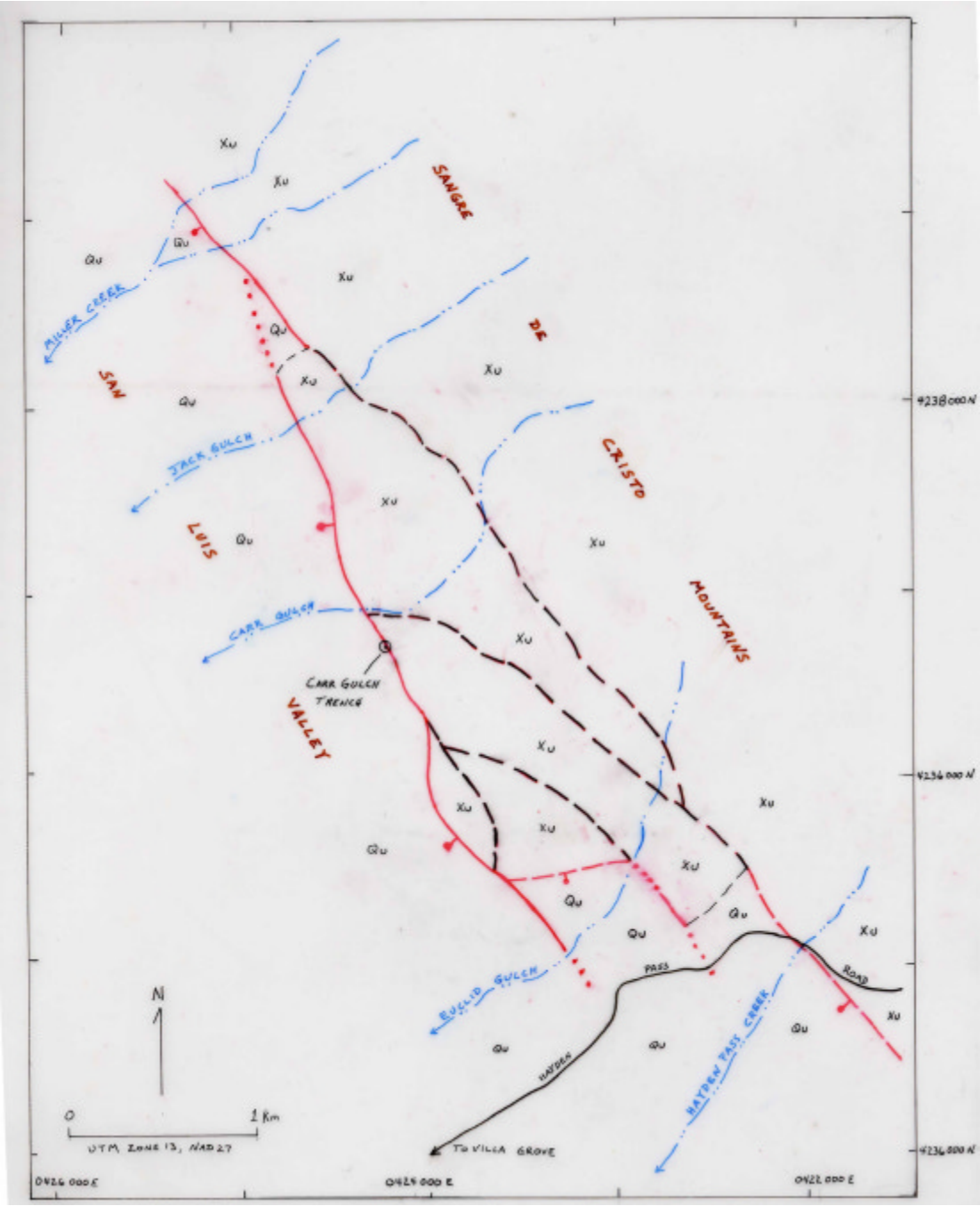


Fig. 9. Structural geology sketch map of the Sangre de Cristo range front near Carr Gulch. Xu, Precambrian X-age rocks, undifferentiated; Qu, Quaternary deposits, undifferentiated. Red lines mark fault traces with young scarps; black lines show older faults without scarps.

Profile	H	SO	Alpha
Pinedale fans			
54	2.2m	1.2m	9 deg.
59	3.5m	2.1m	8 deg.
Bull Lake fans			
55	6.3m	3.4m	9 deg.
56	8.5m	3.8m	12 deg.
57l	9.0m	4.6m	11 deg.
58	7.4m	4.4m	10 deg.

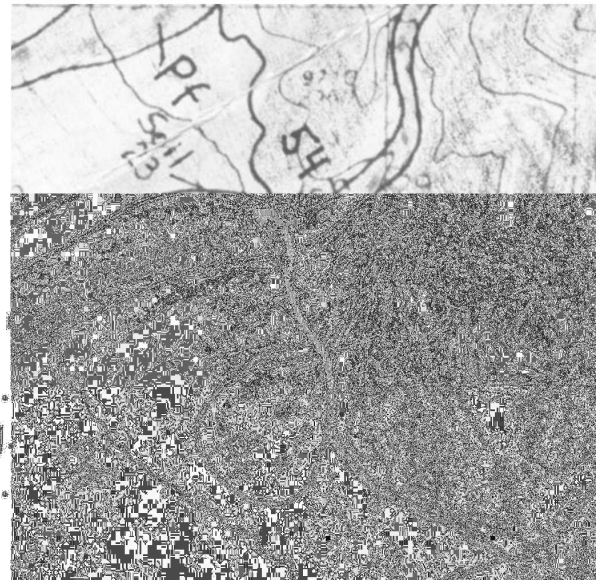


Fig. 10. Geologic map and sites of fault scarp topographic profiles (Right) at and south of Carr Gulch. North is at top. Pf, Pinedale fan (dotted); Bf, Bull Lake fan (no pattern). From McCalpin, 1983. Values at Left show (from left to right), Fault Scarp profile number, fault scarp height (H), fault scarp surface offset (SO), and ambient slope angle of the faulted alluvial fan (alpha, in degrees). Fault scarps crossing Pinedale fans have surface offsets of 1.2-2.1 m, whereas fault scarps crossing Bull Lake fans have surface offsets of 3.4-4.6 m. The Carr Gulch trench of this study is located at profile 55.

