Active Faults and Seismic Hazards to Infrastructure at Great Sand Dunes National Monument and Preserve; FINAL REPORT, v. 2.0

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1. EXECUTIVE SUMMARY

This report is the final report for 2 seismic hazard studies conducted at GRSA between June 2002 and Dec. 2005. For the first study (Cooperative Ecosystem Studies Unit, CESU COOPERATIVE AGREEMENT No. CA-1200-99-007 grant to Crestone Science Center/Utah State University), a preliminary report was issued on Nov. 30, 2003 covering the trenching investigations of 2002 and 2003. At that time most of the radiocarbon and luminescence age dates had not yet been processed, so the ages of paleoearthquakes were estimated mainly from stratigraphic relationships. This final report contains 9 new radiocarbon dates and 5 new luminescence age estimates, and a revised interpretation of paleoearthquake timing.

The second study (SEPAS, Project GRSA 59921) aimed at collecting additional dating information, and describing the specific seismic hazards to GRSA infrastructure from surface fault rupture, ground shaking, liquefaction, and shaking-induced landslides. The specific hazards were analyzed from geologic mapping data originally collected between 1978 and 1980 (McCalpin, 1981, 1982) updated by additional observations from 1991 to 1992 (hydrology of Medano Creek; McCalpin, 1991, 1992a, 1992b) and 2002 to 2005.

In 2002 and 2003 we mapped fault scarps and excavated four trenches in the Morris Gulch and Visitor Center areas. The Morris Gulch scarps exposed evidence for two post-Pinedale (post-15 ka to 35 ka) surface rupturing earthquakes, each with vertical displacements of about 1.7-2.3 m. Those displacements imply the earthquakes had a moment magnitude of about 6.9-7.0. The most recent event occurred about 5300-5500 years ago, while the prior event occurred sometime in the early Holocene (10-15 ka?). In contrast, the Visitor Center trench failed to expose a tectonic fault, but instead exposed an old landslide (?) failure probably related to stream erosion. Therefore, the Visitor Center scarp is probably a fluvial scarp eroded by ancestral Medano Creek, and poses no direct threat to the Visitor Center.

The main structure at risk from future surface rupture of the Morris Gulch scarps is the Water Tank that supplies Park headquarters. However, structural strengthening of this tank to withstand tilting and strong ground shaking may be uneconomic, compared to the cost of simply replacing the tank after an earthquake. If disruption of the headquarters' water supply following an earthquake is unacceptable, then it should be determined if a 50 cm or smaller displacement on the antithetic fault will likely cause failure of the pipe. This estimate could be made by a literature search on lifeline performance during earthquakes.

Although the risk posed by surface rupture at the Water Tank and Visitor Center is low, all structures in the Park would be subjected to strong ground shaking in the event of a M=7 earthquake. This ground shaking could reach horizontal and vertical accelerations of up to 0.5-1 g lasting for 30-40 seconds. However, with a return time of 5,000 to 10,000 years between such earthquakes, the annual probability of having an occurrence is on the order of 1/5000 to 1/10,000. These rough values would form the basis for any cost-benefit analysis of retrofitting existing buildings, or adding structural strengthening to new buildings.

2. INTRODUCTION

2.1 Purpose and Scope of Study

Great Sand Dunes National Monument and Preserve (GRSA) lies at the base of the Sangre de Cristo Mountains of south-central Colorado (Fig. 1) and contains strands of the active range-front fault zone, the Sangre de Cristo fault zone (SCFZ). The SCFZ (Fig. 2) is probably the most active fault in Colorado (Kirkham and Widmer, 2000), having evidence for two large (Magnitude>7) prehistoric earthquakes in the past 15,000 years (McCalpin, 1982). Trenching studies on an adjacent fault segment in the early 1980's showed that the Sangre de Cristo fault last ruptured ca. 7,000 years ago, and has recurrence intervals ranging from 8,000-15,000 years for M>7 earthquakes (McCalpin, 1982). These prehistoric earthquakes caused surface displacement and the creation of surface fault scarps ranging from 1 meter to 5 meters high at GRSA.

All GRSA facilities are clustered on a narrow strip of latest Pleistocene and Holocene alluvial fans east of the dune field. These alluvial fans are traversed by the fault scarps of the SCFZ described above. GRSA facilities were generally placed without regard for the fault scarps, and several critical facilities now exist either astride or adjacent to fault scarps (Table 1). Due to the building types (some are adobe) and structural methods (Colorado is only in seismic zone 1 of the Uniform Building Code), most buildings are at risk in the case of surface rupture or strong earthquake ground shaking.

Table 1. Summary of seismic hazards and facilities at risk at GRSA.

Seismic Hazard	Facilities At Risk
1. Surface rupture	1) main water tank (50,000 gal.) supplying Headquarters, Housing and Maintenance sites is adjacent to inferred active fault (it is also main source of water to fight fires) 2) inferred active fault projects into Amphitheater and Campground 3) inferred older (?) fault scarp passes within 10 m of newly-renovated Visitor Center
2. Ground Shaking	1) several critical structures (Headquarters, Museum) are adobe 2) several buildings are on the National Register of Historic Places 3) ground shaking could be severe due to proximity of most buildings to fault scarps
3. Liquefaction	1) possible hazard to visitor facilities at Dunes access area, where groundwater table is high in Holocene sand
4. Landslides	1) possible hazard to water system from landslides off steep range front facets

The main goal of the CESU project was to characterize the recent displacement history of fault scarps near GRSA facilities via paleoseismic trenching of fault scarps. Paleoseismic trenching and interpretation followed standard methods (McCalpin, 1996). Four trenches were excavated. Trenches 1-3 were excavated near the water supply tanks

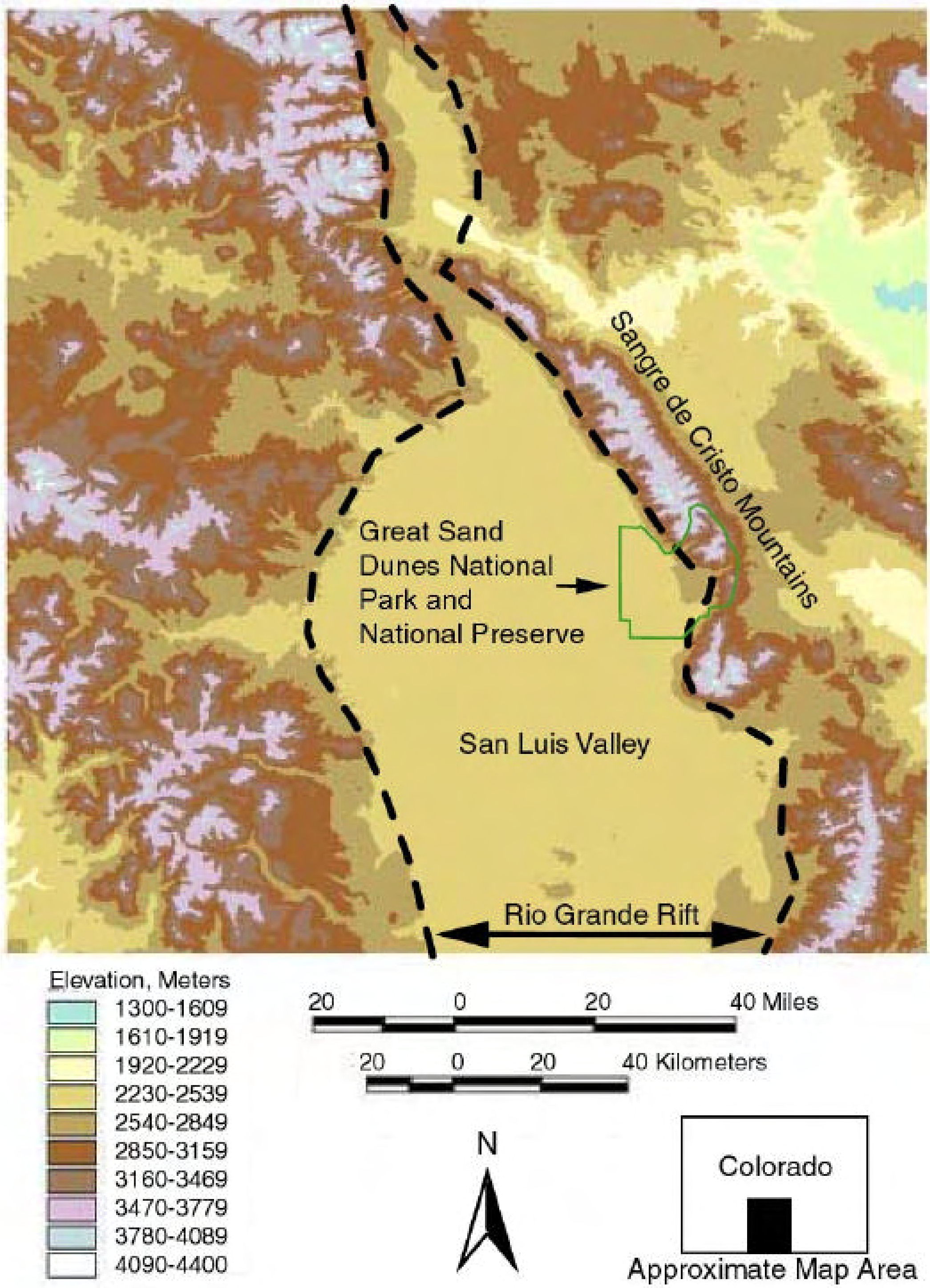

Fig. 1. Location map of Great Sand Dunes National Park. This study covers only the southeastern part of the Park, where all the current infrastructure exists (Park Headquarters, Visitor Center, offices, housing, maintenance buildings, campground, etc.).

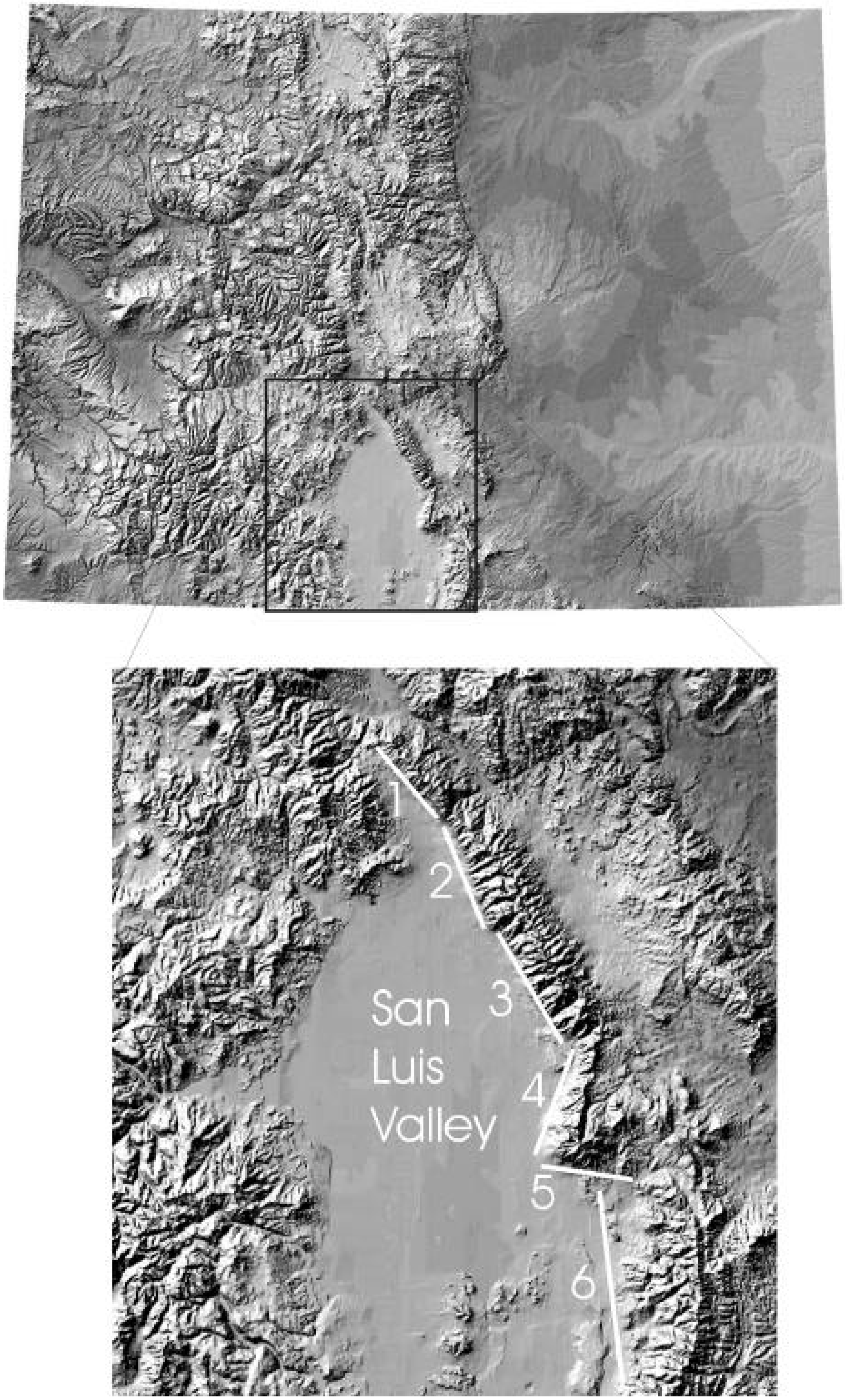

Fig. 2. Map of the study area. Upper part, shaded relief map of Colorado with rectangle centered around San Luis Valley. Lower part, possible segments of the Sangre de Cristo fault are numbered. 1-3 are within the present Crestone section; 4 is the Zapata section; 5 is the Blanca section; 6 is the San Luis section. Great Sand Dunes National Monument is located in the northern part of section 4.

upslope from Headquarters. Trench 4 was excavated on the prominent scarp adjacent to the Visitor Center, about 100 feet north of the addition added in 2004.

A major goal of trenching is to precisely date paleoearthquakes to determine which of the multiple fault traces at GRSA have experienced the most recent displacement, and thus pose more hazard to facilities. The major geochronologic question is whether paleo-surface ruptures at GRSA date so closely to the paleoearthquakes to the north and south that a >65 km-long rupture can be substantiated. The rupture length and displacement observed in trenches were used to estimate the magnitude of past earthquakes at GRSA, based on standard methods (McCalpin, 1996).

The CESU project has a large educational component, in that the trenches were logged by university students as an integral part of GEOL 6800. This 2-week summer field course is offered annually by USU and the Crestone Science Center, a nonprofit school located in Crestone, 15 km north of GRSA. Past enrollees have included university grad students from USU as well as from other US universities.

The trenching work was overseen by James P. McCalpin, Research Associate Professor at Utah State University. Dr. McCalpin performed the original mapping of fault scarps at GRSA (McCalpin, 1982), trenched the SCFZ north and south of GRSA, and headed a 2-year study of groundwater-creek interactions at GRSA in 1991-92. The actual trench logging was performed by students in McCalpin's summer course "Field Methods in Neotectonics and Paleoseismology" (GEOL 6800), offered jointly by USU and the Crestone Science Center, located 15 km north of GRSA.

CESU Products:

1) Final Technical Report (dated Nov. 30, 2003) on the activity and hazard posed by the two trenched fault strands. Report was provided in hard copy and on CD-ROM, and includes digital trench maps.
2) Educational video showing how fault trenching studies are used to assess earthquake hazards, and what those hazards might be for GRSA.

