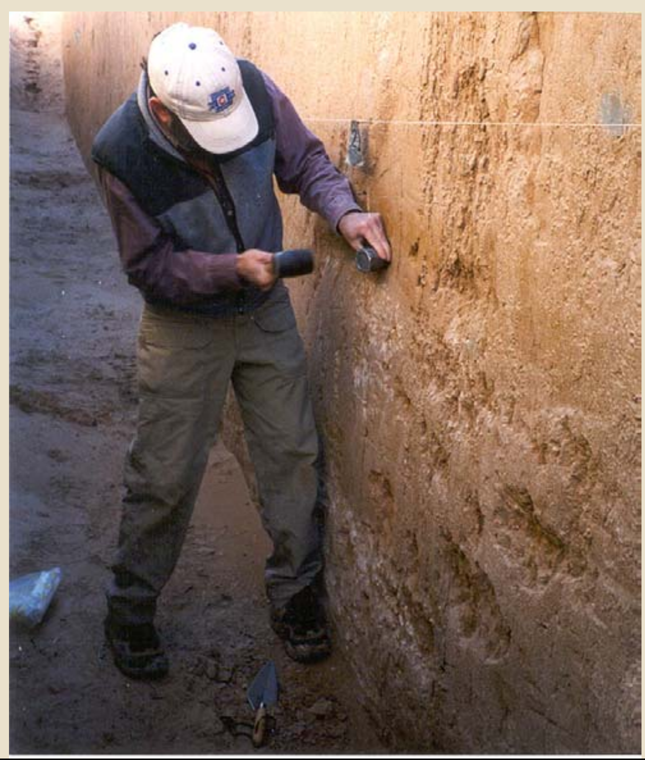
Final Report

PALEOSEISMIC INVESTIGATION OF THE CENTRAL HUBBELL SPRING FAULT, CENTRAL NEW MEXICO



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Abstract

The Hubbell Spring fault (HSF) is near the eastern margin of the Albuquerque-Belen basin in the central Rio Grande rift, and is one of the most active faults in the region. Recent mapping and geophysical studies indicate that the fault geometry is more complex and longer than previously thought, with two dominant west-dipping splays (western and central) extending for over 40 km south of Albuquerque. An enigmatic eastern splay appears buried along its southern 2/3 and may be older than late Quaternary, with possibly a much longer history of deformation than the rest of the HSF. We conducted a paleoseismic investigation of the Carrizo Spring trench site on the central HSF that included mapping, trenching drilling and luminescence analyses. We found structural, stratigraphic, and pedologic evidence for the occurrence of at least 4, and probably 5, large earthquakes that occurred since deposition of piedmont deposits on the Llano de Manzano surface about 83.6 ± 6.0 ka. All of these events included warping across a broad deformation zone, whereas the 3 largest events also included discrete slip across five fault zones. Behavior appears non-characteristic, with preferred vertical displacements per event ranging from 0.4 to 3.7 m. Fault-related deposition was dominated by eolian rather than colluvial sedimentation, similar to previous trench studies of other faults in the region. The total down-to-the-west throw of piedmont deposits is 7.3 ± 0.5 m. Luminescence ages indicate that the timing of the 4 largest surface-deforming events on the central HSF overlaps with the timing of the four youngest faulting events on the western HSF, suggesting coseismic rupture of the central and western HSF. Displacement data and correlation between sites of buried soils on event horizons also supports coseismic rupture. The smallest warping event on the central HSF does not appear to correlate to any events on the western HSF, indicating that independent rupture of the central HSF also does occasionally occur. However, we estimate that over 96% of the late Quaternary strain on the HSF occurred as coseismic rupture of the western and central splays. The average recurrence interval for coseismic rupture over the past 3 complete seismic cycles is 19 (+5, -4) ky, consistent with recurrence intervals estimated for individual cycles, which are 17 ky, 27 ky, and 14 ky. Assuming the eastern splay is no longer active, we estimate a cumulative average vertical slip rate for the past 4 complete seismic cycles on the HSF of about 0.2 mm/yr, making it one of the most active faults in the region. In comparison, slip rates for individual complete seismic cycles vary by an order of magnitude, ranging from 0.044 mm/yr to 0.46 mm/yr. This is due to noncharacteristic behavior, a finding that may have significant implications for seismic hazards elsewhere in the rift. Estimated paleomagnitudes range from M_W 7.0 to 7.5 for coseismic rupture events versus from M_W 6.6 to 7.0 for rupture of the central HSF alone. Additional investigation is needed to determine how activity on the HSF may relate to nearby faults along the eastern rift margin, including the Palace-Pipeline to the west, the Manzano fault to the east, and unnamed faults on the Llano de Manzano to the south.

Cover Photographs: Top – Looking east at the Carrizo Spring trench across the Central Hubbell Spring fault with Bosque Peak of the Manzano Mountains in the background; Middle – Bruce Allen and David Love operating the New Mexico Bureau of Geology and Mineral Resources drill rig; Lower – Steven Forman collecting luminescence samples from Unit 4 in the Carrizo Spring trench.