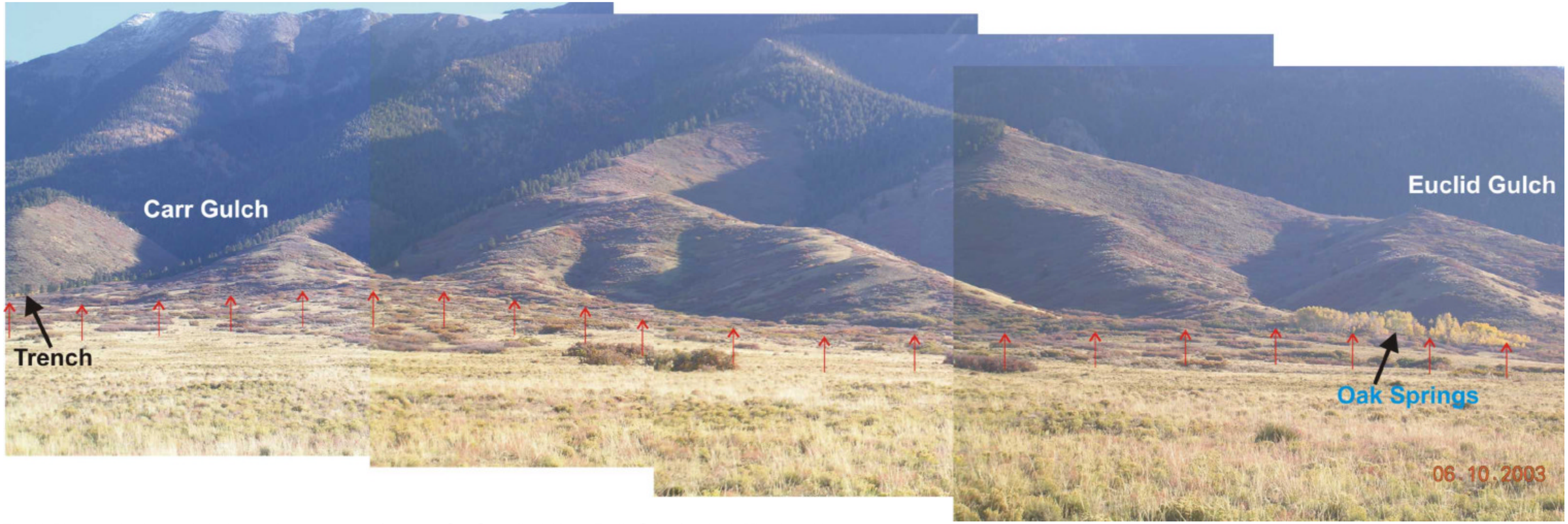


Fig. 11. Photomosaic of the main fault scarp (above red arrows) between Carr Gulch (far left) and Euclid Gulch (far right). View is looking east.

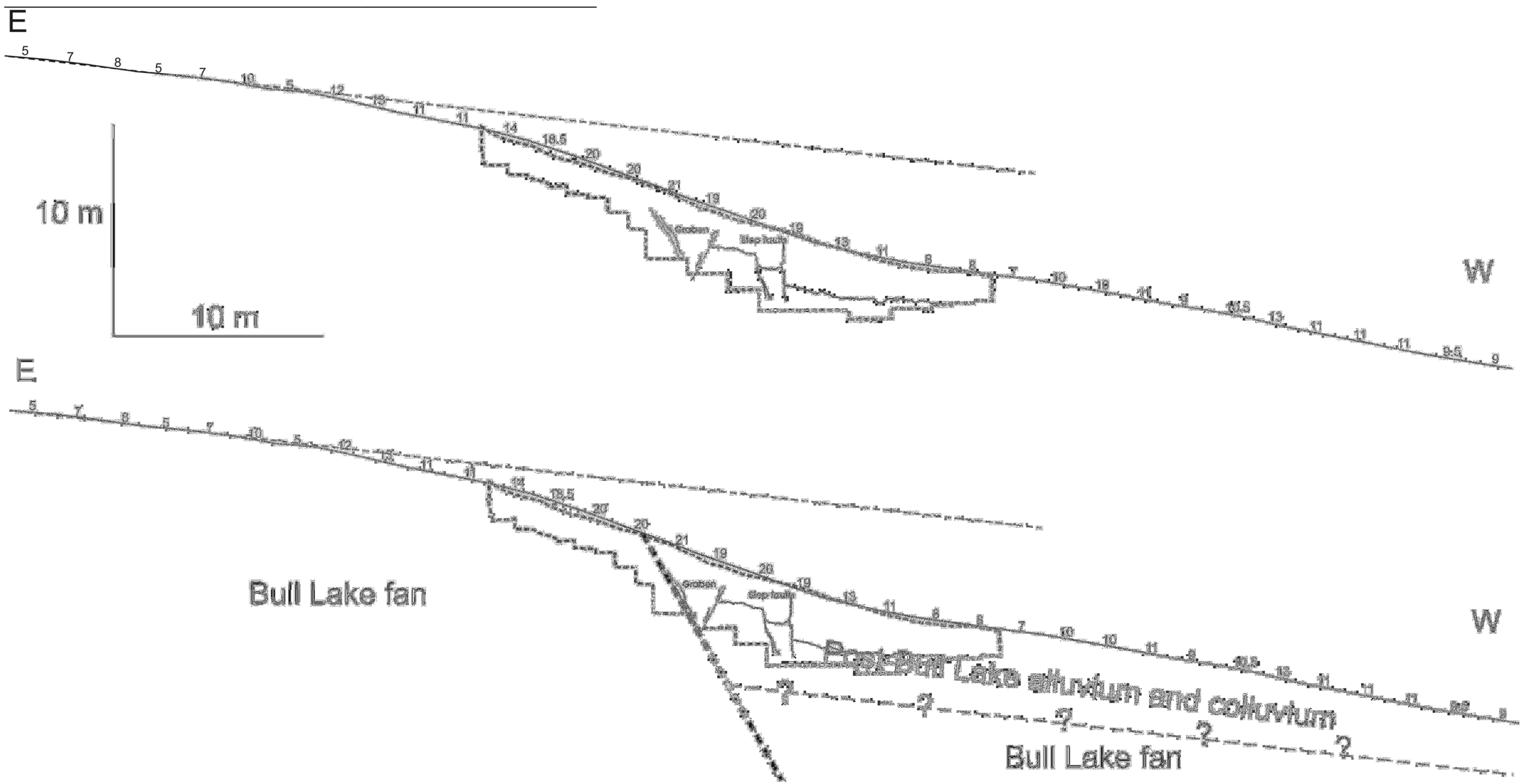


Fig. 12. Topographic profile at the Carr Gulch trench location. Upper part shows profile segments, labeled in degrees, with the Carr Gulch trench outline and major faults superimposed. The vertical surface offset is 4.5 m, measured from the projection of the footwall surface (6.5 degrees) over the hanging wall surface. Lower part shows stratigraphic interpretation, discussed later.

4.2 Carr Gulch Trench

The Carr Gulch trench was located on the range-front fault scarp directly south of the deeply incised channel of Carr Gulch. The trench is 26 m long and 2-3.5 m deep. The south trench wall was vertical and is the logged wall (Fig. 13 and Plate 1); the north wall was benched at mid-height.

4.2.1 Stratigraphy

The Carr Gulch trench exposes alluvial fan gravels on the footwall, and alluvial fan gravels and overlying scarp-derived colluvium on the hanging wall. The footwall alluvial fan gravels comprise the oldest strata exposed in the trench and are numbered unit F1. Unit F1 is subdivided into 5 subunits on the trench log (Fig. 13; from oldest to youngest, F1a through F1e) based on gross texture and sedimentology. Units F1a, F1c, and F1e are matrix-supported, poorly sorted, boulder gravels interpreted as debris flow deposits. Units F1b and F1d are clast-supoorted, better sorted, pebble and cobble gravels interpreted as stream alluvium.

On the hanging wall, the lower part of the trench wall exposes similar alluvial-fan units as exposed on the footwall. In our original trench logging, we correlated the stratified alluvial fan gravels in the footwall and hanging wall, and simply numbered them 1a through 1e. However, after we received the OSL ages, we were forced to consider whether the footwall alluvial fan strata might be older than the hangting-wall alluvial fan strata. At that time we placed an “F” in front of the footwall strata unit numbers, and retained the hanging wall numbers as before.