SEPAS Products:

1) THIS REPORT on the dates of paleoearthquakes on the two trenched fault strands.
2) Maps of various earthquake hazards in the southeastern part of GRSA, and what risks those hazards might pose to the existing and future infrastructure at GRSA.

2.2 Acknowledgements

The 2002 trenches were logged by Bill Lund, Mike Hylland, Bruce Eloff, Greg McDonald, Mike Neville, Yoshi Uemura, Gerald Park, Patty Craw, and Mike Davis. The 2003 trench was logged by L.C. Allen Jones and James P. McCalpin. All trenches were professionally excavated by Dave Roybal. Fred Bunch and Andrew Valdez provided logistical support. Steve Forman provided the luminescence age estimates from trench D and the Visitor Center trench. This study was supported by National Park Service funding to Utah State University and the Crestone Science Center, under the Cooperative Ecosystem Studies Unit (CESU, 2002 funding) and the NPS SEPAS program (2003).

3. GEOLOGIC SETTING

The San Luis Valley of Colorado is the topographic expression of the Rio Grande rift, a 1000 km-long intracontinental rift zone in New Mexico and Colorado. The valley is flanked by the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west. The Sangre de Cristo Mountains are dominantly composed of middle to late Paleozoic sedimentary rocks, but parts of the range are Precambrian basement that was thrust eastward over the Paleozoic rocks during the Laramide Orogeny. The San Juan Mountains are a large constructional pile of Oligocene andesitic volcanic rocks that erupted prior to formation of the rift.

The San Luis Valley is an asymmetrical, east-tilted half graben controlled by the master Sangre de Cristo normal fault on its eastern margin. In cross section the Valley is composed of three elements, from east to west, the Baca graben, the Alamosa horst, and the Monte Vista graben. The Baca graben is the deeper of the two, having about 4000 m of Tertiary rift fill sediments a few km west of the Great Sand Dunes.

While most of the valley floor is covered with a veneer of Holocene eolian deposits, alluvial fans rim the eastern valley margin. These fans are traceable in a few cases to Pinedale or Bull Lake terminal moraines at or near the range front. Accordingly, McCalpin (1982) assumed that the alluvial fans accumulated during glacial times mainly as outwash, and correlated them to the type Pinedale (15-35 ka), Bull Lake (150 ka) and pre-Bull Lake (250-400 ka) glaciations recognized elsewhere in the Rocky Mountains (Porter et al., 1983). Continuing movement on the Sangre de Cristo fault has created fault scarps on these fans near the range front that range from 2 m to 25 m high.

3.1 Previous Fault Investigations

Kirkham and Rogers (1981) published the first detailed description of Quaternary fault scarps along the Sangre de Cristo fault. McCalpin (1982) mapped the Quaternary deposits and fault scarps at 1:50,000 between Poncha Pass and Fort Garland, including those in the Great sand Dunes national Monument, and excavated 5 trenches across scarps. The closest trench to the Great Sand Dunes was at Uracca Creek, about 10 km south of the Monument. That trench across a 2.8 m-high scarp in early Holocene alluvium revealed evidence of only a single post-early Holocene surface rupture, dated at about 5.7 ka.

4. SURFACE FAULT RUPTURE HAZARDS

4.1 Methods

Paleoseismic trenching and interpretation followed standard methods (McCalpin, 1996). Because the trenches were used for instructional purposes, they were logged in several ways; Trench B by manual logging and photomosaic logging, Trench C by manual logging, and Trench D and the Visitor Center trench by photomosaic logging and total station logging.

Students in the 2002 field course “Field Methods in Neotectonics and Paleoseismology” (USU Geology 6800) mapped fault scarps in the southern part of the Monument in three areas termed “mini-project areas” (Fig. 3). Scarps were mapped on acetate overlays on aerial photographs and via GPS surveying. Scarp profiles were measured by stadia rod and Abney level (method of Bucknam and Anderson, 1979).

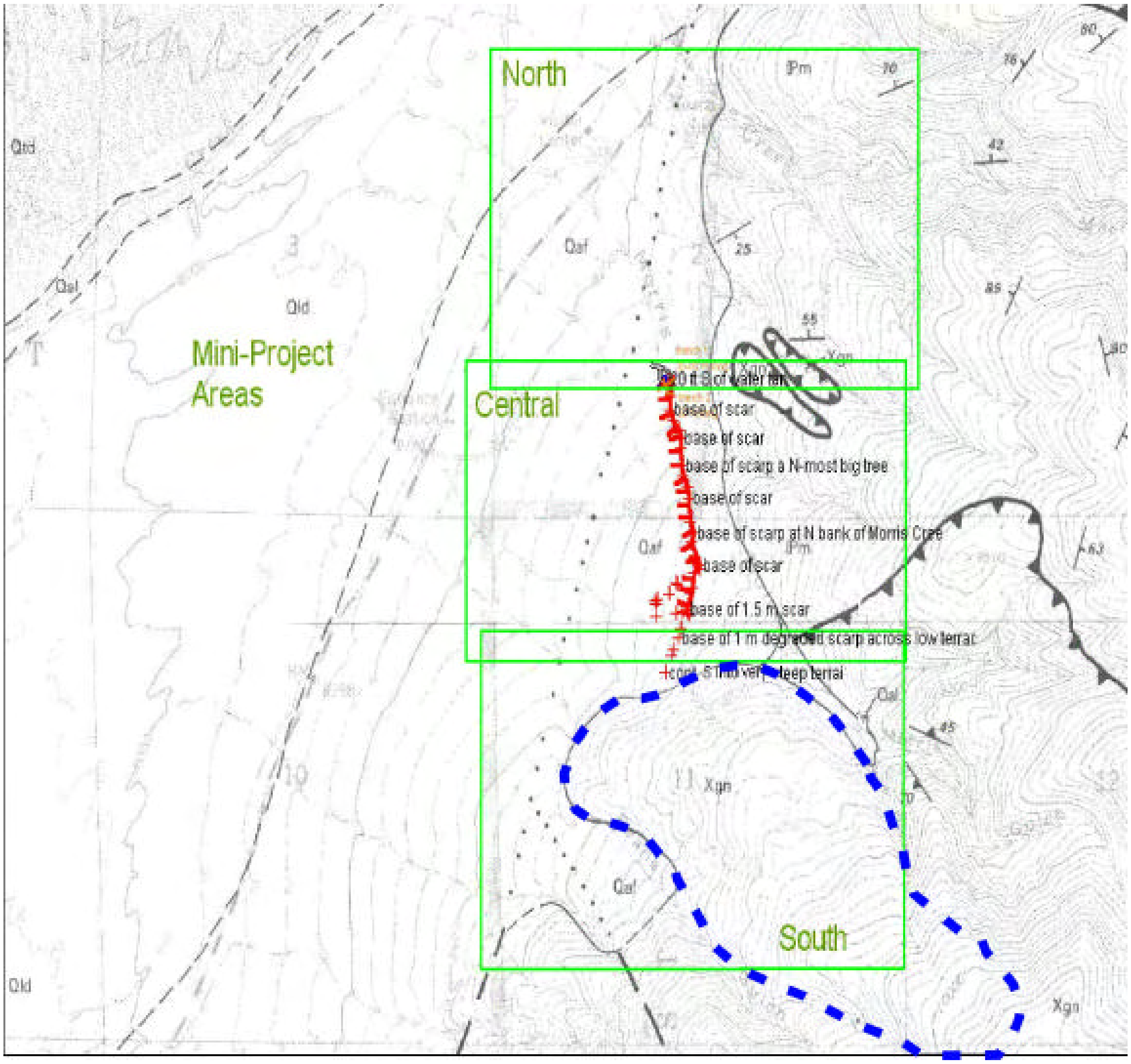

Fig. 3. Student project areas from the 2002 Field Methods course in the southern part of Great Sand Dunes National Monument. Red line shows Scarp B, the longest and most continuous scarp at the mouth of Morris Gulch. Blue dashed line outlines a large landslide in Precambrian gneiss. Geologic base map from Bruce and Johnson, 1991.

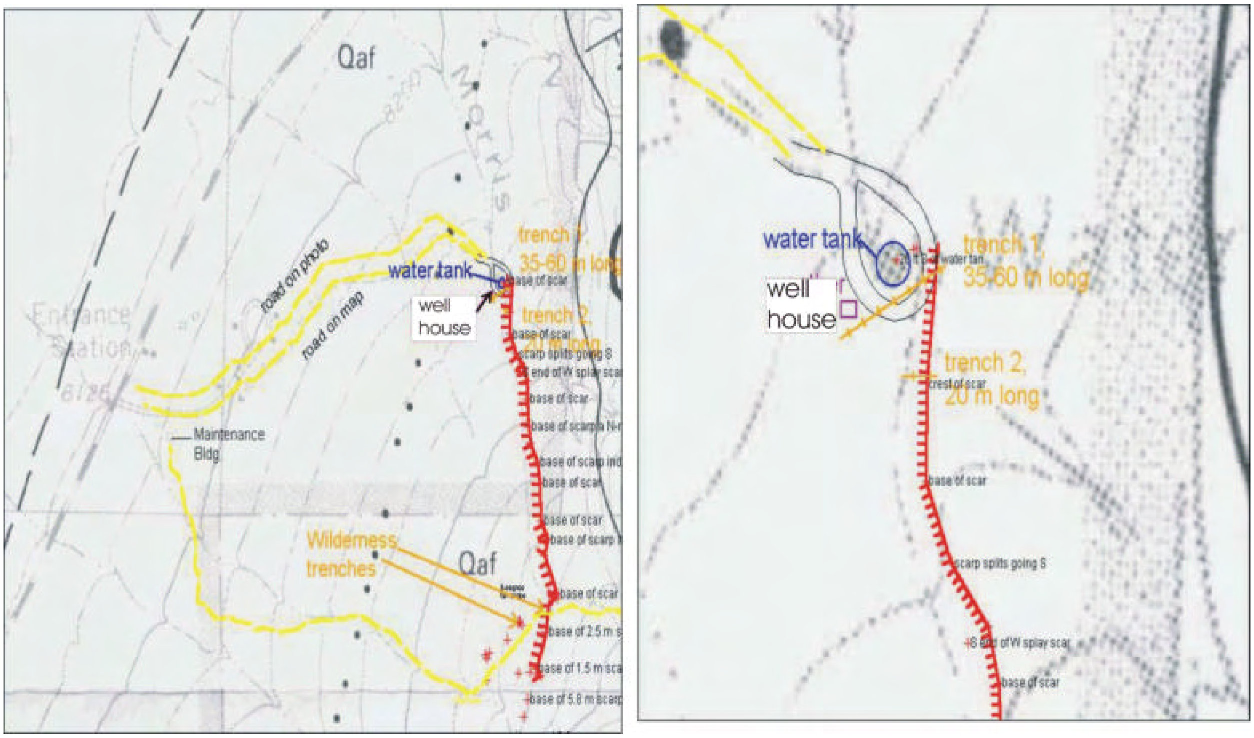

Fig. 4. Close-up of Scarp B relative to Park facilities such as the Entrance Station, Maintenance Building, Water Tank, and Well House. Trench locations shown are from the original research proposal and were changed later based on on-site reconnaissance. Geologic base map from Bruce and Johnson, 1991.

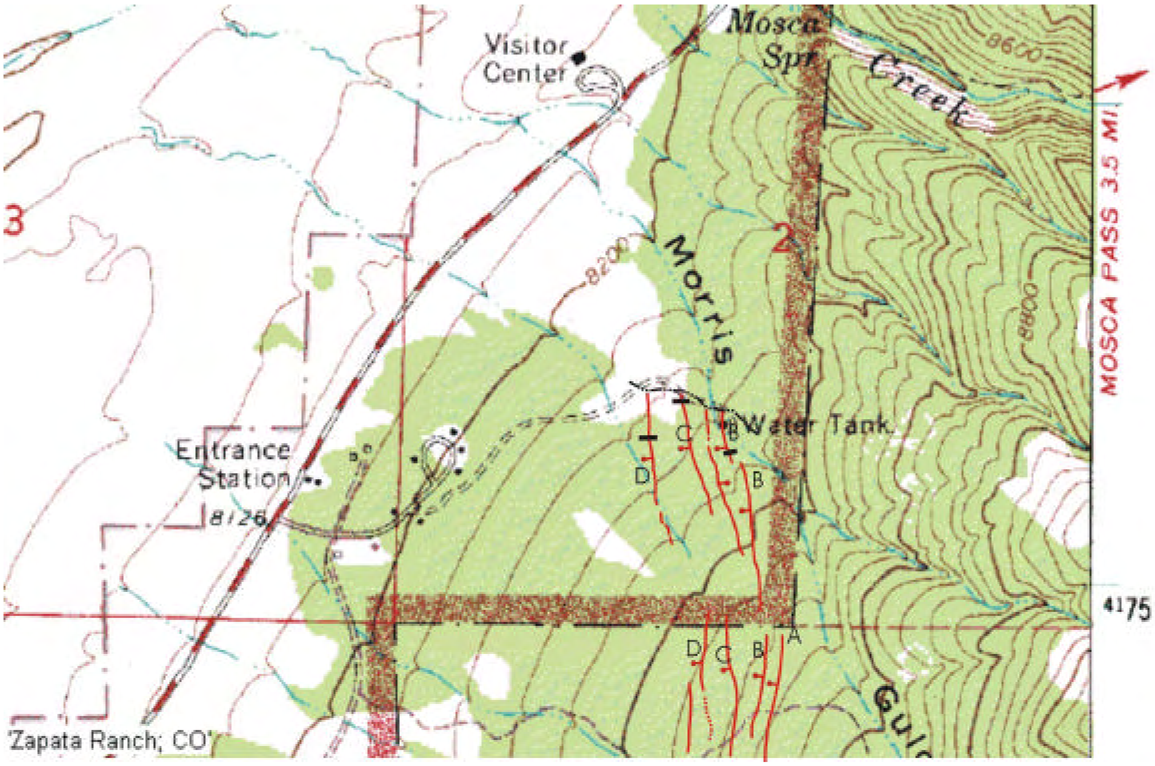

Fig. 5. Map of the fault scarps (A through D) mapped by students in the 2002 Field Methods course, at the mouth of Morris Gulch. The extension of scarp B north of the Water Tank is not shown. Black bars indicate 2002 trench locations. Base map from Mosca Pass 7.5' quadrangle, original scale 1:24,000.

funding). The Principal Investigator of the CESU study at Utah State was Dr. James P. Evans, Department of Geology.

4.2 Scarps South of Morris Gulch

The Sangre de Cristo fault zone south of Morris Gulch is mainly comprised of a single west-facing fault scarp that lies 0- 100 m west of the bedrock range front, and displaces the heads of alluvial fans of Pinedale age (ca. 15,000-35,000 years old). This same scarp continues southward to North Zapata Creek. At the mouth of South Arrastre Creek (scarp profile #71 of McCalpin, 1981) the scarp is composed of two closely-spaced scarps (step-faults). The western scarp is 3.2 m high (2.7 m of vertical separation) and the eastern scarp is 4.2 m high (3.2 m of vertical separation). Together the two scarps have 5.2 m of throw. South of the mouth of North Arrastre Creeek the scarp is very similar (profile #73 of McCalpin, 1981), with the two scarps having a combined throw of 7.2 m. On the north side of the mouth of North Arrastre Creek (profile #72 of Mccalpin, 1981) the scarps merge into a single fault scarp 8.5 m high with 6.4 m of throw. At Denton Spring (profile #70 of McCalpin, 1981) the scarp is a single scarp 8.2 m high with 6.3 m of throw. The average throw on all these scarps is 6.3 m and probably represents the latest 2 surface-faulting events. Thus, single-event displacement is probably on the order of 3.15 m.