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The Hubbell Spring fault (HSF) is one of the most active faults in the Albuquerque-Belen basin in central New Mexico (Personius *et al*., 1999; Figure 1). It is the most significant seismic source to the southern Albuquerque area, particularly to the rapidly growing communities of Los Lunas and Belen (Wong *et al.*, 2000). Recent mapping, geophysical and paleoseismic studies have shed some new light on this complex fault zone, but these studies have also raised significant questions about its late Quaternary behavior and earthquake potential, which are discussed further below. This study answered many aspects of these questions through a paleoseismic trench investigation of the previously untrenched central trace of the HSF.

1.1 GEOLOGIC SETTING

The HSF is a north-striking, west-dipping, intrabasin normal fault zone that lies near the eastern margin of the Albuquerque basin in the central Rio Grande rift of New Mexico (Figure 1). The rift is a physiographic and structural depression that is now recognized as a continental rift zone (e.g., Keller and Cather, 1994). It consists of a series of north trending, *en echelon* structural basins that are flanked by mountain ranges or uplifted plateaus, extending for about 1,000 km from central Colorado, through central New Mexico, and into west Texas and Mexico (Chapin, 1971). The namesake river, the Rio Grande, follows this seismically, tectonically and volcanically active depression, which is actually part of the Basin and Range Province (Hawley, 1986). The Rio Grande rift is characterized by: (1) late Cenozoic extension accommodated by faulting and volcanism that is as young as Holocene; (2) shallow (≤ 13 km) diffuse background seismicity that generally is not associated with specific structures except for some zones that may be correlated with magmatic activity; (3) focal mechanisms that indicate a mix of normal and strike-slip faulting, and a horizontal least principal stress direction of WNW-ESE; (4) high heat flow; (5) deep asymmetric half grabens, and grabens that tend to show opposing symmetries (tilting to the west versus tilting to the east); and (6) large negative gravity anomalies (Chapin and Cather, 1994; Keller and Cather, 1994; Morgan *et al.*, 1986; Sanford *et al.*, 1991).

The Albuquerque basin is nearly 120 km long, 40 to 60 km wide, and is the largest and deepest rift basin in New Mexico (Hawley *et al.*, 1995). Clastic deposits (alluvial, colluvial, eolian, lacustrine and volcaniclastic sediments) and volcanic rocks comprise the Santa Fe Group, the Plio-Pleistocene syn-rift sedimentary fill of Rio Grande rift basins (e.g. Hawley *et al.*, 1969). These basin fill deposits are as thick as 4,570 m (≈15,000 ft) in the Albuquerque basin (Hawley *et al.*, 1995). Although extension in the region initiated 27 to 32 Ma, rift basins were not integrated by the through-going ancestral drainage of the Rio Grande until much later. The axial fluvial and tributary deposits of the ancestral Rio Grande in the Albuquerque basin are part of the Sierra Ladrones Formation of Machette (1978), and were deposited from 7 Ma to sometime after 1.2 Ma (Connell *et al.*, 2001). The top of these deposits formed a Pleistocene basin floor that is now 100 to 200 m above the present Rio Grande, indicating substantial subsequent incision that left extensive alluvial surfaces abandoned (Machette and McGimsey, 1983; Machette, 1985). Based on recent mapping and stratigraphic studies, Connell *et al.* (2001) estimate that the Rio Grande initiated this incision sometime between 0.7 and 1.2 Ma.

The Albuquerque basin is flanked on the east by the east-tilted, fault-block uplift of the Sandia, Manzanita, Manzano and Los Pinos Mountains (Kelley, 1977). These ranges expose Precambrian plutonic and metamorphic rocks that are unconformably overlain by Paleozoic limestones, sandstones and shales. The resulting structural relief is as much as 8,500 m (Woodward 1982). The basin is flanked to the west by the lower-relief uplifts of the Colorado

Plateau. Based on seismic lines, drill holes and gravity data, Lozinsky (1994) and Russell and Snelson (1994) separated the Albuquerque basin into two subbasins: one north of Tijeras Canyon with at least 17% extension and basin fill tilted to the east, and a subbasin to the south of Los Lunas (including most of the HSF) that has 30% extension and basin fill sediments dominantly tilted to the west. They postulated that the Tijeras accommodation zone, a buried west-southwest extension of the Tijeras fault, separated these subbasins. However, subsequent investigators (Maldonado *et al.*, 1999) following Hawley *et al.* (1995) have suggested a buried northwest-trending structure, the Mountain View fault zone, likely separates the subbasins (Figure 2). Regardless, the HSF appears to transect both subbasins and clearly is an intrabasin fault, lying 3 to 10 km west of the basin-bounding Manzano fault, cutting the Tijeras-Cañoncito fault zone near its northern end, lying along-strike of the less-active Sandia fault to the north, and subparalleling the newly discovered Palace-Pipeline fault that lies 2 to 10 km to the west (Figure 2).