Overlying the hanging-wall fan deposits are an older colluvium (unit 2), and intermediate-age colluvium and alluvium (unit 3), and a younger colluvium (unit 4). The older colluvium directly overlies the stratified fan gravels, and is divided into proximal colluvium (2a), distal colluvium (2b), and locally-drived alluvium (2c). The intermediate-age colluvium is subdivided into 2 subunits in the main fault graben (units 3c, 3d), and into 2 units elsewhere (3a, 3b). At the toe of the trench these colluvial units interfinger with a contemporaneous alluvial channel (unit 3a1). The youngest deposit in the trench (unit 4) underlies the ground surface from the main fault to the toe of the scarp, is up to 1 m thick over the main fault zone, and is clearly unfaulted. We interpret this deposit as scarp-derived colluvium deposited after the latest faulting event (Event Z).

4.2.2 Soils

The trench exposes a more-or-less continuous red-brown surface soil that underlies the ground surface along the entire length of the trench. This red-brown soil is best developed on the hanging wall and thinnest (but not entirely absent) on the upper scarp face (between 15 and 21 m), where it has been eroded. We described a detailed soil profile at the scarp toe (station 2.5 m) where the older colluvium (0.5 m thick) was pinching out downslope atop the pre-faulting fan gravels (1.25 m of exposed thickness).

This relict toeslope soil profile (Fig. 12) is developed across both the distal part of the older scarp-derived colluviums (units 2, 3) and the alluvial fan gravels (unit 1e). The soil contains a textural B horizon (Bt) 32 cm thick, developed on both the older colluviums (unit 2, 3; horizon B22t) and the underlying alluvial fan gravels (2B23t). Underlying these Bt horizons are 2 additional cambic B horizons (2B31, 2B32) totaling 42 cm thick. The lowest horizon contains Stage I+ calcium carbonate in 1-2 mm-thick coatings on the bottom of clasts.

This soil matches soils described by McCalpin (1983) on Bull Lake alluvial fans of the Sangre de Cristo bajada. In addition, both McCalpin (1983) and this report (Fig. 8) map the faulted alluvial fan surface south of Carr Gulch as Bull Lake in age, based mainly on the degree of erosional dissevtion. However, as described in the Geochronology section, luminescence dates indicate that the uppermost alluvial fan gravels in the hanging wall of the fault scarp have an age of ca. 27 ka, which corresponds to early Pinedale time.

This discrepancy has two possible explanations, as explained in the Geochronology section.

4.2.3 Structure

The Carr Gulch trench exposed 4 faults on its south wall. The easternmost 2 faults (A and B) underlie the the central, steepest part of the fault scarp (Fig. 11, Plate 1). These 2 faults define a graben. Fault A is a 0.5-1.2 m-wide zone of sheared and rotated alluvial fan gravel, with many clasts having long axes parallel to the fault zone boundaries. Fault A dips west at about 60°-75°. The antithetic fault, Fault B, dips east at 73°. The intervening graben tapers downward, being about 1.7 m wide at the top and 0.3 m wide at the bottom. The vertical separation across the graben (faults A and B) is 2.5 m (measured on the bases of units F1e and 1e), making this the main fault zone in the trench.

The other 2 faults in the trench (Faults C, D) are west-dipping normal faults that lie 3.5 m and 5 m west of the graben, respectively. Both faults dip 80°W in their lower parts, but steepen to vertical to slightly east-dipping in their upper parts. This steepening is probably refraction due to the fault's proximity to the ground surface.

The block of alluvial fan gravels between the graben and Fault C appears to have steeper dips than the other inter-fault blocks on the south wall. This geometry suggests that block has been rotated a few degrees by toppling toward the hanging wall. Such toppling would be consistent with the existence of a pull-apart zone (the strongly-tapering graben) between faults A and B.