At the mouth of Evan Gulch the scarp makes an abrupt turn to the northwest and continues about ½ mile before dying out on the alluvial fan. This splay fault apparently "robs" the range-front trace of most if its displacement, because no scarp lies at the range front between Evans Gulch and Morris Gulch. Instead, the toe of a large bedrock landslide protrudes westward at the range front. It is possible some active fault traces continue beneath the toe of this landslide, as described in a later section.

4.3 Morris Gulch scarps

<u>4.3.1 2002 Trench B</u>

Trench B was excavated in June 2002 across Scarp B about 150 m south of the Water Tank. The fault scarp here is about 4 m high (Figs. 6, 7). The upthrown alluvial fan surface is a smooth, west-sloping geomorphic surface that resembles Pinedale-age alluvial fans elsewhere along the range front (McCalpin, 1982). In contrast, the downthrown surface slopes to the northwest rather than to the west, and is marked by multiple debris-flow lobes and rills. These lobes and rills are restricted to a band about 30 m wide that parallels the fault scarp, and in places is bounded on the west side by an antithetic (east-facing) fault scarp. However, in most places this small (1- 1.5 m-high) scarp is buried by debris flow and alluvial deposits of Morris Gulch. In summary, it appears there is a graben zone about 30 m wide at the base of Scarp B (Fig. 5) that is partly to wholly filled in with debris flows and alluvium from Morris Gulch. These debris flows were assumed to post-date the latest faulting event on the scarp, and trenching validated that assumption. Therefore, the post-Pinedale displacement across the Scarp B graben should be on the order of 3 m (4 m height of the west-facing scarp minus 1 m height of the antithetic scarp).

Fig. 6. Photograph of Trench B, looking east. This photo was taken in Sept. 2003, after the trench was deepened.

Fig. 7. Photograph of the south wall of trench B, after deepening. The grid lines are 1 m apart.

Trench B was excavated in June, 2002, by a rubber-tired backhoe. Due to the loose nature of the fan gravels and the lack of shoring equipment, the trench was excavated with a vertical wall on the south side and a benched wall on the north side. However, to prevent caving and to protect the students who logged the trench, the trench was limited to 2.5 m deep. This depth was initially assumed to be sufficient to expose the complete colluvial wedge sequence, because the base of the trench was about 1.5 m below the ground surface on the downthrown side. However, when the logging was completed we realized that the post-faulting debris flows at the foot of the scarp in the graben were 1.5 m thick, and thus the older part of the colluvial wedge sequence was not exposed in the original trench. Therefore, in September 2003 the western part of the trench was deepened an additional 1.5 m (uncolored units in Fig. 8) to expose the complete colluvial sequence.

The trench was initially logged by students in the Field Methods course in June, 2002. Additional logging was performed by J.P. McCalpin in Sept. 2003.

Stratigraphy: The footwall in the trench is composed entirely of poorly-sorted, poorly-stratified, very loose alluvial fan gravels (units 1a, 1b) of probably Pinedale age (15,000-35,000 yr BP). On the hanging wall the uppermost part of this gravel sequence is exposed in the deepest part of the trench, and is overlain by a sequence of scarp-derived colluviums interbedded with alluvium and debris flows from Morris Gulch (Table 2, Fig. 8).

Table 2. Trench B, description of map units.

Unit	Description	Age & Significance
5	COLLUVIUM; wash facies; mostly eolian sand matrix with rare small pebbles	youngest deposit in trench; contains incipient A horizon of modern soil
4c	ALLUVIUM; poorly sorted stream gravel; deposited at base of scarp by Morris Gulch	post-dates the MRE
4b	ALLUVIUM; well sorted small pebble gravel in a small channel; deposited at base of scarp by Morris Gulch	post-dates the MRE
4a	DEBRIS FLOW; poorly sorted, matrix-supported gravel; deposited at the base of the scarp by Morris Gulch	post-dates the MRE
3b	COLLUVIUM; debris facies; derived from the fault free face following the MRE	Cal age= 1880(1980)2060 yr BP; closely post-dates the MRE
3d1	COLLUVIUM; early wash facies; predates alluvial units 4a-4c	closely post-dates the MRE
3d2	ALLUVIUM; coeval with colluvial unit 3d1; deposited by Morris Gulch at the base of the scarp	closely post-dates the MRE
Most Recent Fault Event (MRE)		
3.5b	ALLUVIUM; sandy gravel; deposited by Morris	between the MRE and PE

	Gulch	
3.5a	ALLUVIUM; well-sorted gravel; deposited in a small channel at the base of the scarp	between MRE and PE
2a	DEBRIS FLOW; big; deposited at base of PE scarp by Morris Gulch; contains paleosol buried by MRE colluvium (unit 3b)	Cal age= 8350(8390)8420 yr BP; top closely predates MRE
1.5	COLLUVIUM; debris facies east of Fault B, wash facies west of Fault B	Cal age= 1720(1830)1900 yr BP; closely post-dates PE
Penultimate Fault Event (PE)		
1b	FAN ALLUVIUM; oxidized zone in uppermost fan gravel on footwall	predates(?) MRE
1a3	FAN ALLUVIUM; well-sorted gravel, uppermost unit of faulted fan alluvium; contains a paleosol buried by PE colluvium	Cal age 2490(3050)3200 yr BP; predates the PE; probably Pinedale in age
1a2	FAN ALLUVIUM; poorly-sorted and cemented gravel	predates the PE; probably Pinedale in age
1a1	FAN ALLUVIUM; moderately-sorted gravel	predates the PE; probably Pinedale in age
1a	FAN ALLUVIUM; undivided; mainly poorly sorted and stratified pebble and cobble gravel	predates the PE; probably Pinedale in age

The uppermost fan gravel on the hanging wall (unit 1a3) carries a paleosol that is assumed to represent the surface soil that existed on the alluvial fan prior to faulting. This paleosol is unconformably overlain by a diamicton (unit 1.5) that is interpreted as scar-derived colluvium deposited after the earliest faulting event on Scarp B (the Penultimate Event, or PE). Unit 1.5 (the PE colluvial wedge) is overlain by a massive, 1 m-thick debris flow (unit 2a). This debris flow was probably deposited at the base of the fault scarp very soon after its formation by the PE, because there is no buried soil between units 1.5 and unit 2a.

Between faults A and B, the PE colluvial wedge (unit 1.5) is directly overlain by the MRE wedge (unit 3b), and both are composed of coarse-grained, debris-facies colluvium. In contrast, west of Fault B the scarp-derived colluvial units (3b, 3d1, 5) interfinger with coeval alluvial (units 3.5a, 3.5b, 3d2, 4b, 4c) and debris flow (unit 4a) deposits from Morris Gulch. It is clear from the geometry of these Morris Gulch deposits that unit 3d2 and younger units post-date the MRE, but units 3.5a and 3.5b may predate the MRE (while post-dating the PE).

Structure: There are two normal faults exposed in the trench. The eastern fault (Fault A) displaces units 1a/1b down to the west by 4.2 m. The western fault (Fault B) has an additional 1.4 m of vertical offset. Total vertical offset on both strands is 5.6 m, measured on the top of the alluvial fan sequence (unit 1b on the footwall, unit 1a3 on the hanging wall). However, if there antithetic fault on the western edge of the graben has a down-to-the-east displacement of 1-1.5 m, then the net vertical offset of Pinedale fan deposits across the entire fault zone is on the order of 4.1 to 4.6 m.

Geochronology: Datable material such as charcoal was absent in the original Trench B. The two buried paleosols on units 1a3 and 2a and the PE wedge were sampled for radiocarbon dating based on a faint appearance of organic matter. However, later examination of these samples in the lab revealed insufficient carbon for a date.

Luckily, four slightly more organic-rich samples were obtained after the trench was deepened in Sept. 2003 (Table 1., samples B1B through B4). These dates are problematic. Three of the 4 radiocarbon samples are considerably younger than anticipated, based on our assumption that unit 1a3 is the Pinedale-age alluvial fan gravel, correlative with the upthrown block strata, and that the soil on unit 1a3 is a latest Pleistocene/ earliest Holocene soil that predates both Holocene paleoearthquakes. The sample from the soil on unit 1a3 (sample B3 in Table 1) yielded a calibrated age of only 3050 cal yr BP, much younger than the assumed age of ca. 10,000 C-14 yr BP. The overlying sample from the PF colluvium (unit 1.5) yielded an even younger age, or 1830 cal yr BP. The stratigraphically next youngest sample (from unit 2a) yielded an age of 8390 cal yr BP, whereas a sample from only a few cm above (MRE colluvium; unit 3b) yielded a much younger age of 1980 cal yr BP.

In general, there are two ways in which radiocarbon samples can yield erroneous ages. The most common way is for young rootlets and other young carbon to intrude the stratigraphic unit, which results in radiocarbon ages much younger than the host sediment. Bulk samples of low-organic-content soils are particularly prone to this type of contamination. The other way is for old detrital charcoal from another stratigraphic unit to be eroded and then re-deposited in a younger stratigraphic unit; this yields radiocarbon ages older than the host sediment. This error only affects charcoal samples.

Three of the 4 samples from trench B are bulk samples of low-organic-content sediments, so are prone to young carbon contamination. We interpret samples B2 and B3 as contaminated with younger carbon, and infer that the host sediment of units 1a3 and 1.5 is considerably older than 1.8-3.0 ka.. However, we do not know exactly how much older. The sample from the base of the MRE colluvial wedge (B4) is also somewhat younger than originally estimated.

The date of 8390 cal yr BP from sample B1b is from small pieces of charred material that was separated from a large bulk sample by Beta Analytic, Inc. These pieces were not visible when the sample was collected. The resulting age is a few thousand years older than the mid-Holocene age originally estimated.

In summary, we believe that 3 of the 4 radiocarbon samples from trench B are contaminated, the oldest two with younger carbon and a younger charred sample with older carbon. The only sample that may not be contaminated is sample B4 from the base of the MRE colluvial wedge.

Interpretation: The presence of two colluvial wedges and two buried paleosols indicates that two surface-faulting events formed Scarp B. The earlier (Penultimate) event occurred soon after deposition of the Pinedale alluvial fan (unit 1a3), based on the weak soil preserved on fan sediments beneath the PE colluvial wedge. The second (Most Recent) event occurred after accumulation of the PE wedge, a debris flow (unit 2a), and a 20 cm-thick weak A horizon. This soil is about as well developed as the other two soils in the trench (the surface soil, and the soil on unit 1a3), suggesting that the 15,000 years following the Pinedale glaciation was approximately divided into 3 subequal periods [ignoring 3 of the 4 radiocarbon dates). During the first period (ca. 15,000 to 10,000 yr BP), a weak soil formed on the abandoned fan surface. The second period (ca. 10,000 to 2,000? yr BP) began with the Penultimate Event, and followed with deposition of units 1.5, 2a, and formation of the soil on unit 2a. The third period (2,000? yr BP to present) began with the Most Recent Event, followed by deposition of units 3 to 5. Although this chronology is crude, it generally matches the chronology derived from other trenches, except that in those trenches the MRE is dated at about 4000-5000 cal yr BP.

Table 1a. Radiocarbon ages from trench samples.

Sample No. (first letter indicates trench)	Lab No. (Beta Analytic, Inc.)	Type of Material	C-14 Age (yr BP; 1-sigma error)	Calibrated Age (cal yr BP) [-1σ(mean)+1σ]	Age Originally Estimated from Stratigraphic Interpretation (cal yr BP)
B1b	β-207518	charred material	7590±40	8350(8390)8420	5000
B2	β-207519	weakly organic sand	1880±40	1720(1830)1900	7000
B3	β-207520	weakly organic sand	2910±40	2940(3050)3200	10,000
B4	β-207521	weakly organic sand	2020±40	1880(1980)2060	5000
C1	β-207522	charred material	3150±40	3320(3370)3460	5000
C2	β-207523	charred material	3700±40	3910(4000,4040,4070)4150	10,000
D1	β-207524	weakly organic sand	2450±40	2350(2470)2730	10,000
VC1A	β-207525	organic sand	4260±50	4650(4840)4870	30,000-40,000
VC2	β-207526	charcoal	5750±40	6440(6530)6650	3000

Table 1b. Optically-stimulated luminescence (OSL) ages from trenches. First two samples are from 2002 Trench D, latter three samples are from 2003 trench at Visitor Center.

Field #	*Laboratory#*	*Equivalent dose(Gy)*	*U (ppm)*	*Th (ppm)*	*K 2 0 (%)*	*H 2 0 (%)*	*Dose Rate(mGy/ yr)*	*OSL age (yr)*
	UIC1072							5300±400
	UIC1073							4800±400
03GSD- 05[b]	UIC1322	17.65 ± 0.30	2.5 ± 0.1	8.6 ± 0.1	3.67 ± 0.04	10 ± 3	4.66 ± 0.20	3790 ± 250
03GSD- 03[b]	UIC1321	43.47 ± 0.62	2.6 ± 0.1	9.6 ± 0.1	3.63 ± 0.04	10 ± 3	4.38 ± 0.20	9910 ± 680
03GSD- 02[a]	UIC1326	236.73 ± 1.54	2.5 ± 0.1	9.2 ± 0.1	3.62 ± 0.04	5 ± 5 5.	90 ± 0.27	40,160 ± 2400

[a] OSL ages by infrared stimulation on the 4- 11 micron polymineral fraction
[b] OSL age by blue stimulation, using SAR protocols on the 100- 150 micron quartz fraction