Even though the HSF is an intrabasin structure, its prominent geomorphic expression, structural relief, and relation to adjacent faults suggest it forms the active rift margin (Machette and McGimsey, 1983). Fault scarps of the HSF extend for over 43 km along the Llano de Manzano, an early to late Pleistocene alluvial surface that extends for over 90 km south of Albuquerque between the Rio Grande to the west and the Manzano Mountains to the east. This gently west-sloping surface was considered by Machette (1985) to be graded to an alluvial terrace that lies 92 to 113 m above the modern Rio Grande. Based on soil studies, and geomorphic and stratigraphic relations, he estimated an age on the order of about 300 ka. Based on more recent detailed mapping, and stratigraphic studies, Maldonado *et al.* (1999) broke out two additional older surfaces, the Sunport and Cañada Colorado, north of Hells Canyon Wash. They estimate a Pliocene age for the Cañada Colorado and early Pleistocene ages for the Sunport and Llano de Manzano surfaces. As an extension of these studies, Connell *et al.* (2001) consider the Llano de Manzano to be a complex surface of a basin fill succession that includes middle Pleistocene piedmont deposits shed off the Manzano Mountains, overlying and truncating axial Rio Grande deposits. They provisionally assign these deposits to the Sierra Ladrones Formation of Machette (1978). Pending further investigation, we follow that nomenclature here. Blanketing much of the Llano de Manzano and other surfaces in the region are eolian cover sands. These eolian sands are particularly significant to fault studies because they tend to dominate over colluvial sedimentation along faults (*eg.*, Personius and Mahan, 2003), they complicate age estimates of the many alluvial surfaces in the region, they mute the geomorphic expression of faults, and they are excellent candidates for luminescence dating.

Despite the eolian cover, scarps of the HSF are as high as 40 m on the Pliocene Cañada Colorado and as high as 25 m on the Pleistocene Llano de Manzano (Machette and McGimsey, 1983). In addition, Permian, Triassic and Tertiary rocks are exposed in some portions of the footwall of the HSF, indicating unusually substantial structural relief across this intrabasin fault (Reiche *et al.*, 1949; Kelley, 1977; Love *et al.*, 1996). Stark (1956) estimated a total throw of ≈2,256 m (7,400 ft) across the central HSF based on footwall bedrock exposures and logs of the Grober No. 1 well that he thought bottomed in the Triassic Chinle Formation on the downthrown side of the fault. However, Hudson and Grauch (2003) reinterpreted this drill hole and concluded it bottomed in Neogene basin fill, not the Chinle Formation, which suggests that the total throw is likely greater.

1.2 PREVIOUS WORK AND UNRESOLVED ISSUES

Read *et al.* (1944) first mapped the HSF and named it the Ojuelos fault for Los Ojuelos Springs on the central HSF about 4 km south of our trench site. Several early investigators also used this name (*eg.*, Reiche *et al.* 1949; Stark, 1956; Titus, 1963), but through time "Hubbell Spring(s)" was added, or replaced "Ojuelos" in the name (*eg.*, Kelley, 1977; Machette, 1982; Machette & McGimsey 1983), and so Machette *et al.* (1998) used the name Hubbell Spring fault, and we retain that nomeclature here.

Machette and McGimsey (1983) mapped, profiled and analyzed fault scarps of the HSF, describing them as "perhaps the most spectacular fault scarps in the central Rio Grande rift." They mapped a complex, anastomozing series of three dominant splays that converged to the north and had a total length of 34 (their text and Table 2) to 43 (their map) km, with only the central trace extending south of Los Lunas (Figure 1). They measured scarp heights of 2 to 40 m on Pliocene to late Pleistocene deposits, with larger offsets on older surfaces clearly indicating recurrent Quaternary movements. Reiche *et al.* (1949) suggested movement was youngest along the southern portion and possibly Holocene. Based on their morphometric analyses, Machette and McGimsey (1983) also concluded movement was younger to the south, breaking the fault into northern and southern segments. However, based on comparison to 5-ka and 15-ka scarps studied elsewhere in the Basin and Range, they concluded that youngest faulting on the HSF was late Pleistocene, but probably considerably older than 15 ka.