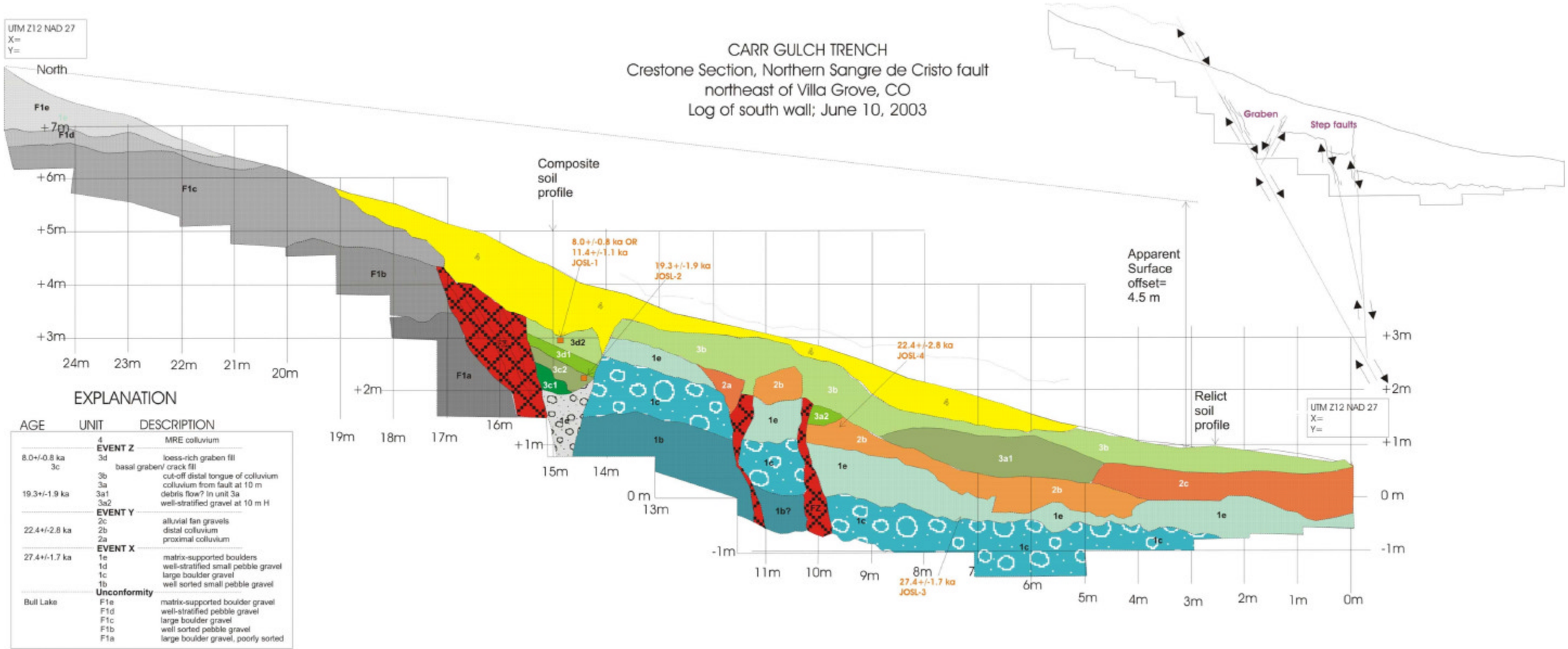
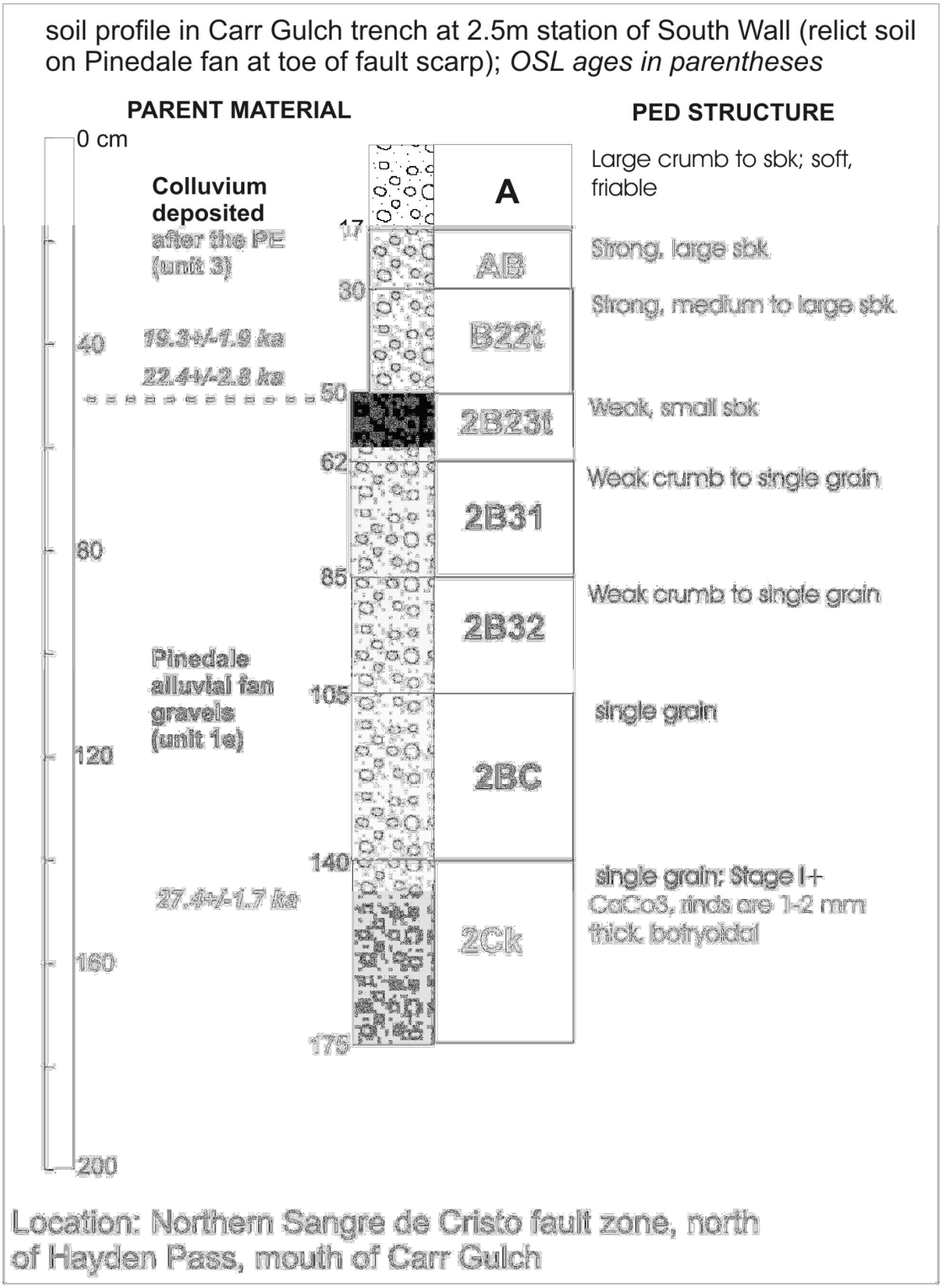


Fig. 13. Log of the south wall of the Carr Gulch trench.



Source: soil description sheet, 16-Oct-2003

Fig. 14. Relict soil profile at toe of trench.

4.2.4 Geochronology

No organic matter was observed on the south trench wall, with the exception of the thin surface A horizon directly beneath the ground surface (not shown on Fig. 11). Therefore, our only age control came from optically-stimulated luminescence (OSL) ages on fine-grained deposits. Most of the deposits exposed in the trench wall were too coarse-grained (or too rapidly deposited) to be good candidates for OSL dating. However, we did collect 4 samples (3 from the older colluvium, and one from the top of the alluvial fan gravels; see Table 1) where the deposits contained less gravel and appeared to contain either eolian or fluvial silt.

Table 1. Stratigraphic setting of the OSL samples from the Carr Gulch trench.

Sample	Unit	Age Constraint
JOSL-1	Top of unit 3e (Event Y colluvium)	Provides close Maximum Age (8.0±0.8 ka) on Event Z
JOSL-2	Near bottom of unit 3 (Event Y colluvium)	Provides Minimum Age (19.3±1.9 ka) on Event Y; Maximum on Event X
JOSL-3	Eolian sand matrix of unit 1e (Pinedale? fan alluvium)	Provides moderately close Maximum Age (27.4±1.7 ka) on Event X
JOSL-4	Middle of unit 2b (Event X colluvium)	Provides Minimum Age (22.4± 2.8 ka) on Event Y

The samples were dated by separating the 4-11µm silt fraction and using the multi-aliquot method (Huntley and Berger, 1995). Samples were prepared by Glenn Berger at Desert Research Institute, Reno, NV, and dosimetry and luminescence measurements (Table 2) were made by George Brook at the Geochronology laboratory at the University of Georgia.

Table 2. Summary of multi-aliquot infrared-stimulated luminescence measurements on the fine silt fraction; detection at 420 nm; errors are one sigma.

Lab No.	Sample	U (ppm)	Th (ppm)	K (%)	Dose Rate* (Gy/ka)	Mean (Gy) Paleodose	Mean Age (ka)	Min.(Gy) Paleodose	Minimum Age(ka)
UGA06OSL-337	JOSL-1	4.24±1.03	6.34±3.52	3.01	4.4±0.4	see below	see below	see below	
UGA06OSL-339	JOSL-2	3.91±0.54	5.07±1.87	2.5	3.7±0.2	71.54±5.73	19.3±1.9	61.81±6.62	16.6±2.0
UGA06OSL-344	JOSL-3	3.08±0.41	5.08±1.4	2.95	3.9±0.2	108.05±4.81	27.4±1.7	98.88±8.78	25.0±2.5
UGA06OSL-338	JOSL-4	3.1±0.54	5.44±1.87	3.23	4.2±0.2	95.13±10.93	22.4±2.8	80.11±11.09	18.9±2.8

*Assumed water content: 5 % ± 2 %; Cosmic dose rate: 150±30 (µGy/yr)

JOSL-1 has a bimodal distribution. We calculated two ages, one for each mode.

	Mean Paleodose(Gy)	Mean Age (Ka)
the younger mode	34.76±2.01	8.0±0.8
the older mode	49.67±2.54	11.4±1.1

The 4 OSL ages are in correct stratigraphic order and indicate that the youngest alluvial fan deposits at this location (at least, those on the hanging wall) were deposited about 27.4 ka. The overlying "older colluvium" (unit 2) was deposited beginning about 22.4 ka, and the intermediate colluvium (unit 3) was deposited ca. 19.3 ka. The "younger colluvium" (unit 4) began to be deposited shortly after 8.0 ka and is continuing to be deposited to the present.