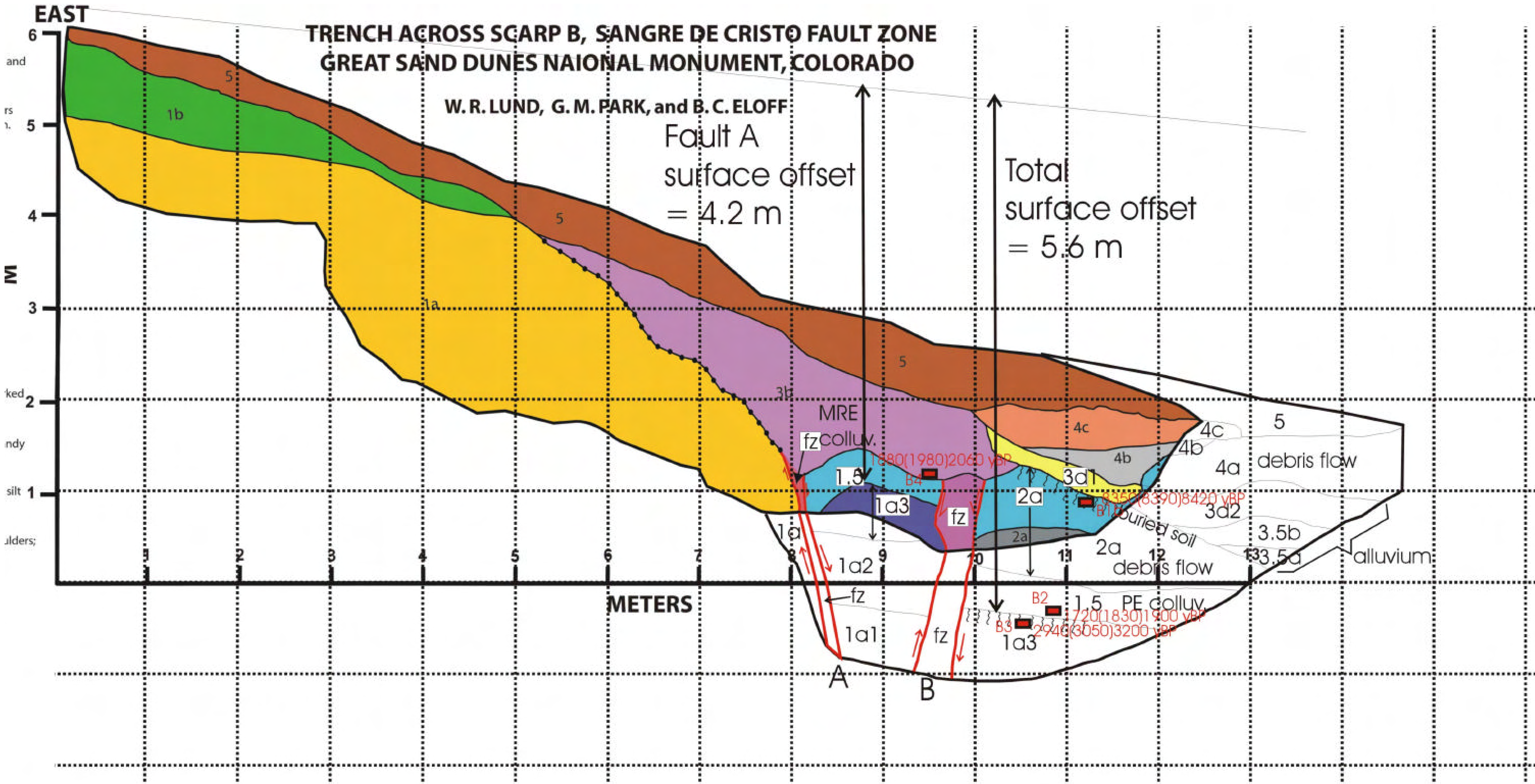

Fig. 8. Log of the south wall of Trench B. Colored parts logged by students of Field Methods course in June, 2002. Uncolored part excavated and logged by J.P. McCalpin in September, 2003. Explanation of map units is in Table 1.

4.3.2 2002 Trench C

Trench C was excavated in June 2002 on Scarp C about 50 m south of the stables, and about 10 m south of the active channel of Morris Gulch.

Stratigraphy: The footwall in the trench is composed entirely of poorly-sorted, poorly-stratified, very loose alluvial fan gravels (units 1a-1j) of post-Pinedale age (younger than 15,000 yr BP). On the hanging wall similar units underlie a sequence of colluvium, debris flows, and eolian sand (Table 3, Fig. 9).

Table 3. Trench C, description of map units.

Unit	Description	Age & Significance
5	COLLUVIUM; wash facies; mostly eolian sand matrix with rare small pebbles	youngest deposit in trench; contains incipient A horizon of modern soil
4, 4a	DEBRIS FLOW; poorly sorted, matrix-supported gravel; deposited over the scarp by Morris Gulch	Cal age= 3320(3370)3460 and 3910(4040)4150 cal yr BP; post-dates the MRE
3	EOLIAN SAND; massive, well sorted sand blown onto the colluvial wedge from the west	Pos-dates the MRE
2	COLLUVIUM; debris facies; derived from erosion of the fault free face following the MRE	closely post-dates the MRE
Most Recent Fault Event (MRE)		
1j	FAN ALLUVIUM; poorly sorted gravel	Predates the MRE
1i	FAN ALLUVIUM; loose sand matrix	"
1h	FAN ALLUVIUM; gravel with loose sand matrix	"
1g	FAN ALLUVIUM; poorly sorted fluvial gravel	"
1f	FAN ALLUVIUM; well sorted small gravel	"
1e	FAN ALLUVIUM; dirty fluvial gravel	"
1d	FAN ALLUVIUM; sandy gravel	"
1c	FAN ALLUVIUM; small pebble gravel	"
1b	FAN ALLUVIUM; large pebble gravel	"
1a	FAN ALLUVIUM; very hard silty gravel	"

There are no buried soils in Trench C, and combined with the weak surface soil and small scarp height (1.7 m), this suggests that Scarp C where trenched is a single-event scarp developed in post-Pinedale fan alluvium. The fan stratigraphy in this trench is obscure, and units cannot be traced continuously along the length of the trench, but instead interfinger in a facies relationship (depicted on Fig. 9 by squiggly lines). Due to the obscure stratigraphy, the correlation of beds across the fault zone is not certain, but is based on a similarity of beds offset about the same amount (1.7 m) as the scarp height.

The post-faulting stratigraphy is a bit more straightforward, consisting first of a basal colluvium (unit 2) that truncates the fault zone and lies at the base of an eroded free face cut into unit 1. This deposit is interpreted as scarp-derived colluvium shed from the MRE free face. Unit 2 is overlain by a massive sand that is probably eolian sand, partly direct airfall and party retransported from the upthrown to downthrown block by sheetwash. The eolian sand is unconformably overlain by a thin, stony diamicton interpreted as a debris flow. This unit parallels the modern ground surface and appears to represent a debris flow that exited Morris Gulch in late Holocene time and traveled over the scarp. Finally, the ground surface is underlain by a massive eolian sand (unit 5) of very recent age.

Structure: The fault zone in Trench C is as poorly expressed as is the fan stratigraphy. The only zone of inferred shear is an east-dipping, 20-30 cm-wide zone of weakly oriented pebbles and cobbles that underlies the thickest part of the MRE colluvial wedge. This “shear zone” and a thinner one 1 m to the east were not observed by the students who initially logged this trench, who concluded that there was no fault exposed in the trench. The log and interpretation described herein were made by J.P. McCalpin in September 2003. The east dip of the shear zone probably represents refraction of a normal fault in the near surface to an “overhanging” dip.

Geochronology: Datable material such as charcoal was rare in Trench B. Two samples of organic carbon were collected from unit 4 (post-MRE debris flow), but both were very small, and neither closely constrains the timing of the MRE. Both samples yielded similar late Holocene ages of 3320(3370)3460 cal yr BP and 3910(4040)4150 cal yr BP. Because this debris flow deposit drapes the degraded scarp profile and stratigraphically overlies the MRE colluvium (note intervening unit 3), it postdates the MRE by a considerable time span. That is, the MRE must be considerably older than 3370-4040 cal yr BP.

Interpretation: The presence of one colluvial wedge indicates that one surface-faulting event formed Scarp B, at least at this location near to the active channel of Morris Gulch. After the MRE occurred, a small colluvial wedge (maximum thickness = 50 cm) was deposited, and was buried by eolian sand. The sand was then buried by a thin debris flow that traveled across the entire scarp, sometime around 3370-4040 cal yr BP. This flow was later buried by eolian/slopewash sand, a process which continues today. The MRE thus predates 3370-4040 cal yr BP by several hundred to a few thousand (?) years.

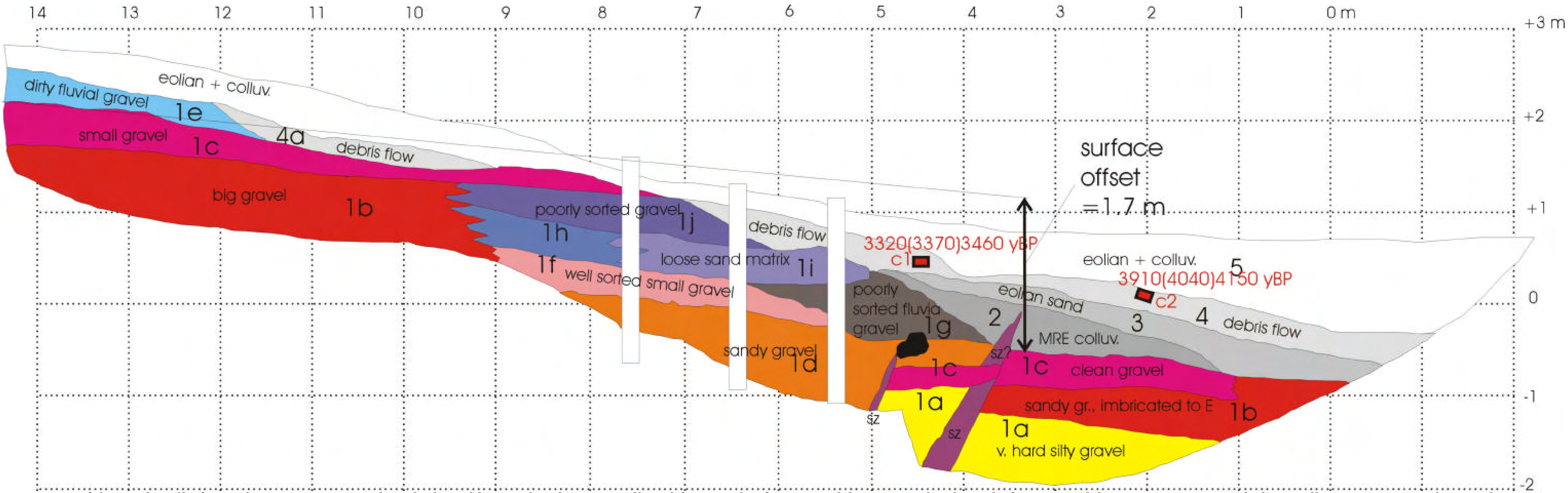

Fig. 9. Log of the south wall of Trench C. Map units are described in table 2. Colored units are alluvial fan gravels of post-Pinedale age near the channel of Morris Gulch. Gray units are post-faulting colluvium (unit 2), eolian sand (unit 3), a debris flow deposited over the scarp from Morris Gulch (unit 4), and recent eolian sand (unit 5). Sz= shear zone. Boxes labeled c1 and c2 are samples of detrital (?) charcoal. The dates indicate that the colluvium shed after the Most Recent Event (MRE colluvium) is older than 3370 to 4040 cal yr BP, which provides a loose minimum age constraint on the MRE.

4.3.3 2002 Trench D

Trench D was excavated on Scarp D about 100 m southwest of the stables, across a scarp about 3 m high. Due to the extremely loose and friable nature of the fan gravels, trench depth was limited to about 2 m, except at the extreme western end.

Stratigraphy: The footwall in the trench is composed entirely of poorly-sorted, poorly-stratified, very loose alluvial fan gravels (units 1-4) of probable Pinedale age (15,000-35,000 yr BP). On the hanging wall similar units underlie a sequence of colluvium and reworked eolian sand (Table 4, Fig. 10). The scarp-derived colluvium is composed of two units, the lower of which (10a) is displaced by faults and the upper of which truncates the faults. At the toe of Trench C the eolian-colluvial sequence lies atop a weak soil developed in the uppermost alluvial fan gravels.

Table 4. Trench D, description of map units.

Unit	Description	Age & Significance
20	COLLUVIUM; wash facies; mostly eolian sand matrix with rare small pebbles	OSL age of base= 5300±400 yr BP; youngest deposit in trench; contains incipient A horizon of modern soil
15	DEBRIS FLOW?; poorly sorted, matrix-supported gravel; deposited against toe of scarp by scarp-parallel ephemeral stream	post-dates the MRE
10b	COLLUVIUM; debris facies; scarp-derived colluvial wedge from the free face formed during the MRE	OSL age= 4800±400 yr BP; Post-dates the MRE
	Most Recent Fault Event (MRE)	
10a	COLLUVIUM; debris facies; scarp-derived colluvial wedge from the free face formed during the PE	Post-dates the PE
	Penultimate Fault Event (PE)	
9	FAN ALLUVIUM; debris flow deposit	Predates the PE
4b	FAN ALLUVIUM; fluvial sandy gravel with cobbles (4bA= A horizon developed on 4b)	Cal age= 2350(2470)2730 yr BP; predates the PE
4a	FAN ALLUVIUM; well sorted fluvial sandy gravel with cobbles	predates the PE
3c	FAN ALLUVIUM; poorly sorted fluvial sandy gravel with silt and cobbles	“
3b	FAN ALLUVIUM; poorly sorted fluvial silty sandy gravel with cobbles	“
3a	FAN ALLUVIUM; poorly sorted fluvial sandy cobbly gravel with silt	“
2b	FAN ALLUVIUM; poorly sorted fluvial sand and gravel with cobbles	“
2a	FAN ALLUVIUM; moderately sorted, imbricated gravel and cobbles	“

1	FAN ALLUVIUM; poorly sorted sandy cobbly gravel with silt	“

Structure: Trench D contains two shear zones beneath the approximate center of the fault scarp, each of which dips steeply west. Alluvial fan units are displaced down to the west across both shear zones, a total of about 3.3 m. The shear zones are each 20-30 cm wide and contain only a few strongly oriented pebbles that show shear. In the meter-wide zone between the shear zones, fan gravels (unit 4b) dip anomalously steeply to the west, as if the fault-bounded block rotated or toppled clockwise (as viewed on the log). The eastern of the two faults displaces the lower colluvial wedge (unit 10a) but not the upper one (unit 10b).

Geochronology: As in Trenches B and C, the friable fan gravels exposed in Trench D contained little organic matter for dating. The only unit that contained any hints of carbon was the very weak buried soil developed atop the fan gravels (unit 4bA). This unit had an inferred age of earliest Holocene/ latest Pleistocene, because it underlies the colluvium from the PE, and thus predates both the MRE and PE. However, the sample yielded an anomalously young age of 2350(2470)2730 cal yr BP, rather than the expected age of 10,000-15,000 years.

Samples were also collected from the base of the eolian-slopewash deposit (unit 20) for OSL dating. These two samples yielded OSL age estimates in reversed stratigraphic order, with the upper one from the base of unit 20 dating at 5300±400 yr BP and the lower one from unit 10b dating at 4800±400 yr BP.

Interpretation: The two colluvial wedges, the displacement of the older wedge (unit 10a) by faults, and the net vertical displacement of 3.3 m all suggest that Scarp D was formed by two surface-faulting events in post-Pinedale time. The timing of the MRE is constrained by the two OSL age estimates from the toe of the trench, at about 4800-5300 yr BP. The timing of the PE is unconstrained by numerical ages, but must have occurred between Pinedale time (ca. 15 ka) and 5 ka. The lack of a soil between the two colluvial units suggests that the PE may have only predated the MRE by a few thousand years.