More recent detailed mapping of late Cenozoic sediments along the northern HSF in the Isleta Indian Reservation (e.g., Love *et al*., 1996; Love, 1998; Maldonado *et al*., 1999) suggests that the fault geometry is even more complex and some traces are much longer than previously mapped by Machette and McGimsey (1983; cf. Figures 1 and 2). In particular, Maldonado *et al*. (1999) map several anastomosing, discontinuous fault traces that still form three dominant north-south trending fault splays (western, central and eastern), and merge together to the north (Figure 2). However, Machette and McGimsey (1983) showed the western and eastern traces dying out northeast of Los Lunas (Figure 1), whereas Maldonado *et al*. (1999) extend these traces at least another 15 kilometers to the south (Figure 2). Although they mapped the three splays of the HSF extending south of Hells Canyon, the eastern splay is somewhat enigmatic as it appears to show down-to-the-east offset in the subsurface, but has down-to-the-west scarps that die out south of Hells Canyon. The eastern splay may actually have a longer more complicated kinematic history than the rest of the HSF, with only the northern portion having been reactivated during Pleistocene extension. Additionally, the newly identified Palace-Pipeline fault (Love, 1998) is a zone of faults located just west of the western HSF (Figure 2) that was not included in the Quaternary fault compilation of Machette et al. (1998) (Figure 1). This fault zone strikes north-south and offsets the Pleistocene Sunport and Llano de Manzano surfaces down to the west by as much as 15 m (Maldonado et al., 1999). Maldonado et al. (1999) extend the Palace-Pipeline fault at least as far south as El Cerro Tome, making it at least 18 km long. Recent airborne aeromagnetic surveys (Grauch, 2001) support Maldonado *et al*.'s mapping and suggest that the eastern and western splays of the HSF and the Palace-Pipeline fault potentially extend even farther south, up to 45 kilometers or more, and are as long as the central HSF (Figure 3). However, additional mapping is needed south of the Isleta Indian Reservation to confirm how far south Quaternary fault scarps actually extend.

This raises questions about which is the most dominant and active fault splay of the HSF, or if the three splays all rupture coseismically. Based on available evidence, previous studies have suggested that the central HSF forms the active margin along this portion of the Rio Grande rift (Machette *et al*., 1998). Overall, the central HSF has the most prominent geomorphic expression on the Llano de Manzano, forming the Hubbell bench on the upthrown side of the fault. However, this may be partly due to the fact that the central splay is the only trace with bedrock exposed in the footwall along much of its length, and thus it's prominent geomorphic expression may not necessarily be indicative of the greatest late Quaternary rate of activity. The central HSF is also most closely associated with a strong north-south trending gravity gradient along the Hubbell Bench (Figure 2), however, recent gravity and aeromagnetic modeling studies suggest that the major basement offset is actually > 2 km west of the central HSF (Grauch and Hudson, 2002). Although Machette and McGimsey (1983) measured scarp heights of 4 to 25 m on early to late Pleistocene deposits along the central HSF, very little is know about its paleoseismic behavior. Similarly, nothing is known about the Quaternary behavior of the eastern HSF. Despite the prominent aeromagnetic signature of the eastern HSF (Figure 3), it has a poor geomorphic expression, no associated gravity gradient (Figure 2), and may actually be a relict fault from a pre-Quaternary period of extension.

In comparison, the western HSF exhibits some of the highest scarps on the youngest deposits and may actually record the greatest late Quaternary activity. A recent paleoseismic investigation of a 7-m-high scarp on the western HSF near Hubbell Spring at its northern end (Figure 1) revealed evidence for four surface-faulting events that occurred since deposition of fan deposits on the Llano de Manzano (Personius *et al*., 2001) probably around 92 ± 7 ka (Personius and Mahan, 2003). These events resulted in 5 to 8 m of throw and average displacements per event of 1 to 2 m (Personius *et al*., 2001). The luminescence ages of colluvial /eolian deposits associated with faulting indicate that the most recent, penultimate and antepenultimate events occurred around 12 ± 1 ka, 29 ± 3 ka, and 56 ± 6 ka, respectively (Personius and Mahan, 2003). The age of the oldest event is poorly constrained but it occurred prior to the antepenultimate event and some time after 92 ± 7 ka.. The relatively large per event displacements supports either longer rupture lengths for the western HSF, as mapped by Maldonado *et al*. (1999), or coseismic rupture with the central HSF, or possibly both (a longer length for the western HSF and coseismic rupture with the central HSF).

In summary, recent studies raise several questions about the late Quaternary behavior and earthquake potential of the HSF, including: were all of the traces (western, central, and eastern) equally active, did they rupture coseismically or independently, and were late Quaternary ruptures on the central HSF as large as on the western HSF? These questions are all important to assessing seismic hazards in the region (Wong *et al*., 2000).

1.3 PURPOSE AND SCOPE

The purpose of this study was to develop a better understanding of the late Quaternary paleoseismicity of the central HSF fault through a detailed trench investigation. Our study included: (1) interpretation of black and white stereo aerial photographs of the trench site at different scales (≈1:41,000-scale 1996 NAPP, and ≈1:52,000-scale 1953 AMS photographs); (2) detailed mapping of the surficial geology at the trench site; (3) topographic profiling of fault scarps; and (4) excavation, interpretation and logging of trench and soil pit exposures; (5) description of soil profiles and lithologic units; (6) luminescence analyses of samples to determine numerical ages; and (7) drilling, logging, and interpretation of three shallow boreholes at the trench site.