These ages are all much younger than we expected, based on the previous age estimate of the alluvial fan as Bull Lake age (McCalpin, 1983), and the presence of thick textural and cambic B horizons in the surface soil. We discuss this contradiction below.

4.2.5 Interpretation of the Trench

The discrepancy between the Pinedale-age OSL dates and the Bull Lake-age appearance of the fan surface, might be explained in several ways.

Explanation #1: The OSL age estimates are all wrong, and the deposits are indeed Bull Lake in age.

Advantages: 1—A Bull Lake age for the alluvial fan is consistent with previous age estimates from regional mapping, based on the degree of soil development and fan dissection.

Disadvantages: 1—If the alluvial fan deposits are actually Bull Lake in age (ca. 150 ka), the OSL age from unit 1e (27.4 ka) is a factor of 5 too young. So are the ages of the overlying deposits, because there is no large hiatus (buried soil) between them and unit 1.

It is difficult for an OSL age to be younger than the true age of the deposit; this requires that the dated samples be younger material that was physically introduced into the host deposit. We saw no evidence of such relationships in unit 1e, where the dated material was a well-sorted (eolian?) sand that apparently blew onto the fan between the deposition of units 1c and 1e. Nor did we see evidence of material intrusion in the other 3 samples.

2—If all 4 dated samples were younger material physically intruded into the host strata, it is very coincidental that the contaminated ages come out in such nice stratigraphic order.

Conclusion: Explanation #1 is unlikely.

Explanation #2: The OSL age estimates from the hanging wall are correct.

Advantages: 1— We do not have to disregard the OSL ages.

2—The OSL ages may be correct for the deposits on the hanging wall, but not for those on the footwall, which are actually older deposits.

Disadvantages: 1—If the hanging wall alluvial fan deposits are actually Pinedale in age (27.4 ka), the soil developed on them is much stronger than on (inferred) Pinedale fans elsewhere along the range front. The only reasonable explanation for this would be if the precipitation at Carr Gulch was much higher than at the sites where McCalpin (1983) developed his soil chronosequence, or the deposits contained more primary clay. However, we have no evidence that either of these contentions is true.

2—A similar explanation would be needed to explain why a Pinedale-age fan at Carr Gulch displays fan-head dissection more consistent with Bull Lake fans elsewhere.

Conclusion: We believe the OSL ages are correct, at least for hanging-wall strata.

Explanation #3: The OSL age estimates from the hanging wall are correct (Pinedale), but they represent younger alluvial and colluvial deposition restricted to the hanging wall directly downslope from the fault scarp. The remainder of the faulted alluvial fan is Bull Lake in age.

Advantages: 1— We do not have to disregard the OSL ages.

2—The dated hanging wall deposits exposed in the trench merely record some retricted, post-faulting deposition events that have occurred on a Bull Lake age alluvial fan, in close proximity to the fault scarp. These deposits would represent small fans and channels at the base of the fault scarp that formed immediately after post-Bull Lake faulting, and before the major incision of Carr Gulch. The dated deposits do not extend very far away from the fault scarp, and are underlain by alluvial fan deposits of the more widespread Bull Lake fan at shallow depths. The trench was simply not deep (or long) enough to expose those Bull Lake fan deposits on the hanging wall.

3—This explains why the dissection of the fan above and below the fault scarp appears similar to that of other Bull Lake fans, because most of the fan volume is Bull Lake in age.

Disadvantages: 1— The correlation of footwall and hanging wall beds shown on Fig. 11 is incorrect. In this Explanation, units 1a-1e on the footwall are much older (Bull Lake, ca. 150 ka) than units 1b-1e on the hanging wall (Pinedale, ca. 27-35 ka).

2—The 2.5 m displacement shown across the main graben zone in Fig. 11 is incorrect, because the beds on which it is based are not correlative. In contrast, the displacements across Faults C and D are correct.

Conclusion: We believe this is the most likely explanation.

Our preferred explanation of the geomorphology and OSL dates implies several additional conclusions. First, the 4.5 m surface offset of the fault scarp does not represent the cumulative post-Bull Lake displacement, because the hanging wall beds are Pinedale in age, much younger than the footwall beds. However, neither does the 4.5 m surface offset necessarily represent the cumulative post-Pinedale displacement either, because there may have already been some fault scarp relief when the Pinedale strata were deposited on the hanging wall. If the Pinedale hanging-wall deposits had completely buried the scarp at 27.4 ka, then there has been 4.5 m of displacement across the graben since 27.4 ka. In contrast, if the hanging-wall deposits only partially buried the scarp, there has been less than 4.5 m cumulative displacement. Thus, the 4.5 m of surface offset is a maximum estimate for cumulative displacement since 27.4 ka.

Second, the 2 m displacement of Pinedale strata across faults C and D is a true measure of the stratigraphic displacement across those faults since ca. 27.4 ka.

5. CONCLUSIONS

The Carr Gulch trench exposed evidence for 3 paleoearthquake displacements in the past 27.4 ka. The existence of 3 colluvial deposits (units 2, 3, 4) argues that the ca. 4.5 m of surface offset was formed during 3 surface-faulting events with an average displacement of about 1.5 m each. This history is summarized in the slip-history diagram of Fig. 15.

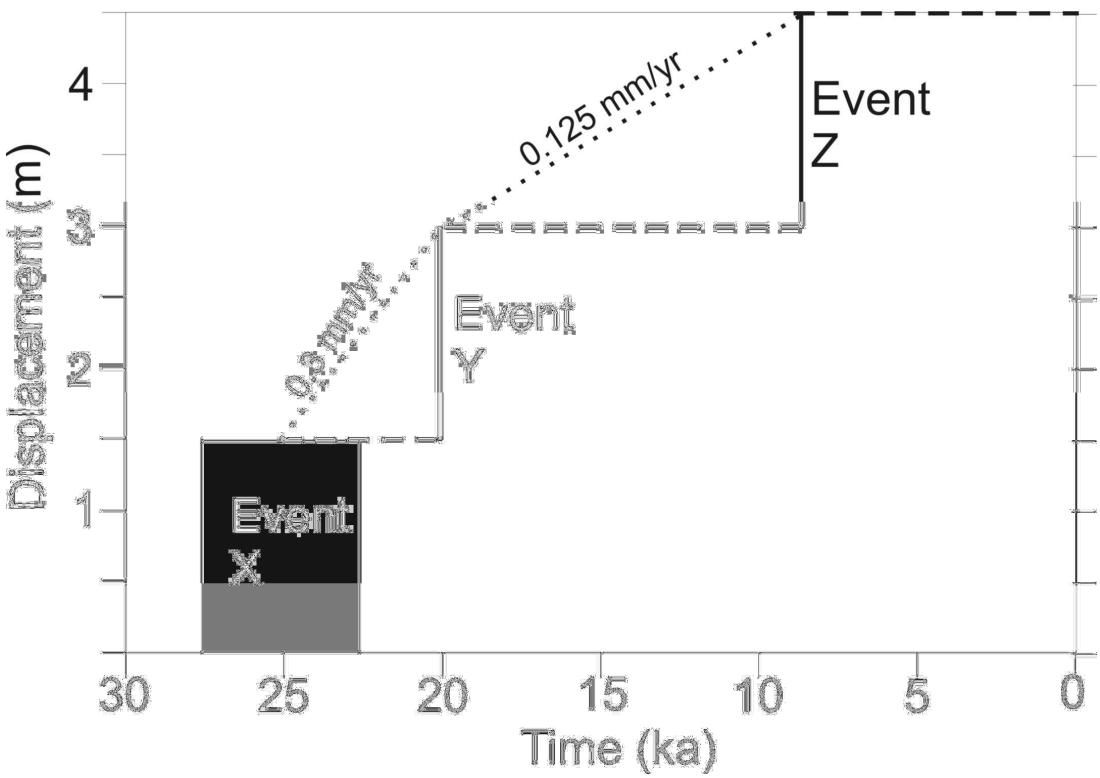


Fig. 15. Slip-history diagram of the latest 3 faulting events exposed in the Carr Gulch trench.