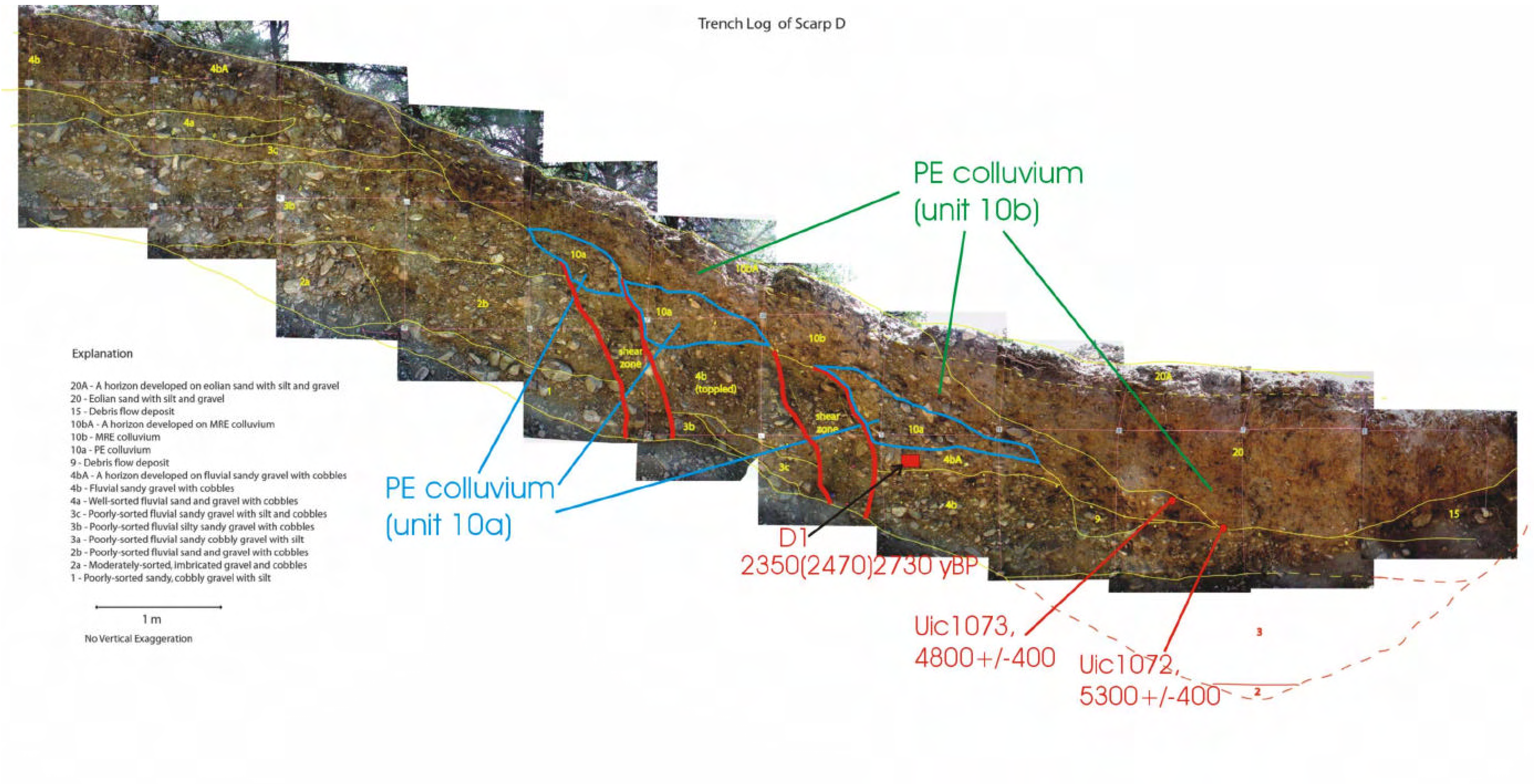

Fig. 10. Log of the south wall of Trench D. Log made by Greg McDonald and Mike Neville, June, 2002. OSL dates at toe of trench from Steve Forman, University of Illinois, Chicago. C-14 date is in calendar years BP with 1-sigma errors. We suspect that the C-14 sample was contaminated with young carbon, because it requires that both paleoearthquake events (MRE, PE) occurred subsequent to about 2470 years BP. Other trenches (B, C) do not support 2 paleoearthquakes in the late Holocene. We interpret the MRE to be older than 4800 to 5300 yr BP, and the PE to have occurred in the broad time span between 5300 and 15,000 years BP.

4.3.4 Interpretation of Paleoearthquake Characteristics

The Morris Gulch scarps (A, B, C, and D) represent two surface-faulting events that displace the surface of a Pinedale-age alluvial fan in a wide zone of parallel scarps. The cumulative vertical displacement across the scarps is on the order of 3 m + 1.7 m + 3.3 m, or 8 m., which is slightly greater than the 5.2-7.2 m of throw calculated for scarps south of Morris Gulch. There may be an unmeasured component of inter-scarp rotation of the alluvial fan surface at Morris Gulch, which would tend to exaggerate the height of the fault scarps in this complex zone, compared to the throw on the fault at depth.

Trenches B, C, and D indicate that the per-event displacement on each scarp during these events ranges from about 1.5 m (the 3 m net displacement on Scarp B, divided by 2), to 1.7 m (single-event displacement from Trench C), to 1.65 m (net displacement of 3.3 m in trench D, divided by 2). The average cumulative displacement per event on all three scarps would thus range from 3.15 m (without the single Scarp C event) to 4.85 m (with the Scarp C displacement), if we neglect any component of back-rotation between the scarps. These displacements of 3.15-4.85 m are roughly similar to those measured south of Morris Gulch, where the average per-event displacement was 3.15 m. Those per-event displacements imply earthquakes of moment magnitude M=6.96-7.10 if the displacements are assumed to be the maximum that occurred in the event, or M=7.10-7.22 if they are assumed to represent an average displacement (Wells and Coppersmith, 1994). The larger magnitude is probably a better estimate, considering the fact that each surface rupture was associated with meter-scale displacement on at least 3, if not 4, parallel fault strands.

The available geochronologic data indicate the MRE occurred about 4.8-5.3 ka, at least on Scarp D. Simultaneous rupture on Scarps B and C is supported by their overall stratigraphy. This age is similar to the age of surface rupture deduced by McCalpin (1982) at the Uracca Creek trench south of the Monument, which had a closely limiting maximum age of about 5.5 ka.

The age of the PE is not constrained by numerical ages, but must be post-Pinedale. The degree of soil development in Trench B suggests that the interevent time between the MRE and PE is on the same order as the time between the MRE and present, or roughly 5000 years. However, McCalpin (1982) estimated that the long-term (post-Bull Lake) recurrence on the Zapata section of the SCFZ was on the order of 10-20 ka

4.4 Visitor Center Scarp

The Visitor Center scarp is a north-trending, west-facing scarp about 4-5 m high that lies directly west of the Visitor Center. This scarp provides the elevation that gives the Visitor Center such a good vantage point for viewing the dunes. The scarp has been eroded away by Mosca Creek about 50 m north of the Visitor Center, and it does not reappear farther north. South of the Visitor Center the scarp extends for about 100 m and then is eroded away by an unnamed intermittent drainage. McCalpin (1981) mapped the small hill on which the Visitor Center sits as a horst of Bull Lake-age fan gravels, with Pinedale and Holocene alluvial fans to the north and south destroying the scarp. Thus, the scarp was interpreted as a subsidiary, down-to-the-west normal fault scarp that had been active after the Bull Lake glaciation but before the Pinedale glaciation. Despite the inferred antiquity of this scarp, we felt it must be trenched due to its close proximity to the Visitor Center.

4.4.1 2003 Visitor Center Trench

In September of 2003 we excavated a 26 m-long, up to 4 m-deep trench about 50 m north of the Visitor Center, as part of the SEPAS project. At the base of the scarp where we trenched is a 30 m-wide broad swale that parallels the scarp. This swale may be a graben related to the scarp. At present this swale is used as the septic leach field for the Visitor Center. The trench was prevented from crossing the toe of the scarp and the graben because we could not cut across the sewer line connecting the Visitor Center to the leach field.

Stratigraphy: The trench can be subdivided into two general parts. The eastern 20 m of the trench is shallow (1.5 m) and exposes poorly sorted gravels from the alluvial fan of Mosca Creek, overlain by 30-40 cm of recent eolian sand (Figs. 11, 12). Beginning at about the 8 m mark (Fig. 13) the eolian sand thickens rapidly (units 7-13) into a large wedge at the scarp toe, until it composes the entire 4 m depth of the trench at its western end. The lowest units in this colluvial package (units 7, 8) are gravelly and clasts display a consistent downslope fabric to the west. These units were clearly derived from erosion of a gravelly free face. Higher units (9, 10) have progressively less gravel and more eolian sand matrix. Unit 11 is mainly sand that has been moderately cemented by calcium carbonate and has weak ped structure at the top. The entire package of units 7-11 is a fining upward sequence capped by a paleosol developed in unit 11.

Unit 11 is unconformably overlain by units 12 and 13, and the contact is marked by a distinct stone line. With the exception of the stone line, units 12 and 13 are eolian sand. A cumulic soil A horizon is developed in unit 13.

The most intriguing deposit in the trench is the oldest fluvial deposit (unit 1) beneath the alluvial fan gravels, which is exposed in the deepest part of the trench between 6 m and 7 m. This alluvium is composed of planar-bedded sand with thin stringers of very fine gravel. It is totally unlike any of the alluvial fan deposits that lie above it, which are very poorly sorted and dominated by large angular clasts, as one would expect from streamflow and debris flow deposition emanating from Mosca Creek. Instead, these planar-bedded sediments are identical to sediments being deposited today by the braided portion of Medano Creek as it flows adjacent to the dune field. Accordingly, I interpret these deposits as alluvium of an ancestral course of Medano Creek.

Structure: The only "structure" exposed in this trench is the steep contact between units 1 and 2, and units 7 and 8, at about the 6 m mark in the trench. This contact sharply truncates unit 1 and juxtaposes it against colluvial unit 7. Initially I thought this contact was a fault, because it was so abrupt. However, after the photomosaic was made I dug a pit 60 cm deep into the trench floor along this supposed fault. This new exposure showed that the "fault" steadily decreased in dip downward, from about 65° in unit 2, to 50° in the upper part of unit 1, to 40° at the bottom of the trench. This listric shape is not characteristic of normal fault traces exposed in trenches. Rather, tectonic normal faults almost always dip at least 60° in trenches, as a result of Mohr-Coulomb law. Instead, the listric shape is much more suggestive of an erosional contact or landslide headscarp, rather than a tectonic normal fault.

The most plausible explanation for this listric contact is that it is a landslide failure surface caused by lateral stream erosion into units 1 through 4. The stream (perhaps Medano Creek) eroded eastward into the old (Bull Lake?) alluvial fan deposits from Mosca Creek, and exposed the very weak, friable sandy alluvium of ancestral Medano Creek in the streamcut. This weak material then slumped into the cut, undermining and carrying the overlying fan gravels with it. Subsequently, the slumped streamcut eroded back and colluvium (units 7 and 8) were deposited up against the scarp.

Table 5. Visitor Center trench, description of map units.

Unit	Description	Age & Significance
13	EOLIAN SAND; mostly retransported, loose eolian sand from the scarp face; contains rare pebbles	youngest deposit in trench; contains A horizon of modern soil
12	EOLIAN SAND; mostly retransported eolian sand from the scarp face; contains a coarse basal stone line, indicating that gravel was temporarily exposed on the scarp surface	Today no gravel is exposed at the scarp surface
11	EOLIAN SAND; mostly retransported eolian sand from the scarp face; contains a calcareous paleosol	The unit 11/12 contact is a major unconformity
10	COLLUVIUM; mostly retransported eolian sand from the scarp face; but contains abundant gravel clasts with downslope fabric	Post-dates formation of the scarp
9	COLLUVIUM; gravelly colluvium with a matrix of retransported, brown eolian sand	“
8	COLLUVIUM; gravelly colluvium with a matrix of gray sand derived from units 1-4	“
7	COLLUVIUM; gravelly colluvium with good downslope fabric	“
6a	EOLIAN SAND; mostly retransported eolian sand that fills in a “hole” beneath the scarp crest	Time of formation of the “hole” is unknown
5a	COLLUVIUM; gravelly colluvium with good downslope fabric, fills “hole” beneath scarp crest; derived from unit 4b	“
4b	FAN ALLUVIUM; well sorted, angular large pebbles and small cobbles, sparse sandy matrix	Predates formation of scarp
4a	FAN ALLUVIUM; mainly medium sand with rare stringers of small pebbles	“
4	FAN ALLUVIUM; small pebble gravel, moderately sorted and stratified	“
3a	SAND; fluvial sand with rare floating pebbles	“
3	FAN ALLUVIUM; poorly sorted sandy gravel	“
2	FAN ALLUVIUM; thick unit containing multiple beds of poorly- to well-sorted, pebble and cobble gravel	“
1	ALLUVIUM; very well sorted sand with thin stringers of small pebbles; well-developed planar beds; probably deposited by ancestral Medano Creek	“

A subsidiary “structure” exists beneath the crest of the scarp between the 19 and 21 m marks (Fig. 12). Here a large “hole” about 2 m wide and 1 m deep exists in the alluvial fan gravels, and has been filled with eolian sand. On both edges of the hole gravel clasts have a downslope fabric, indicating they raveled off the walls and slid into the hole. Initially this hole was thought to be a graben. Therefore we excavated the trench floor down beneath this hole. This new excavation failed to expose any displacement in strata beneath the hole; in other words, the hole is “rootless.” There were also no signs of liquefaction or soft-sediment deformation adjacent to or beneath the hole. In a forested area, I would interpret this “hole” as a crater formed by tree throw. However, there are presently no trees in the area large enough to have produced a crater of this size. Perhaps at one time trees on this scarp were larger. At any rate, the hole does not appear to be a tectonic feature.

Geochronology: We dated 3 luminescence samples (Table 1b) and 2 radiocarbon samples (table 1a) from this trench. A large burn layer was sampled from the top of unit 7 and has been submitted for radiocarbon dating. The burn layer looked anthropogenic, meaning it is less than about 12 ka. This maximum age means that the stream that eroded and formed the streamcut scarp here did so before about 12 ka but after about 150 ka (Bull Lake time). These age constraints do not tell us anything about tectonic activity here, except that there is no evidence of tectonic faulting in the past ca. 12 ka.

Interpretation: Although the original mapping of McCalpin (1982) depicted this west-facing scarp as a fault scarp, and there appears to be a graben at the base of the scarp, the “structure” exposed in the bottom of the trench does not resemble a tectonic fault. Instead, it is a listric structure that resembles a landslide failure plane. It is possible that there is a tectonic fault somewhere beneath this scarp, but if so, it lies beneath the floor of the present trench.

The Visitor Center scarp is herein interpreted as an erosional scarp carved by lateral migration of Medano Creek. The trench revealed a steeply-dipping “structure” at the bottom of the trench, but its listric shape suggests it is a slump-related failure rather than a tectonic fault. It is possible that tectonic faults underlie the scarp beneath the floor of the trench, but this investigation did not expose them. The fact that the scarp is truncated to the north and south by Pinedale and younger fan surfaces indicates that, even if there were tectonic faults beneath this scarp, they have not been active since Pinedale time (past 15-35 ka). Altogether, the inactivity of this scarp suggests that it poses minimal threat of surface rupture to the Visitor Center. However, it should be noted that the northern extension of Scarp B from Morris Gulch lies only a few hundred meters east of the Visitor Center, and that fault has experienced two post-Pinedale earthquakes of about **M**=7.2. Therefore, the Visitor Center is potentially subject to strong ground shaking during future earthquakes.