2.1 SURFICIAL GEOLOGY

The Carrizo Spring trench site is located near the along-strike midpoint of the central HSF, about 16 km south-southeast of Los Lunas and the Rio Grande (Figure 1), three kilometers south of Meadow Lake, and one kilometer north of Carrizo Spring (Figure 4). The site is about 11 km due west of Bosque Peak, which at 2929 m is the third highest peak in the Manzano Mountains. In contrast, the site is at ~1646 m elevation along the Hubbell Bench of the Llano de Manzano surface, which is about 175 m above the Rio Grande. At this latitude, discontinuous and anastomasing fault scarps of the western HSF lie about 7 km to the west of the central HSF and offset the Llano de Manzano, whereas the eastern HSF appears to be buried by late Pleistocene piedmont deposits of the Llano de Manzano about 2 km to the east.

Near the trench site, the central HSF is marked by an alignment of springs along a well-defined but broad, single, simple, west-facing scarp on the Llano de Manzano (Figure 4). There is no evidence for any antithetic faults or backtilting along this section of the fault. Scarp heights range from 3 to 15 meters, decreasing to the north as the fault splits into multiple scarps near the town of Meadow Lake. To the south the fault continues as a single scarp, increasing in height and becoming more dissected as it transects the Tome Land Grant, and eventually (roughly 5 km south) exposes Triassic and Permian sedimentary rocks in the footwall, becoming a bedrock-alluvium fault contact. Immediately to the north and south of the trench site, ephemeral drainages have incised 1 to 11 m into the Llano de Manzano, generally showing greater incision on the upthrown side of the central HSF. For example, the drainage along Maes Spring is the largest locally (Figure 4) and is incised 7.6 to 10.7 m in the footwall, versus 4.6 to 6.1 m in the hanging wall. However, all of the local drainages are relatively small and are not incised extensively. Thus, they appear to be graded locally to the Llano de Manzano and not to the Rio Grande (Connell *et al.*, 2001). Some very small drainages have small Holocene fans formed at the base of the central HSF scarp, such as the small drainage and fan immediately south of the trench site (Figure 4). Overall, the Llano de Manzano in the area is underlain by late Quaternary piedmont alluvium shed off the Manzano Mountains, which is blanketed by a thin cover of eolian sand, creating a remarkably uniform surface (except for drainages and fault scarps) that slopes gently (2° to 4°) westward. The dominant wind direction is from the southwest and eolian deposits have built up to form small local dunes (Unit H_e on Figure 4), particularly where deposits have banked up against fault scarps such as at the trench site. Based on age analyses from the trench (discussed in Section 2.2), these loose eolian sands likely span a range of ages from mid-Holocene to modern. Deposits not shown on Figure 4, but which turned out to be important to this study, are small localized spring deposits along the fault. These are visible as light-colored patches of concentrated carbonate on the surface, and are most prominent around Carrizo and Maes Springs, but notably small patches are visible in a gully just north of the trench site and also exposed in the drainage to the south.

The Llano de Manzano provides a good datum on which to measure long-term late Quaternary offsets from topographic profiles. A very long topographic profile (P1 on Figure 4) measured across the central HSF at the trench site yielded a net vertical tectonic displacement of 7.5 ± 1.0 m down-to-the-west (Figure 6a, inset) and a maximum scarp angle of 12°. The profile shows no evidence for antithetic faults or backtilting of the hanging wall toward the fault. The scarp crest is very broad and is located about 35 m east of the maximum scarp angle that forms the only bevel on the scarp face. No net offset was apparent across two small swales occupied by ephemeral drainages located about 115 and 220 m east of the scarp crest. Another scarp profile measured at our alternate trench site about ¾ km to the south (P2 on Figure 4), yielded a net vertical tectonic displacement of 7.0 ± 1 m down-to-the-west. Here, eolian dune sand is banked up over the scarp crest. The scarp crest is still broad, but the profile shows a double bevel and a maximum scarp angle of only 8°.