5.1 Displacement per Event and Paleomagnitude

The existence of 2 colluvial deposits (units 2, 3, 4) argues that the 4.5 m of surface offset was formed during 3 surface-faulting events with an average displacement of about 1.5 m each. This average displacement is similar to the average per-event displacements computed by McCalpin (1982, p.80) elsewhere on the NSCF (1.7 m at Rock Creek, 1.4-1.8 m at Major Creek). According to Wells and Coppersmith (1994), a normal-fault displacement of 1.5 m is associated with an M7.1 earthquake if it is the average surface displacement, and with an M6.9 earthquake if it is the maximum displacement.

5.2 Recurrence Intervals

The ages of the 3 paleoearthquakes (Events X, Y and Z) are roughly constrained by the 4 OSL dates. The latest event (Z) occurred slightly after 8.0±0.8 ka. This age is similar to the age of the latest event on the Crestone segment at Major Creek, dated by McCalpin (1982) as slightly before 7660±120 C-14 yr BP (or 8187 to 8728 cal yr BP; 1-sigma age range from Reimer et al,

2004). Event Y occurred slightly before 19.3±1.9 ka, when the basal part of unit 3 colluvium was deposited. Likewise, Event X occurred before 22.4±2.8 ka and after 27.4±1.7 ka (the midpoint of that time span is 24.9 ka).

These OSL age constraints indicate variable recurrence intervals between events. For example, if we round the ages of Events Z, Y, and X to 8 ka, 20 ka, and 25 ka, respectively (as done in Fig. 15), then the recurrence time between Events Z and Y is 12 ka but between Events Y and X the recurrence time is only 5 ka.

5.3 Slip Rate

In the past 27.4 ka there have been 3 paleoearthquakes but only 2 complete seismic cycles on which to compute closed-cycle slip rates. According to Fig. 15, the slip rate during the Event Y cycle was 0.3 mm/yr and in the Event Z cycle was 0.125 mm/yr.

5.4 Implications for Segmentation of the Northern Sangre de Cristo fault zone

In our proposal to NEHRP, we proposed to *"test the strength of potential segment boundaries in the Crestone section by analyzing fault scarp height trends across the boundaries, and by comparing dates on the MRE and PE from the trenches described above. The scarp heights on geologic deposits of various ages will be used to compute interval slip rates, as described in the next section. An abrupt change in slip rate across a suspected segment boundary will be taken as evidence that the boundary is persistent. If the ages of the MRE and PE vary widely between trenches, we will take that as supportive evidence that the rupture events are not the same, which supports the idea of a segment boundary."*

Fig. 16 compares the slip-history of paleoearthquakes at the Carr Gulch site with that at the Major Creek site, which lies far south of the proposed segment boundary near Hayden Pass.

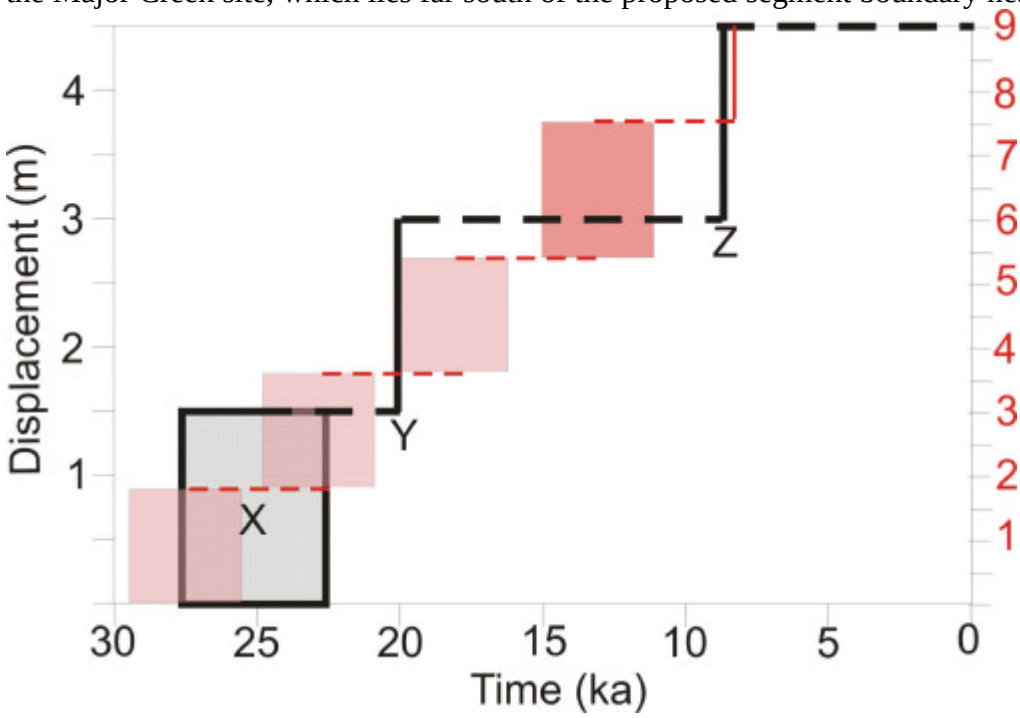


Fig. 16. Comparison of the slip-histories of the Carr Gulch trench (black lines and letters) and the Major Creek site (redlines and letters). Note difference in the displacement scales for the 2 sites.

At the Carr Gulch site there has been a maximum of 4.5 m of displacement in the past 27.4 ka. In contrast, at the Major Creek site there has been 8.9 m of displacement in a similar time period (since early Pinedale time). The displacement-per-event, reconstructed from trenches at both sites, is similar (1.5 m at Carr Gulch; 1.4-2.2 m at Major Creek). Therefore, the difference in displacement implies that fewer events have occurred at Carr Gulch than at Major Creek.

The latest event at both sites occurred at nearly the same time (Fig. 16). The penultimate event at Major Creek, however, occurred between about 11 ka and 15 ka, much younger than the penultimate event at Carr Gulch (ca. 20 ka). At Major Creek we have no direct dating control on the earlier events, so Fig. 16 shows three hypothetical events of average displacement (pink) spread equally in time back to ca. 30 ka. The youngest of these 3 events could conceivably correlate with the penultimate event at Carr Gulch. The oldest event at Carr Gulch could correlate with either the oldest or second-oldest event at Major Creek.

Despite the ambiguities of event-matching with such fragmentary dating control, it is clear that there have been 5 inferred faulting events at Major Creek since early Pinedale time, but only 3 events at Carr Gulch. Only the latest event appears to be a possible simultaneous rupture at both sites. The penultimate events at Carr Gulch and Major Creek cannot be the same event, if the age constraints at each site are correct. Some of the earlier events may have ruptured at both sites, but all of them could not have.