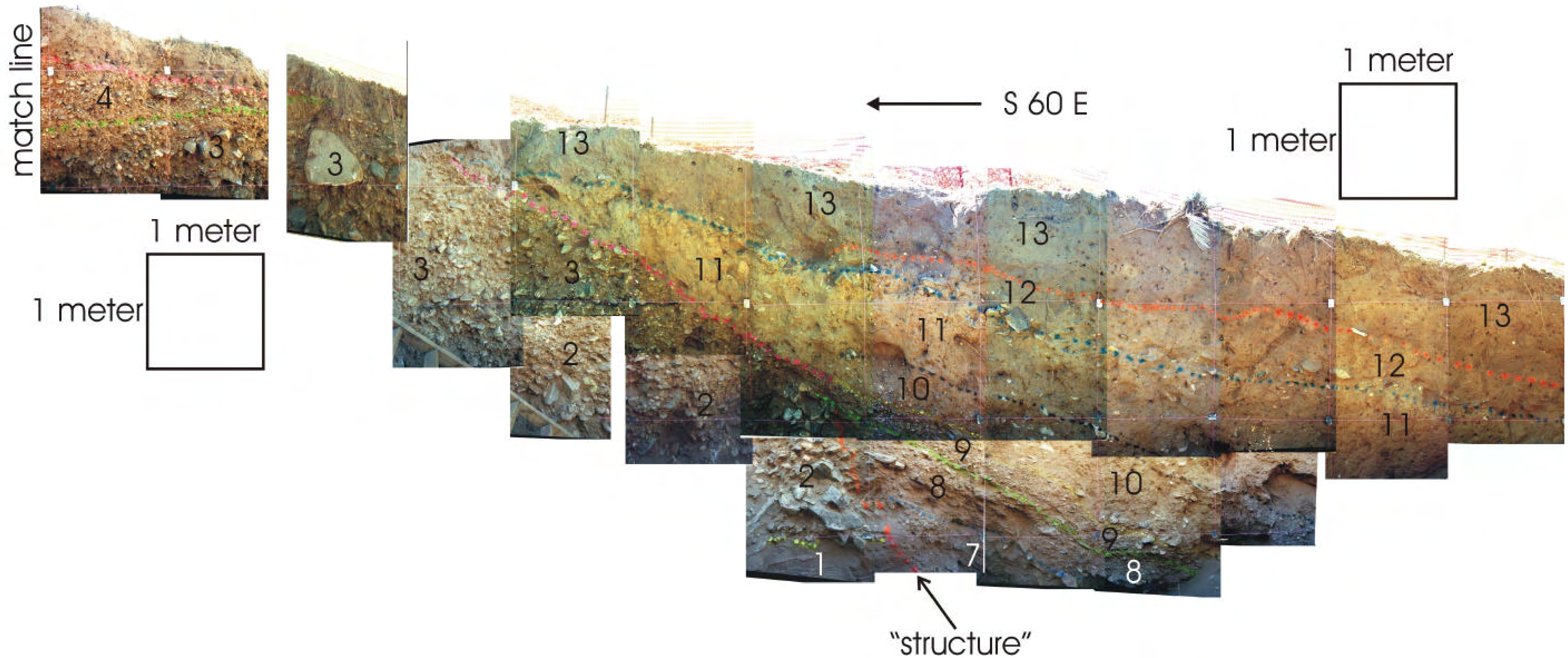

Fig. 11. Log of the western part of the south wall of the Visitor Center trench of September, 2003. Boundaries between map units (numbered; see Table 5) are shown by lines of spray-painted dots of various colors. Units 7-13 are colluvium, with an increasing proportion of eolian sand closer to the surface.

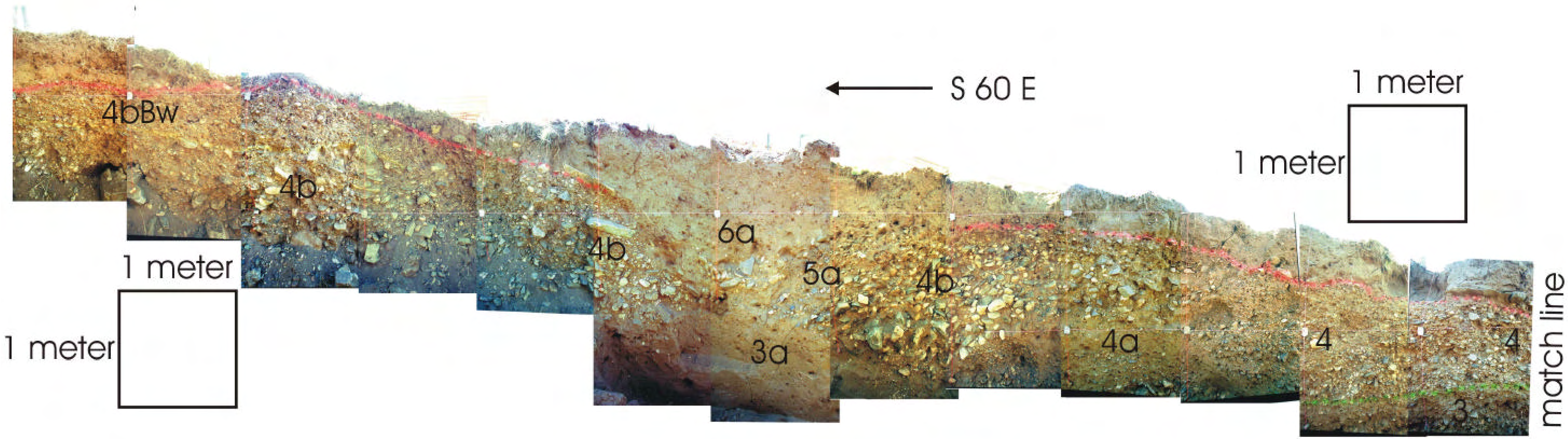

Fig. 12. Log of the eastern part of the south wall of the Visitor Center trench of September, 2003.

4.5 Scarps between the Morris Gulch fan and Pinon Flats Campground

North of Mosca Creek there is only one Quaternary fault scarp mapped (Plate 1). The scarp lies east of the road, is a bit less than half a mile long, has a sinuous shape, and hugs the downslope limit of pinyon-juniper trees on the alluvial fan. According to McCalpin (1981), the scarp is about 3.6 m high. Without additional data, we cannot determine if this 3.6 m of displacement represents only a single event (the MRE or PE), or both events with diminished displacement. This fault dies out northward in the vicinity of the Amphitheater and cannot be traced through the Pinon Flats Campground.

4.6 Scarps north of Pinon Flats Campground

McCalpin (1981) did not map any fault scarps in Quaternary deposits north of the Pinon Flats Campground. Instead, he mapped an inferred normal fault (dashed purple line on Plate 1) at the topographic break in slope at the range front, where longitudinal dunes are burying the toes of faceted spurs developed on bedrock. There may have been surface faulting in this area during the MRE and PE, but surface fault scarps would not have been preserved in loose eolian sand. Therefore, at this time we do not define a surface rupture hazard zone along this part of the SCFZ.

4.7 Possible Buried Faults Beneath Eolian Sand

Although there are no Quaternary fault scarps preserved in the eolian sand deposits west of the fault scarps described above, there are 2 lines of indirect evidence for buried faults. First, water wells Nos. 1, 3 and 4 are all located west of the known Quaternary fault scarps, yet most of their 250-375 foot depth is logged as being in "fractured basement rock" or "hard rock" (Chatman et al., 1997, p. 52-54). Similar shallow depths to bedrock (<200 feet) were interpreted beneath the piedmont (Amphitheater area) by the Colorado School of Mines Geophysics Field Camp in 1992. If Precambrian bedrock is that shallow beneath the alluvial fan piedmont, then additional down-to-the-west normal faults must exist to explain why the top of Precambrian rock is >10,000 feet below the surface at the western edge of the active dunefield (McCalpin, 1981).

Second, step-faults are common on rift margins, particularly where the margin changes strike to form an acute angle, as it does at GRSA (50° bend at Little Medano Creek). A similar fault geometry to that of the SCFZ at GRSA has been documented on the eastern side of the Gulf of Suez (Fig. 13). There, the rift margin forms both an obtuse angle and an acute angle of 40°. South of the acute bend, two ramp-edge splay faults diverge from the rift margin master fault and trend valleyward. Their strike is essentially parallel to the strike of the rift margin master fault north of the acute bend. Each fault takes a component of the vertical displacement away from the master fault, but that component decreases with distance away from the master fault, and eventually dies out.

There are also two ramp-edge splay faults at GRSA. The southern splay fault lies south of Evans Gulch and diverges about 55° counterclockwise from the master range-front fault strike, as measured around Denton Springs. This scarp is a single, simple fault scarp that loses height to the NW, and dies out as a mappable feature upslope of the NPS service road that extends south of the Maintenance Area and the stockpile area ("boneyard").

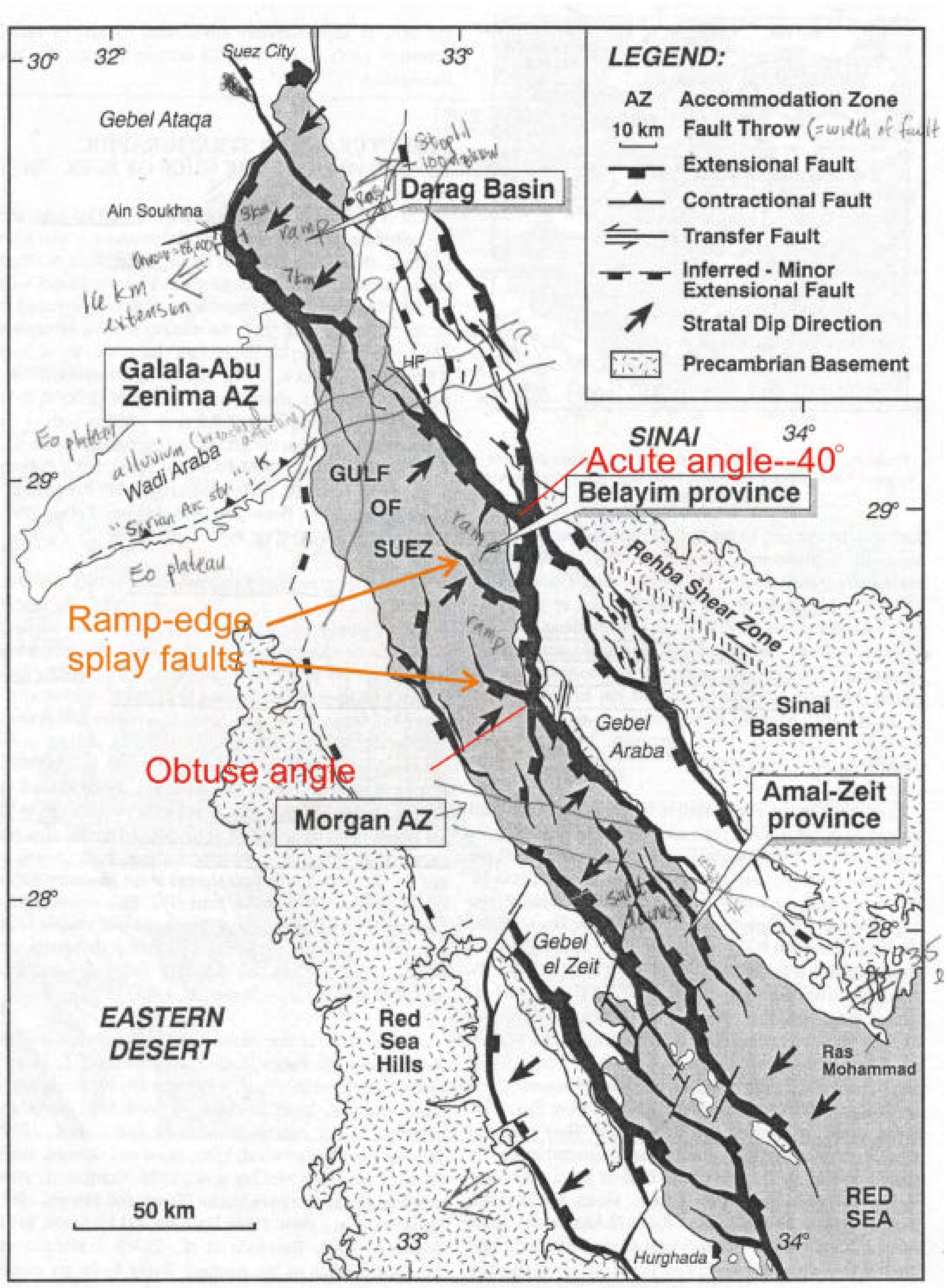

Fig. 13. Map of faults in the Gulf of Suez, Egypt; thickness of black line indicates amount of vertical displacement. On the eastern rift margin south of the acute bend, 2 ramp-edge splay faults diverge from the rift margin master fault, and extend into the basin with a trend similar to that of the master fault north of the acute bend. This same geometry exists at GRSA. From Bosworth and McClay, 2001.

The northern splay fault composes the entire NNE-trending zone of parallel fault scarps on the Morris Gulch alluvial fan. All of these scarps trend 35°-40° counterclockwise compared to the trend of the rift margin fault farther south. The smaller scarps (C, D) appear to die out to the NNE, as expected, but the largest scarp (B) appears to slowly wrap back around to parallel the range front south and north of Mosca Creek.

4.8 Summary of Surface Fault Rupture Hazards

Future surface rupture on the Morris Gulch scarps poses two potential hazards to Park infrastructure. The first hazard is tilting of the Water Tank, which lies in the graben west of Scarp B. When grabens settle during surface rupture events they often tilt, because of unequal displacements on the synthetic and antithetic scarps (McCalpin, 1996). Tilting of the Water Tank would probably not induce collapse by itself, although the tank might buckle or collapse due to strong ground motion during the earthquake. If re-leveling of the Water Tank was required for it to continue functioning, it is doubtful whether this could be done for less money than simply replacing the tank. And tank replacement would be necessary anyway if it was damaged due to shaking.

The second potential hazard is displacement of the water line leading to the Park headquarters area by displacement on the antithetic scarp. However, the antithetic scarp is mapped as dying out near the Water Tank, so displacements would probably be on the order of 50 cm or less on the antithetic scarp. It is unknown if the buried water line would be able to sustain a 50 cm vertical displacement without breaking. If it broke, the headquarters area would temporarily be without water until the pipe was repaired.

5. GROUND SHAKING HAZARDS

Ground shaking hazards at GRSA are associated with earthquakes spanning the range from relatively frequent small earthquakes to rare large earthquakes. The largest earthquake expected at GRSA would be a surface-rupturing earthquake on the mapped trace of the Sangre de Cristo fault zone (SCFZ), or the so-called "characteristic earthquake." There are 2 ways to estimate the magnitude of past surface-rupturing earthquakes (and thus, of future earthquakes) at GRSA. The first way is to merely cite the value for the characteristic earthquake on the SCFZ used in the National Seismic Hazard Map of the US (U.S. Geological Survey; http://eqhazmaps.usgs.gov/html/faults2002.html). This value, derived from all estimates made in published literature, is **M** 7.5 (**M**= moment magnitude).However, this magnitude is based on an assumed full-length rupture of the 90 km-long Crestone segment of the SCFZ; recent unpublished work by McCalpin indicates the Crestone segment is actually composed of two shorter, independent segments.

The second way is to calculate a magnitude based on the vertical fault displacement in past paleoearthquakes. The per-event displacements reconstructed at and south of Morris Gulch range from 3.15-4.85 m. Those per-event displacements imply earthquakes of moment magnitude M=6.96-7.10 if the displacements are assumed to be the maximum that occurred in the event, or M=7.10-7.22 if they are assumed to represent an average displacement (Wells and Coppersmith, 1994). The larger magnitude is probably a better estimate, considering the fact that each surface rupture was associated with meter-scale displacement on at least 3, if not 4, parallel fault strands.
Given that **M** 7.5 is probably an overestimate, and **M** 7.0 is a minimum value, we assume a value of **M** 7.2 for the characteristic earthquake at on the SCFZ at GRSA.