2.2 SUBSURFACE INVESTIGATIONS

We excavated one trench across the fault (Figures 4, 5, 6a, and 6b) and one soil pit located about 43 m west of the trench (inset on Figure 6a). We also augered three shallow boreholes in the hanging wall of the fault (B1, B2, and B3 on Figure 6a inset). The trench was over 60 m long and 4½ m deep. The soil pit was nearly 3 m deep and about 5 m long. Boreholes were between 5.7 (B3) and 10.4 m (B1) deep. Boreholes were augered with a SIMCO 2800 HS drill rig provided and operated by the New Mexico Bureau of Geology and Mineral Resources (Middle cover photograph). Samples were continuously collected on the 4" diameter auger stems. Except for some sloughing in limited zones, this method worked relatively well for holes B1 and B2. Unfortunately, challenges with keeping the hole vertical for B3 resulted in significant sample disturbance for much of the hole, making stratigraphic interpretations from B3 less reliable. Both the trench and soil pit were excavated with a rubber-tire backhoe using a 3-foot (0.9 m) wide bucket. Walls were scraped and cleaned to remove bucket smear. The trench was logged at a scale of 1 inch = 1 meter (≈1:40 scale) on a planimetric grid (Figures 6a and 6b), whereas only a profile was logged for the soil pit (Figure 7). In the trench, we strung level lines and marked stations at one-meter intervals to provide reference lines. Locations of samples, faults, and stratagraphic and pedologic contacts were marked with nails and/or spray paint, and measured relative to a level line to the nearest centimeter. Total errors of measured points on the logs are estimated to be ≤ 5 cm. Original trench logs were then simplified during drafting, primarily by reducing detail in clast fabrics and using generalized patterns for some units (Figures 6a and 6b).

We collected 11 samples from the trench for luminescence analyses to provide numerical age constraints for faulting events (Figures 6a and 6b). However, we only had enough funds to analyze 8 samples (Table 1). Successful application of thermoluminescence dating of sediments in paleoseismic studies of normal faults began in the 1980s (e.g., Forman *et al.*, 1988) and recent developments have made applications even more robust. Thermoluminescence is the release of light when mineral grains are heated above 150°C and sediments acquire thermoluminescence from background radiation. Thermoluminescence in sediments increases steadily with time and age estimates are made by determining the ratio of the equivalent dose (proportional to the luminescence signal accumulated since burial) to the dose rate (or background radiation at the sample site) (see Forman *et al.*, 1999, for further discussion). Thus, analyses provide the time since deposition and burial. Thermoluminescene is released during exposure to sunlight. Therefore, during transport the "thermolumenescence clock" is reset if enough sunlight reaches individual grains, such as for eolian deposits and fine-grained slopewash. These types of deposits are excellent candidates for luminescence dating. The recent development of using infrared stimulated luminescence (IRSL), which measures luminescence of the infrared portion of the light spectrum, has some significant advantages for paleoseismic applications (Spooner *et al.*, 1990; Forman, 1999). Measuring this portion of the spectrum generally provides smaller errors and broader applications to a greater variety of depositional environments as this portion of the spectrum is zeroed or reset very quickly. For example, in comparison of traditional thermoluminescence analyses and IRSL analyses of a modern dune near the Hubbell Spring trench, Personius and Mahan (2003) found that the IRSL analyses had smaller errors and an order-of-magnitude smaller residual or inherited signal (~300 vs. 2,000 years) than the thermoluminescence analyses.

Samples for IRSL analysis for this study were collected by first scraping the trench wall back 20 cm, driving a PVC sampling tube into the wall, extracting the tube and sealing the ends with duct tape. During sampling, care was taken to avoid obviously bioturbated areas, including insect and animal burrows and large roots. In the laboratory, samples were extracted, the ends shaved and discarded, and IRSL analyses were completed on the 4-11 micron polymineral fraction of the sample. The resultant blue emission is isolated by 5-58 and GG-400 Corning filters and measured by a standard photomultiplier tube. The total bleach method was used with the residual level defined by 1 hour sunlight exposure. An exponential or linear fit were used to model the additive dose response with the interpolation to the residual level <20% of the highest applied beta dose. The equivalent dose was calculated for 3 to 90 seconds after initial exposure to infrared excitation (880 ± 80 nm). The precision of analysis was very good, with dispersion in additive dose response usually ≤ 10%. Dose rate estimate was calculated from alpha counting to determine U and Th content (assuming secular equilibrium) and elemental analysis to provide for ^{40}K component. Moisture contents of 5 ± 2% and 10 ± 3% were assumed in the final age calculation (Table 1). Errors of 1 σ are reported for all IRSL ages.

2.2.1 Trench Exposure

The trench exposed piedmont alluvium, slopewash colluvium, playa deposits, and eolian sands that included several buried soils throughout the section (Figures 6a and 6b). A broad deformation zone consisting of fractures, faults, and warping, offset these deposits down to the west. Several of the stratigraphic units and buried soils that were exposed in the footwall could be traced across the deformation zone and into the hanging wall. However, units and particularly soil horizons were generally thicker in the hanging wall. Also, some units and soils were partially or entirely eroded away in the area of maximum deformation and some soil catenas showed dramatic differences in properties downslope. In addition, the trench and soil pit were not deep enough to expose the oldest buried soil (S_1) on the downthrown side of the fault. Therefore, we drilled three shallow borings (B1, B2, and B3) in the hanging wall to measure the throw on this oldest buried soil.

Despite all of the complexities, the trench, soil pit, and boreholes revealed stratigraphic, pedologic, and structural evidence for the occurrence of at least 4, probably 5, large earthquakes on the central HSF. All of these deformation events included warping down to the west, however, only the three largest events showed definitive discrete slip across faults. The evidence for all events, along with their timing, is described in detail in the following sections. We refer to these events with reversed alphabetical labels; Event Z being the youngest and Event V the oldest.