This pattern of fault behavior suggests that there is a nonpersistent segment boundary between the Major Creek and Carr Gulch sites. We propose that this segment boundary lies at the junction of the Villa Grove fault zone and the NCSF. Based on the record at Carr Gulch, about half of the range-front ruptures south of the VGFZ will continue north past the segment boundary. The other half of the ruptures will be deflected out onto the VGFZ. Therefore, we propose to subdivide the Crestone section (as defined by Widmann et al, 1998) into 2 rupture segments, with a common boundary where the VGFZ joins the NCSF. This subdivision is identical to the suggestion of Jack Benjamin and Associates and Geomatrix Consultants (1996), that the Crestone section should be subdivided into a 38-km-long segment north of the Major Creek/Kerber Creek thrust fault zone, and a 52-km-long segment south of it. We propose the name Hayden Segment for the northern segment and Major Segment for the southern segment. However, at this point we do not know exactly where the southern end of the Major segment is.

5.4.1 Refine slip rate measurements from existing geomorphic data

At present the National Seismic Hazard Map assumes a slip rate of 0.18 mm/yr for the entire Sangre de Cristo fault, despite the fact that McCalpin (1982) proposed three segments (A, B, C), Jack Benjamin and Associates and Geomatrix Consultants (1996) proposed 4 segments, and Widmann et al. proposed 3 sections. The scarp height data in McCalpin (1982) show a sharp decrease in displacement values across the junction of the VGFZ and NSCF (Fig. 2). Therefore, since our results suggest that there is a segment boundary within the current Crestone section, we need new slip rate estimates for these 2 new segments. In addition, we have to compute the seismic source parameters of a 2-segment rupture that involves the entire 90 km-long Crestone section.

5.4.2 Source Characteristics of the Major Segment

The Major Segment is 52 km long and has an per-event displacements of 1.4 (MRE) and 2.4 m (PE;Major Creek site); 2.2-2.8 m (San Isabel site), and 1.8-2.9 m (Willow Creek site) based on the size of single- and double-event fault scarps (McCalpin, 1982). The average of these 6 per-event displacement estimates is 2.15 m and the maximum is 2.9 m. In some cases, the variance of displacement between events at a site is opposite to that expected. For example, absolute dates suggest that the MRE at Major Creek occurred about 8 ka and probably ruptured the entire 90 km-long Crestone section, yet the displacement at Major Creek was only 1.4 m. During the PE at Major Creek the displacement was much larger, but dating suggests that this event did not affect the Hayden segment, so must have been restricted to the Major Segment and VGFZ (combined length 71 km). So, the longer rupture had a smaller displacement at Major Creek, and the shorter rupture the larger displacement at that same site. This kind of randomized variability of displacement along strike is typocal of normal fault ruptures (e.g., McCalpin and Slemmons, 1999; Youngs et al, 2000).

According to Wells and Coppersmith (1994), the rupture length of 71 km implies an earthquake of M7.3, the average displacement of 2.15 m implies an earthquake of M7.0, and the maximum displacement of 2.9 m implies an earthquake of M6.9 (Table 3). We believe that the uncertainty in displacement measurements is greater than the uncertainty in length measurements. Therefore, we compute a preferred value of the magnitude of the characteristic earthquake (M_{char}) as $0.67*M_{char\text{-}L} + 0.33((M_{char\text{-}Davg+}M_{char\text{-}Dmax})/2)$.

Table 3. Estimated source characteristics for the NCSF in three rupture scenarios.

Rupture Segment	**Length (km)**	**Davg (m)**	**Dmax (m)**	**Mchar[1]**	**Recurrence Interval (ka)**
Hayden only	38	1.5	1.7?[2]	6.9	5-12 ka
Major and VGFZ	52+19= 71	2.15	2.9	7.2	5-8 ka
Hayden and Major[3]	90	2.15	2.9	7.3	12-30 ka[4]

[1] computed as $0.67*M_{char\text{-}L} + 0.33((M_{char\text{-}Davg+}M_{char\text{-}Dmax})/2)$.
[2] displacement of MRE at Rock Creek (McCalpin, 1982, p. 80)
[3] a 2-segment rupture (Hayden+Major) spanning the entire 90 km-long Crestone section
[4] assuming that 2-segment ruptures account for about 40% of all ruptures

5.4.3 Source Characteristics of the Hayden Segment

The Hayden Segment is 38 km long and has average per-event displacements of 1.5 m (latest 3 events) at Carr Gulch. The only other displacement estimate is the MRE surface offset at Rock Creek (1.7 m; McCalpin, 1982). We use these values as Davg and Dmax, respectively.

According to Wells and Coppersmith (1994), the rupture length of 38 km implies an earthquake of M6.9, the average displacement of 1.5 m implies an earthquake of M6.9, and the maximum displacement of 1.6 m implies an earthquake of M6.8 (Table 3). These values yield an estimate of M6.9 for Mchar. The average recurrence interval over the latest 2 closed seismic cycles (5 ka and 12 ka) is 8.5 ka.

5.4.4 Source Characteristics of a 2-Event Rupture (Major+Hayden Segments)

The combined length of the Major and Hayden segments is 90 km. According to Wells and Coppersmith (1994), a rupture length of 90 km implies an earthquake of M7.4. For the 2-event rupture we use the same $M_{char\text{-}D}$ values as for the Major segment. Therefore, we compute a preferred value of the magnitude of the characteristic 2-segment earthquake (M_{char}) as 7.3.

The space-time diagram of Fig. 16 suggests that only about 3 out of 5 (60%) of events that rupture at Major Creek also rupture at Carr Gulch. Thus, if only about 60% of ruptures are 2-event ruptures, the recurrence period of such ruptures should be approximated by dividing the recurrence interval of the individual segments by 40%. This yields a recurrence for 2-segment ruptures of ca. 12-30 ka.

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7. ACKNOWLEDGMENTS

This trenching study would not have been possible without the support and landowner permission granted by the Bureau of Land Management. BLM geologist Diane Gese assisted in getting permission to trench. Trenches were logged by J.P. McCalpin, R.M. Kirkham, and E.

Karlstrom (Cal State, Stanislaus). Dr. Glenn Berger (Desert Research Institute, Reno, NV) prepped the luminescence sampling and Dr. George Brook (University of Georgia) dated them.

APPENDIX 1
DATABASE ENTRY FOR THE Crestone Section of the Northern Sangre de Cristo fault, from the U.S. Geological Survey's Quaternary Fault and Fold Database
(http://qfaults.cr.usgs.gov/faults/FMPro)

Complete Report for Northern Sangre de Cristo fault, Crestone section (Class A) No. 2321a

Brief Report || Partial Report

Compiled in cooperation with the Colorado Geological Survey

citation for this record: Kirkham, R.M., compiler, 1998, Fault number 2321a, Northern Sangre de Cristo fault, Crestone section, in Quaternary fault and fold database of the United States, ver 1.0: U.S. Geological Survey Open-File Report 03-417, http://qfaults.cr.usgs.gov.