The expected ground shaking from a large-magnitude, "characteristic" earthquake on the Sangre de Cristo fault is computed using the standard **deterministic procedure**. This procedure computes ground motion at various sites away from the mapped fault trace, assuming that ground motion is greatest at the fault trace and decreases exponentially away from the fault trace. Therefore, the input parameters into a deterministic computation are: (1) earthquake magnitude (**M** 7.2 in this case), (2) distance to the fault trace, and (3) the appropriate empirical regression equation (called an "attenuation equation").

In order to calculate the peak horizontal ground acceleration (PGA) generated in GRSA by the characteristic earthquake, 3 additional parameters must be specified.

First, the appropriate attenuation relationship. For this we choose the recently-published equation of Pankow and Pechmann (2004). Their equation is an update and revision of the SEA96 (Spudich et al, 1996, 1997) and SEA99 (Spudich et al., 1999) attenuation equations made specifically for extensional tectonic regimes such as the Rio Grande rift.

Second, we measure the distance from various sites to the Sangre de Cristo fault trace as mapped, in the manner specified by SEA96 and SEA99, and by Pankow and Pechmann (2004, p. 342, 344).

Third, we determine if the site being analyzed is classified as rock or soil, according to the definitions of SEA96/99. The SEA96/99 equations define soil as having an average shear wave velocity in the upper 30 m (Vs30) of about 310 m/sec, and rock as having a Vs30 of about 620 m/sec. By this definition, all sites on Quaternary deposits west of the range front are soil sites.

The Pankow and Pechmann (2004) attenuation equation predicts essentially the same PGA for everywhere within the area between the Sangre de Cristo range front and Medano Creek, because this area lies entirely above a vertical projection of the plane of the fault (assumed dip of 60 degrees to a depth of 3 km). That PGA value, for an **M** 7.2 earthquake affecting soil sites, is 0.60 g.

Ground shaking of 0.60 g is extremely strong and could cause widespread damage to above-ground facilities at GRSA. Fortunately, the return period for this degree of ground shaking is very long, ca. 5,000-20,000 years.

Of more immediate concern is the possible ground shaking expected over shorter time spans, due to small- and moderate-magnitude earthquakes, not necessarily arising from the main trace of the Sangre de Cristo fault. To assess the cumulative ground shaking hazard at GRSA from all possible fault sources, over a time span of 50 years, we queried the US Geological Survey Seismic Hazard Map (website http://earthquake.usgs.gov/hazmaps/) for the expected ground motions in a 50 year period, that had only a 10% and a 2% chance of being exceeded. We specified 6 sites on an east-west transect between the Water Tank supplying Headquarters and the toe of the alluvial fan, at 200 meter intervals. These predicted ground motion values were calculated by USGS using a procedure known as **Probabilistic Seismic Hazard Analysis** (PSHA). The PSHA method inventories all the historic seismicity in an area, and assumes that the same rate of earthquake activity will continue into the future. In addition, if surface-rupturing earthquakes have occurred on faults in the area, but those faults have no associated historic seismicity (such as at GRSA), the PSHA method adds an additional rate of seismicity for that fault. To calculate the long-term seismic release rate of this currently-dormant fault, PSHA assumes that, given the magnitude and return period (recurrence interval) of the characteristic earthquake on the active fault, that smaller earthquakes are also generated with shorter return periods according to the Gutenberg-Richter frequency-magnitude relationship (b=1).

The expected ground motions at all 6 sites were identical, that is, there was no apparent attenuation away from the fault trace within a 1000 m distance from the Water Tank, which sits on the main fault trace. In a 50 year period, there is only a 10% chance that ground motions will occur larger than 0.06g and a 2% chance that ground motions will be stronger than 0.19g. These predicted values are relatively low, and result from the long return period between characteristic earthquakes on the SCFZ.

However, we should mention there is considerable controversy in the geologic community on whether the deterministic or probabilistic method is better. Detractors of the probabilistic method say that individual faults do not obey the Gutenberg-Richter relationship, but release almost all their energy in large-magnitude earthquakes, and have very few if any small- to moderate-magnitude earthquakes. If this is true, then the probabilistic method is assuming the future occurrence of many small- and moderate magnitude earthquakes on an active that will in fact not occur. In that case, the probabilistic estimate will overestimate the strength of ground shaking for time periods that are short (say 50-100 years) compared to the return period of the characteristic earthquake (say, 5000-10,000 years). This is because, over such short time periods, there is a very small probability that the characteristic earthquake will occur, so almost all the predicted seismicity in the model is from small to moderate events. For areas of small historical seismicity and one large active fault, such as GRSA, the small to moderate earthquake activity assumed in a PSHA to be released from the active fault comprises almost all the predicted seismic activity during 50-100 year periods. So, if this activity does not occur, there will be very little seismic activity from any other source, and the actual level of seismicity in the 50-100 year period will be considerably less than the PSHA method predicts.

In contrast, the PSHA method predicts essentially the same strength of ground shaking as does the deterministic method, if we calculate hazard for time periods equal to the recurrence interval for the characteristic earthquake. That is because, the strongest ground shaking in the area will be caused by the characteristic earthquake, and both methods use the same magnitude and distance for that event.

The threshold of nonstructural building damage is about 0.10g and serious damage can begin above 0.20g, and the threshold for liquefaction is about 0.10g. Therefore, the chance that serious damage will occur to infrastructure at GRSA appears to be less than 10% in the next 50 years, and probably in the range of 2-5%, if we assume that the PSHA predictions are valid. In contrast, there is a small but finite probability that, in any 50-year period, the characteristic earthquake will occur and generate ground motion of 0.60 g for periods of 30-45 seconds. A rough approximate of the probability of this happening in any 50 year period can be derived by dividing 50 years by the average return period of characteristic earthquakes (5000-20,000 years). This results in probabilities of 0.25% to 1%.

6. LIQUEFACTION HAZARDS

Liquefaction refers to the process in which saturated sandy sediments temporarily experience a total loss of bearing strength and act more like liquids than like solids (i.e., become "quicksand"). Liquefaction occurs in response to any sudden extreme increase in fluid pore pressure between the sand grains. Such an increase can be caused on a small scale by repeated tapping of one's foot on the surface of some saturated sand (try this in the floodplain of Medano Creek), or on a much larger scale by repeated ground shaking during an earthquake.

If the fluid pressure within any saturated sandy stratum rises to equal or exceed the weight of the overlying sediment, then that overlying weight is no longer being borne by sand grain-to-sand grain contacts in the affected stratum, but rather by the fluid itself. Because fluids have no shear strength, the entire sand-plus-water mixture in the affected stratum now has no shear strength, and begins to act as a liquid. This slurry of sand and water may find its way to cracks in the ground surface created during earthquake shaking, resulting in slurry geysers and sand volcanoes

Earthquake-induced liquefaction typically occurs in saturated, well-sorted, sandy to gravelly unconsolidated sediments that lack significant clay and silt. [Clay and silt possess interparticle cohesion that is not diminished by rises in pore fluid pressure]. Liquefaction normally occurs only in saturated, uncemented, normally consolidated, sandy strata less than 30 feet below the ground surface; at greater depths, the overburden pressure is too high to be totally negated by pore fluid pressure.

Assessing liquefaction hazards is a 2-step process. First, the <u>liquefaction susceptibility</u> of the terrain must be determined. This determination requires delineating all areas where these conditions exist: (1) sediments are saturated at depths of less than 30 feet below the surface, (2) sediments are dominantly sand without significant silt, clay, or large gravel, and (3) sediments are young (Holocene), so are likely to be normally consolidated and uncemented.

The next step is to determine the <u>liquefaction opportunity</u>. This determination requires delineating all areas that might be subjected to strong earthquake ground shaking in the future, which would be greater than the threshold value needed to cause liquefaction. For GRSA, the eastern side of the Park is so close to the Sangre de Cristo fault that basically all the developed areas are potentially subject to ground shaking strong enough to cause liquefaction (0.60 g in the characteristic earthquake).

Finally, liquefaction hazard is determined by multiplying liquefaction susceptibility times liquefaction opportunity, as shown in Table 6.

Table 6. Classes of liquefaction hazard at GRSA west of the mountain front (in bold), as determined by susceptibility and opportunity.

	Liquefaction Susceptibility	
Liquefaction Opportunity	Low (alluvial fans)	High (floodplain of Medano Creek)
Low to Medium	very low	medium
High (all of developed area)	**low**	**high**

Based upon the results of drilling, there appear to be five important hydrostratigraphic units underlying the Medano Creek channel within the upper 100 feet (Fig. 14). The uppermost unit **(upper perched aquifer, 0-17 feet**) is composed of 6-12 feet of loose medium sand underlain by 5-8 feet of increasingly gravelly sand. The depth to groundwater in this aquifer ranges from about 14 feet in the winter and early spring, to at the ground surface when Medano Creek is flowing in the vicinity. The second unit (**confining bed**) is a hard silty sand with some clay and gravel from 17 to 19 feet, that acts as a confining bed beneath the upper perched aquifer. The third unit (**intermediate unconfined aquifer**) is a medium to fine to silty sand with a basal gravel unit from 19 to 90 feet. However, during the period 1991-1993 this interval was unsaturated and comprised a 70 foot-thick vadose zone beneath the upper perched aquifer. The fourth unit (**lower confining bed**) is a hard clayey sand from 90 to 94 feet that acts as an aquatard. The fifth unit (**confined aquifer**) is a medium sand from 94 to at least 100 feet, that constitutes a confined aquifer beneath the lower confining bed.

Given this hydrostratigraphy, it is apparent that the upper perched aquifer has high liquefaction susceptibility, because it is comprised of loose, well-sorted medium sand that is saturated to within 1 to 14 feet (depending on the season) of the ground surface.

The exact horizontal extent of the upper perched aquifer beyond the active floodplain of Medano Creek is unknown, because all the monitoring wells to date have been drilled within the active floodplain. To be conservative, we have extended the zone of high liquefaction susceptibility slightly beyond the geomorphic floodplain, particularly at the confluence with Mosca Creek, where there may be a high groundwater table extending up that creek.

In summary, the liquefaction opportunity is high throughout the developed area, which means that liquefaction hazard is either low (on the alluvial fans) or high (in the floodplain of Medano Creek).

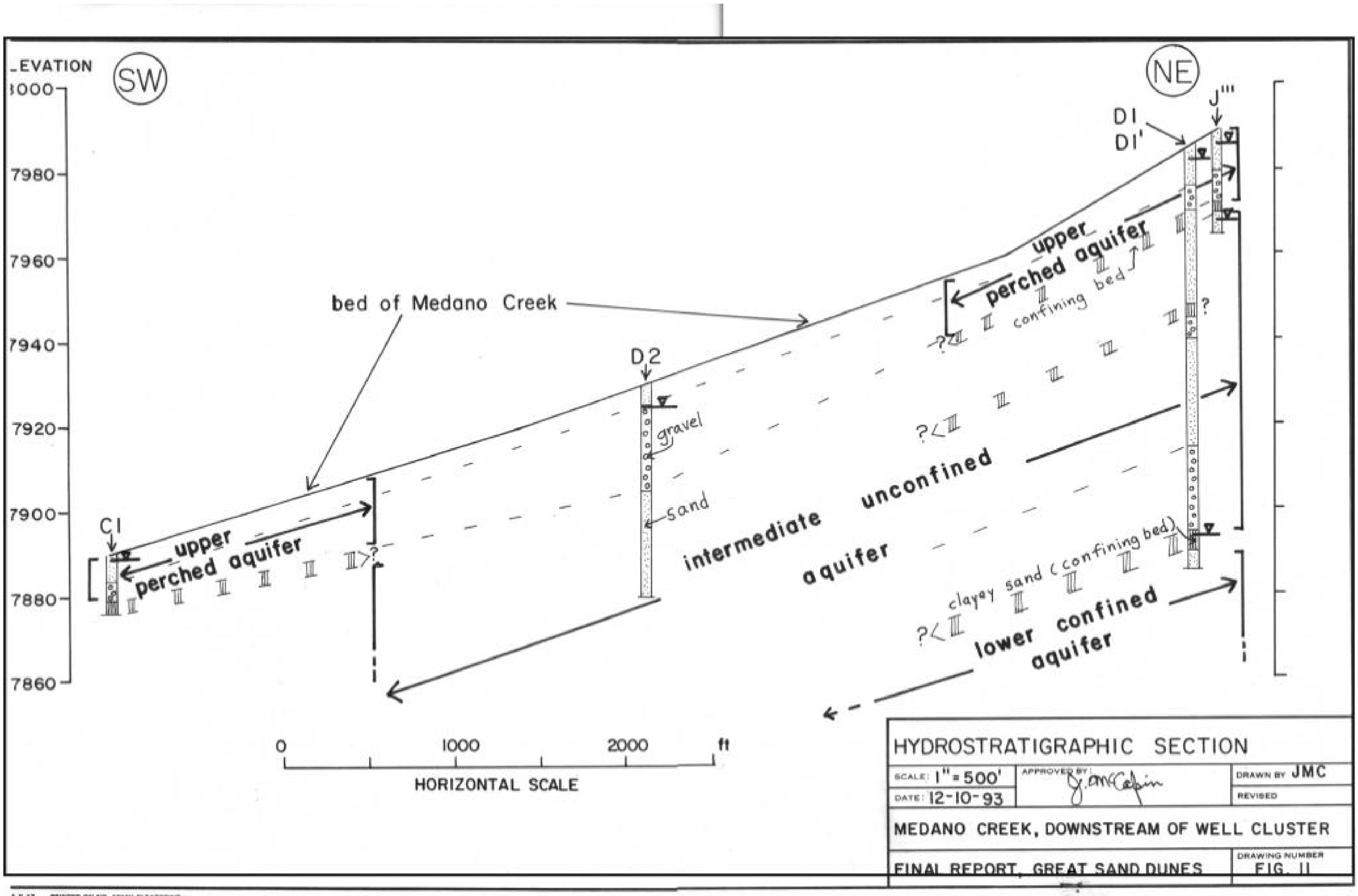

Fig. 14. Hydrostratigraphic cross-section down Medano Creek, between the monitoring well cluster opposite the Dunes Parking Lot, and well C1 6700 feet downstream. From McCalpin, 1993.

7. EARTHQUAKE-INDUCED LANDSLIDE HAZARDS

The strong ground shaking that accompanies large earthquakes, such as the characteristic earthquake on the SCFZ, can trigger landsliding of slopes that are already near their threshold of stability. Certainly, ground accelerations of much less than the 0.60 g predicted at GRSA have caused landslides in earthquakes elsewhere in the world. One common setting for such landslides is a failure of part of the uplifted rift margin, which detaches and slides into the adjacent basin. Such failures involve failure of the fractured bedrock that underlies the range-front faceted spurs. Normally, fractured bedrock on a rift margin will be strong enough, and well-drained enough, to resist failure under most hydrologic-climatic conditions. Strong earthquake shaking, especially during a wet period, can be enough to initiate slope movement, although the movement often ceases when the shaking ceases. Thus, if shaking does not exceed a duration of more than a few tens of seconds, the sliding bedrock mass may not gain enough momentum to continue sliding after the shaking stops. In that case, the landslide mass will mainly remain on the uplifted (mountain) side of the rift margin, and will not slide wholesale across the rift margin fault and onto the alluvial piedmont.