2.2.1.1 Stratigraphy

We logged 14 stratigraphic units in the trench exposure with Unit 1 being the oldest and Unit 14 the youngest. Abbreviated unit descriptions are shown on Figure 6b and detailed descriptions are shown in Appendix A. The stratigraphic units included 7 buried soils (S_1 through S_7) and the tops of these catenas are shown on Figures 6a and 6b. Detailed soil profile descriptions for several locations (Figures 6a and 6b) are included in Appendix B. The following descriptions summarize characteristics relevant to deciphering the faulting history.

Unit 1 consists of older piedmont deposits of the Llano de Manzano and is the oldest unit exposed in the trench. It is clearly warped and faulted, and was only exposed east of st. 41 m in the trench (Figures 6a and 6b). It includes three subunits (1a, 1b, and 1c) as well as a stage II buried soil (S_1). Unit 1a consists of fluvial channel gravels interbedded in Unit 1b, and was only exposed locally mid-trench near the deformation zone. Clasts are dominantly pebble-sized, but range as large as boulders. They are sub-angular to rounded and dominantly composed of granitic, gneissic, greenstone, and other metamorphic rocks, with rare limestone and sandstone clasts. Smaller granitic clasts are generally grussified (crumbling to the touch) and some of the metamorphic clasts are also extremely weathered to clays so that we could slice through them with a soils knife. Clasts are stratified and weakly imbricated to the northeast. Based on its stratigraphic characteristics, we interpret Unit 1a to have been deposited by streams draining the Manzano Mountains east of the trench site, where dominantly Precambrian granitic and metamorphic rocks are exposed at the base of the range front, with Paleozoic limestones exposed near the tops of peaks (*eg.*, Bosque Peak; Karlstrom *et al.*, 2001).

Unit 1b is a greenish to pinkish sand with discontinuous pebbly, silty, or clayey lenses. It is weakly-stratified, overall fining upward, and is interpreted to be interbedded overbank, slopewash, and eolian deposits. This subunit is stratigraphically continuous with Unit 1c, but is distinguished by the lack of carbonate nodules characteristic of the buried soil S_1, developed in Unit 1c east of st. 29 m. Indeed the carbonate in S_1 appeared dissolved from Unit 1b, as evidenced by "ghost" nodules (nodular-shaped zones of silt that did not react to HCL) between st. 28 and 30 m, and the intense amount of manganese oxide and limonitic staining between st. 28 and st. 40 m. Additionally, although fractures and warping are evident where S_1 dies out near st. 29 m, no stratigraphic offsets or significant shearing are evident in Unit 1a or 1b, so S_1 is not cut out by faulting. However, some of the soil carbonate does appear to have been remobilized and precipitated into fracture networks within the deformation zone. These fracture networks are characterized by numerous vertical and bedding-parallel fractures similar to those observed by Personius *et al.* (2001) at the Hubbell Spring trench site. As estimated from the trench and boreholes, the total apparent throw of S_1 was about 7.3 ± 0.5 m down to the west.

Two samples from Unit 1b (CHSF02-3 and CHSF02-4 on Figure 6b) yielded an average IRSL age of 83.6 ± 6.0 ka (Table 1). These are the first absolute ages for Llano de Manzano piedmont deposits and it is noteworthy that they are much younger than the early to middle Pleistocene ages estimated by previous studies (*eg.*, Machette, 1985; Maldonado *et al.*, 1999; Connell *et al.*, 2001). This suggests that either the Llano de Manzano surface is much younger than previously thought or, more likely, spans a broader range of ages from early to late Pleistocene.

Unit 2 is only locally present on the downthrown side of of FZ3. It pinches out to the east at st. 37 m, and is faulted and warped down at its west end below the base of the trench west of st. 43.5 m. This dark brown sandy silty clay overlies Unit 1b and is overlain by Unit 3a and Unit 4. It is weakly bedded with fine sand partings, mottled with MnO staining, and generally lacks carbonate. Based on its location, and limited extent, and stratigraphic characteristics, we interpret Unit 2 to be a sag pond deposit at the base of a normal fault scarp created during Event V by warping and offset on faults (FZ1, possibly FZ2, and FZ3 on Figure 6b). Due to the subsequent dissolution of carbonate in Unit 1b, stratigraphic relations are unclear as to whether Unit 2 was deposited before or after development of S_1. However, an IRSL sample from Unit 2 (CHSF02-1 on Figure 6b) yielded an age of 65.2 ± 5.6 ka (Table 1), which is consistent with the IRSL ages from the underlying Unit 1 and the degree of intervening soil development of S_1, suggesting that S_1 developed before Event V occurred and before deposition of Unit 2.