Synopsis:	**General:** The Northern Sangre de Cristo fault is a west-dipping normal fault that is the structural boundary between the Sangre de Cristo Range/Culebra Range on the east and the San Luis basin on the west. The fault is divided into four sections for this compilation based on mountain-front geometry and fault-scarp morphology. All four sections show evidence of multiple late Quaternary movements, including ruptures during the Holocene. Scarp profiles are available for all of the sections. The Crestone and Zapata sections have been trenched. **Sections:** This fault has 4 sections. The Northern Sangre de Cristo fault includes the following sections from north to south: the Crestone section, the Zapata section, the Blanca section, and the San Luis section. McCalpin (1981 #2723; 1982 #791) had defined three segments for the part of the Northern Sangre de Cristo fault from near Poncha Pass to the south side of the Blanca Peak Massif. These three segments are herein called sections. A fourth section (San Luis) extends generally southward from the south side of the Blanca Peak Massif to Jarosa Creek near the Colorado - New Mexico state line. Jack Benjamin and Associates and Geomatrix Consultants (1996 #2703) suggested the Crestone section used herein should be further divided into a 38-km-long segment north of the Major Creek/Kerber Creek thrust fault zone, and a 52-km-long segment south of it, but this additional subdivision, although perhaps valid, has not been used in this compilation.
	Name Comments: **General Name Comments:** The Sangre de Cristo fault zone borders the eastern side of San Luis basin

	from near Poncha Pass, Colorado, to near Taos, New Mexico. This fault zone has been subdivided into two discrete faults for this compilation: the Northern Sangre de Cristo fault and the Southern Sangre de Cristo fault. Most of the Southern Sangre de Cristo fault is in New Mexico. The Northern Sangre de Cristo fault is further subdivided into four sections. **Section Name Comments:** The Crestone section of the Northern Sangre de Cristo fault corresponds to segment 'A' of McCalpin (1982 #791). The name "Crestone section" was first used by Widmann and others (1998 #3441) for this compilation. The Crestone section extends from near Poncha Pass on the north to the Great Sand Dunes National Monument on the south. **Number Comments:** Fault number Q69a of Widman and others (1998 #3441); fault 116 in Kirkham and Rogers (1981 #792); fault 131 in Witkind (1976 #2792); fault 3 of Colman (1985 #1953).
State(s):	Colorado
County(s):	Saguache
AMS sheet(s):	Pueblo Trinidad view map
Physiographic province(s):	Southern Rocky Mountains province
Geologic setting:	The Northern Sangre de Cristo fault is a major down-to-west normal fault within the Rio Grande Rift. It forms the eastern boundary of the east-tilted half-graben of San Luis basin. The deepest part of San Luis basin lies adjacent to the Northern Sangre de Cristo fault (Gaca and Karig, 1965 #2690). Estimates of the maximum thickness of synorogenic basin fill in that part of San Luis basin have widely ranged. Gaca and Karig (1965 #2690) suggested a maximum thickness of about 9.7 km; Huntley (1976 #2698; 1976 #2699) reported it at about 5 km; Stoughton (1977 #2750) at 6,000 m; and Kluth and

	Schaftenaar (1994 #1183) at 6.4 km. Estimates of the amount of vertical displacement on the Northern Sangre de Cristo fault also vary widely. Recently Kluth and Schaftenaar (1994 #1183) suggested the Northern Sangre de Cristo fault has approximately 9.2 km of vertical separation.
Reliability of location:	Good. Compiled at 1:125,000 scale. *Comments:* All or parts of this section were mapped by Wychgram (1972 #2796; scale 1:24,000), McCalpin (1982 #791; scale 1:50,000), Colman and others (1985 #1954; scale 1:125,000), Tweto and others (1976 #2774; scale 1:250,000), Scott and others (1978 #2735; scale 1:250,000), Witkind (1976 #2792; scale 1:500,000), Kirkham and Rogers (1981 #792; scale 1:500,000), and Colman (1985 #1953; scale 1:1,000,000). The trace used for this compilation is from Colman and others (1985 #1954).
Length (km):	This section is 79.1 km of a total fault length of 163.6 km. *Comments:*
Average strike:	N30°W (for section) versus N19°W (for whole fault)
Sense of movement:	Normal *Comments:*
Dip:	60° W *Comments:* The dip of the Crestone section of the Northern Sangre de Cristo fault is debatable. Scott (1970 #1141) suggested it is near vertical. Tweto (1979 #2767), Burroughs (1981 #2661), and Brister and Gries (1994 #1178) described it as a high-angle fault, a value supported by trench exposures mapped by McCalpin (1981 #2723, 1982 #791). Based on seismic reflection and gravity data, Kluth and Schaftenaar (1994 #1183) concluded the fault dip is about 60°, the value used herein. Morel and Watkins (1997 #2724), using seismic reflection and drill-hole data, reported it is a low-angle detachment fault that flattens to subhorizontal in Precambrian rocks.
Paleoseismology studies:	McCalpin (1981 #2723, 1982 #791) and Colman and others (1985 #1954) profiled several scarps on the Crestone section. Three trenches were

	excavated across this section by McCalpin (1981 #2723, 1982 #791) and are herein labeled as sites 2321a-1, 2321a-1, and 2321a-3. Major Creek site [2321a-1]. This trench crossed the fault at Major Creek and displayed evidence of two fault movements that were constrained in time by two carbon-14-dates. Willow Creek site [2321a-2]. This trench was excavated in Holocene fan alluvium near Willow Creek and contained evidence of one fault rupture with 2.3 m of displacement. Willow Creek site [2321a-3]. This trench was excavated in Bull Lake alluvium near Willow Creek and exposed evidence of perhaps three rupture events.
Geomorphic expression:	A series of discontinuous, prominent, west-facing scarps are developed on late Quaternary deposits along the Crestone section of this fault. The mountain front is marked by striking triangular faceted spurs (Kirkham and Rogers, 1981 #792; McCalpin, 1982 #791).
Age of faulted surficial deposits:	Pre-Bull Lake, Bull Lake, Pinedale, and Holocene fan alluvium is offset in several areas along the Crestone section of the fault (Kirkham and Rogers, 1981 #792; McCalpin, 1981 #2723, 1982 #791).
Year of historic deformation:	
Most recent prehistoric deformation:	Latest Quaternary (<15 ka) *Comments:* This section was recognized as a young fault by Scott (1970 #1141). Results from trenching at site 2321a-1 at Major Creek (McCalpin,1981 #2723, 1982 #791) indicated the latest rupture occurred shortly before 7,600±120 yrs B.P., and that a second movement occurred before 10,100 ±110 yrs B.P.
Recurrence interval:	5.0 -11.7 k.y. (0-70? ka) *Comments:* McCalpin (1981 #2723, 1982 #791) suggested that the part of the Crestone section south of the Major Creek/Kerber Creek fault zone has a recurrence interval of 5.0 -11.7 k.y. during post-early Pinedale time (ca. <70? ka), whereas the part north of this fault zone has a slower uplift rate and

	longer recurrence interval. He reported that the recurrence interval appears to be longer during Pinedale to Bull Lake time and during pre-Bull Lake time.
Slip-rate category:	Less than 0.2 mm/yr *Comments:* McCalpin (1981 #2723, 1982 #791) reported an average slip rate of 44 mm in 1 k.y. (0.044 mm/yr) for the Willow Creek area.
Compiled or modified by and affiliation:	Robert M. Kirkham, Colorado Geological Survey, 1998
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