At GRSA, there is one large area between Evans Gulch and Morris Gulch where the geomorphology of a ridge in the Sangre de Cristo Mountains suggests incipient landsliding. We have no direct proof that this incipient sliding was caused by earthquakes, and testing such a hypothesis is difficult (see Jibson, 1996). However, the fact that the failed mass is composed of Precambrian granitic gneiss, which normally is too strong to fail, suggests that an earthquake trigger may have been required.

7.1 The Landslide at Morris Gulch

South of Morris Gulch faults scarps end at the flank of a west-protruding bedrock ridge, but then reappear at the range front south of the ridge (red and purple lines in Fig. 15). The surface morphology of this ridge does not resemble that of any other ridge along the range front of the Sangre de Cristo Mountains. Rather than being a narrow-crested, steep erosional ridge as is typical of faceted-spur range fronts, this ridge has a broad, low-gradient crest composed of alternating benches and scarps (yellow lines in Fig. 15). In addition there are several closed or nearly closed depressions on the ridge crest. Overall the ridge looks like a giant landslide, yet the entire ridge is mapped by Bruce and Johnson (1991) as Precambrian gneiss.

Field reconnaissance reveals that outcrops of Precambrian gneiss do exist throughout the ridge crest, but the foliation directions appear rather random. More importantly, gullies cut into the flanks of the ridge expose outcrops of red sandstones and siltstones of the late Paleozoic Minturn Formation about 10-15 m below the ridge crest. As shown in Fig. 3, this part of the Sangre de Cristo Range is composed of thrust sheets of Precambrian gneiss thrust eastward over Paleozoic sedimentary rocks. North of Morris Gulch the Precambrian thrust sheet is so thin that windows have been eroded through it, exposing the Minturn Formation beneath the thrust. The largest window extends for over a mile in width from north of Morris Gulch to north of Mosca Creek. In that area, the strike and dip of the thrust can be measured as the thrust crosses the 8800, 9000, 9200, and 9400 foot contours. In that area the thrust strikes N05°-10°E and dips 19° W.

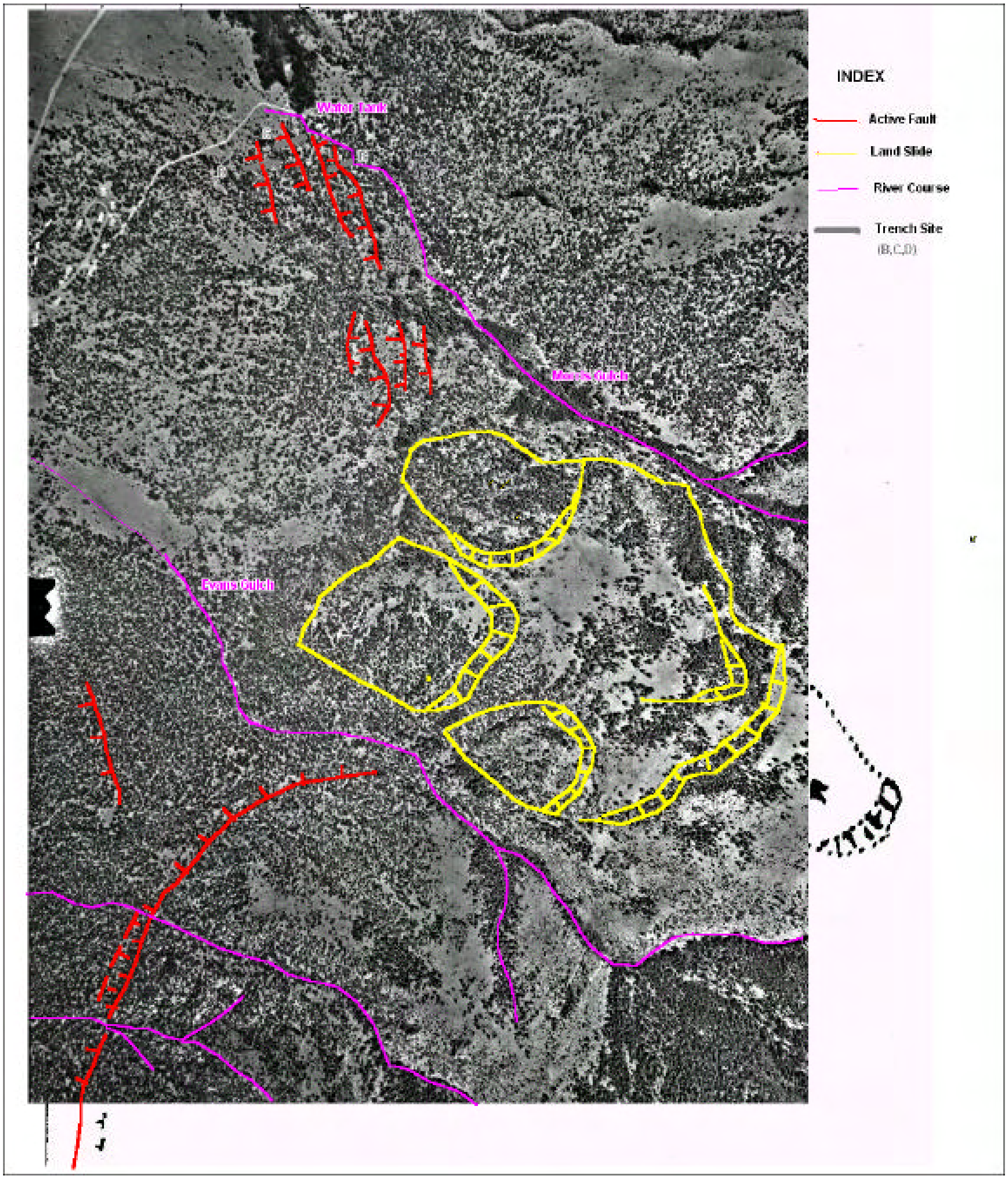

Fig. 15. Photogeologic map of the landslide ridge south of Morris Gulch. Landslide boundaries are shown by yellow lines, landslide headscarps by pairs of yellow lines with hachures. Streams are shown in purple, fault scarps in Quaternary deposits are shown in red.

It appears that the landslide ridge south of Morris Gulch is underlain by a thin sheet of highly fractured Precambrian gneiss no more than 10-15 m thick, lying on a ca. 19° west-dipping Laramide thrust fault (Fig. 16). The moderately steep dip of this thrust fault toward the valley and its weak material properties have combined to induce incipient westward landsliding and dismemberment of the Precambrian slab.

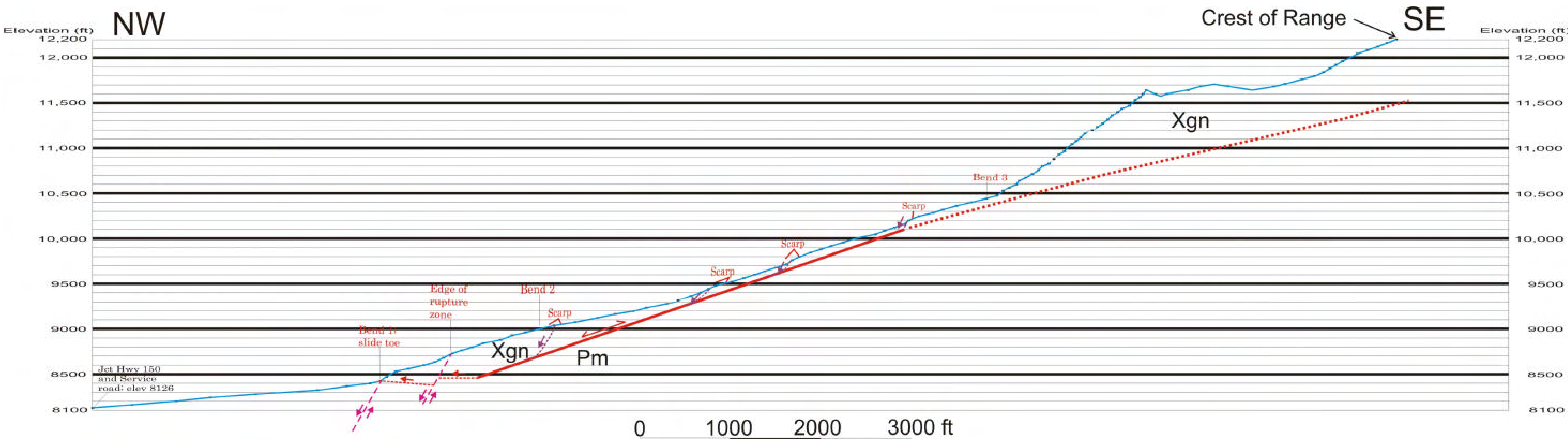

Fig. 16. Cross-section down the axis of the landslide south of Morris Gulch. Line of section and stationing are shown on Plate 1. Blue line shows modern ground surface. Xgn, Precambrian granitic gneiss. Pm, Minturn Formation, Permian. Solid red line shows the inferred Laramide thrust fault dipping 19 degrees to the west, overlain by a slab of highly fractured Precambrian gneiss. The slab is about 50 ft thick in the center of the landslide, but must thicken downslope if the reactivated thrust (double-headed red arrow) maintains the same dip. Purple lines show secondary rotational failure planes inferred to underlie the several arcuate internal scarps within the failed slab. The toe of the landslide is inferred to have overridden part of the Sangre de Cristo fault zone, so the toe is shown as interacting with inferred west-dipping normal faults (pink dashed lines and arrows).

Westward slippage was probably also induced by the strong earthquake shaking that accompanies M>7 earthquakes on the Sangre de Cristo fault here roughly every 10,000 years. As the range has been uplifted above the valley floor, this west-dipping Laramide thrust fault has been progressively "daylighted" on the range front slopes. The daylighting removes the lateral support from the downslope end of the west-tilted slab, allowing it to begin to stretch and extend valleyward.

8. CONCLUSIONS AND RECOMMENDATIONS

In this study we mapped fault scarps and excavated four trenches in the Morris Gulch and Visitor Center areas. The Morris Gulch scarps exposed evidence for two post-Pinedale (post-15 ka to 35 ka) surface rupturing earthquakes, each with vertical displacements of about 1.7-2.3 m. Those displacements, if added together for the MRE or PE, imply the earthquakes had a moment magnitude of about 7.2. The most recent event occurred about 5300-5500 years ago, while the prior event occurred sometime in the early Holocene (10-15 ka?). In contrast, the Visitor Center trench failed to expose a tectonic fault, but instead exposed an old landslide (?) failure probably related to stream erosion. Therefore, the Visitor Center scarp is probably a fluvial scarp eroded by ancestral Medano Creek, and poses no direct threat to the Visitor Center.

The main structure at risk from future surface rupture of the Morris Gulch scarps is the Water Tank that supplies Park headquarters. However, structural strengthening of this tank to withstand tilting and strong ground shaking may be uneconomic, compared to the cost of simply replacing the tank after an earthquake. If disruption of the headquarters' water supply following an earthquake is unacceptable, then it should be determined if a 50 cm or smaller displacement on the antithetic fault will likely cause failure of the pipe. This estimate could be made by a literature search on lifeline performance during earthquakes.

Although the risk posed by surface rupture at the Water Tank and Visitor Center is low, all structures in the Park would be subjected to strong ground shaking in the event of a M=7.2 earthquake. This ground shaking could reach horizontal and vertical accelerations of up to 0.60 g lasting for 30-40 seconds. However, with a return time of 5,000 to 20,000 years between such earthquakes, the annual probability of having an occurrence is on the order of 1/5000 to 1/20,000. These rough values would form the basis for any cost-benefit analysis of retrofitting existing buildings, or adding structural strengthening to new buildings.

High liquefaction hazard appears to be restricted to the saturated floodplain of Medano Creek and the fringes of the eolian sand deposits adjacent to the floodplain. The only existing structures in this area are the Dunes Parking Lot, the restroom complex east of the Dunes Parking Lot, and the armadas south of the Dunes Parking Lot. The main hazard posed by liquefaction to the restroom building, the only building that is occupied by the public, is the loss of foundation bearing strength and differential settling. Because this building is a relatively heavy structure, excess differential settling could cause water and sewer lines to break where attached to the building. For the armadas and parking lot, liquefaction could crack the pavement and sand blows and sand volcanoes could occur. This would constitute a maintenance problem, but should not endanger human life.

The only recognized hazard due to earthquake-induced landsliding lies between Morris Gulch and Evans Gulch, where a large incipient landslide exists on the range front. Although this landslide may have slid a few tens of meters valleyward in the past, it has not previously suffered total detachment and catastrophic sliding onto the valley floor. Whether the landslide has the potential to do that is unknown, and would require a detailed geotechnical study which is beyond the scope of this report. At present there are no infrastructure elements near the toe of this landslide complex, and the nearest buildings are the Maintenance complex about 1 mile downslope from the toe. The farthest runout distance for a range-front landslide that the author is aware of, in a rift-margin setting, was about 1.0 miles in Star Valley, Wyoming (McCalpin et al., 1990). However, that landslide was a fluidized rockfall avalanche that fell from a steep faceted spur hundreds of meters high. The slope of the range-front landslide at GRSA is much too gentle to generate the high sliding velocity needed for acoustic fluidization. Therefore, although this incipient landslide does pose a hazard, there is not any infrastructure at risk from this hazard at present.

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Appendix 1; Deterministic Calculation of Ground Motion at GRSA from a Characteristic Earthquake (M7.2) on the Zapata Segment of the Sangre de Cristo fault

1. SEA99 EQUATION (Spudich et al., 1999)

$Log_{10}(PGA) = b1 + b2(\mathbf{M}-6) + b3(\mathbf{M}-6)^2 + b5(\log_{10}D) + b6\ \tilde{A}$

Where:
PGA= peak horizontal ground acceleration (g)
b1, b2, b3, b5, b6, h = regression coefficients
M= earthquake moment magnitude
D= distance in km, from the equation

$D = (r_{jb}^2 + h^2)^{1/2}$

Where:

r_{jb}= Joyner-Boore distance; closest horizontal distance to the vertical projection of the fault rupture on the Earth's surface

$\tilde{A}$= 0 for rock sites, 1 for soil sites (where soil site has >5 m of "soil" over bedrock)

2. Pankow and Pechmann EQUATION (Pankow and Pechmann, 2004; revised regression coefficients)

$Log_{10}(PGA) = 0.237 + 0.229(\mathbf{M}-6) + 0(\mathbf{M}-6)^2 + -1.052(\log_{10}D) + 0.174\ \tilde{A}$

3. Pankow and Pechmann EQUATION applied to soil sites west of the Sangre de Cristo fault at GRSA:

$Log_{10}(PGA) = 0.237 + 0.229(7.2-6) + 0(7.2-6)^2 + -1.052(\log_{10} 2.7\text{ km}) + 0.174\ (1)$

Where: $D = (r_{jb}^2 + h^2)^{1/2}$
$= (0^2 + 7.27\text{ km}^2)^{1/2} = 7.27\text{ km}$

Simplifies to:

$Log_{10}(PGA) = 0.237 + 0.229(7.2-6) + 0(7.2-6)^2 + -1.052(\log_{10} 7.27\text{ km}) + 0.174\ (1)$
$= 0.237 + 0.275 + 0 - 0.906 + 0.174$
$= -0.22$

PGA= 0.60 g