Unit 3 is dominantly a pink fine sand that is faulted, warped down to the west, and appears to have been eroded away west of st. 38 m. We interpret Unit 3 to be younger piedmont deposits of the Llano de Manzano, and similar to Unit 1, Unit 3 includes two subunits, 3a and 3b, with the latter distinguished by a buried soil, S_2. Subunits 3a and 3b are similar to and unconformably overlying Units 1b and 1c, respectively. Unit 3a is a pinkish silty sand that contains some small gravel stringers and intraclasts. This unit is similar to the upper portion of Unit 1b and we interpret it be a mix of slopewash and eolian deposits. Unit 3a is stratigraphically continuous with Unit 3b, but lacks the carbonate of the Stage II nodular buried soil (S_2) included in Unit 3b. Similar to S_1, the carbonate in S_2 appears to have been dissolved from Unit 3b west of st. 28 in the deformation zone. East of st. 18 m, the carbonate in S_2 increasingly overprints the underlying S_1 buried soil and they became indistinguishable east of st. 11 m. The total apparent throw on S_2 as estimated from the trench and boreholes is 6.5 ± 0.5 m down to the west.

Unit 4 unconformably overlies the buried S_2 soil, and Units 3 and 2. Although it is warped and cut by fractures in the deformation zone, Unit 4 did not appear offset by faults. This reddish coarse to fine sand contains discontinuous coarser beds. It thickens on the downthrown side of faults, where sediments are generally coarser and include some intraclasts. Based on these characteristics, we interpret Unit 4 to be colluvium and eolian sediments deposited after a faulting event, Event W. However, similar to observations made by Personius *et al.* (2001) in the Hubbell Spring trench, this post-faulting unit is dominated by eolian deposition, and thus does not show many of the typical characteristics of fault-scarp derived colluvial wedge deposits along normal faults, such as distinct debris and slopewash facies forming wedged-shaped deposits (Nelson, 1992). An IRSL sample from Unit 4 (CHSF02-6 on Figure 6a) yielded on age of 30.2 ± 2.2 ka. This sample was collected from an eolian dominated portion in the footwall because sediments in the deformation zone showed undesirable characteristics for luminescence dating (intraclasts, coarser sand, and extensive FeO and MnO staining). Thus, although the eolian sediments that were sampled clearly post-date faulting, they may have been deposited well after faulting and their age may not provide a close minimum limiting-age for Event W.

Unit 5 is a well-sorted reddish fine to medium eolian sand that contained faint planar laminations, little carbonate, and extensive FeO and MnO staining. It conformably overlies Unit 4 and includes a buried soil, S_3, which apparently extended nearly the full length of the trench. However, the S_3 catena varies considerably across the trench exposure (cf., Soil Profiles CS2, CS5, and CS1, Appendix B), probably due to the different soil forming conditions across the slope of the fault scarp. S_{3a} extends from st. 0 to st. 8 m and is characterized by a mottled Btk horizon with a stage II to III carbonate morphology. Carbonate coatings on peds suggests overprinting of the original Bt horizon, likely similar to S_{3b}, by carbonate related to development of overlying buried soils, S_5 and possibly S_6. S_3 is apparently eroded away between st. 8 and st. 9 m. S_{3b} extends from about st. 9 m to about st. 35 m and is characterized by a Bt horizon that is up to 0.5 m thick and well-cemented with sesquioxides. S_3 is stripped away between st. 35 and st. 37. S_{3c} extends from about st. 37 to the west end of the trench and is characterized by a mottled Btk horizon similar to S_{3a} but more disseminated. S_{3c} entirely overprints Unit 5 and the top of Unit 4, obscuring the contact between these units in the hanging wall.

Although Unit 5 is cut by fractures and warped down to the west with a total apparent throw of 2.8 ± 0.6 m down to the west (as measured in the trench and boreholes), we observed no discernible fault offsets of this unit. However, Unit 5 thinned dramatically between st. 30 and 38 m. The top, including S_3, is clearly stripped at the crest of the zone of maximum warping. The angular discordance between the base of Unit 5 and overlying stratigraphic and pedologic horizons suggests that this erosion occurred after a warping event, Event X.

Unit 6 unconformably overlies Unit 5. Unit 6 is a buff colored silty very fine eolian cover sand that is very well-sorted and relatively homogeneous, lacks carbonate, and has some faint planar laminations. It appears to have been eroded away east of st. 9 m. West of st. 35.5 m, it is overprinted by carbonate from the overlying soil horizon, S_5, and became indistinguishable from underlying and overlying units. Two IRSL samples from Unit 6 (CHSF02-5 and CHSF02-7 on Figures 6b and 6a, respectively) yielded an average age of 26.8 ± 2.4 ka (Table 1).

Unit 7 is a pinkish tan clayey silty fine sand that conformably overlies Unit 6, extending from about st. 17 m to st. 32 m. This very well-sorted eolian cover sand is similar to Unit 6, but includes a weakly developed buried soil horizon, S_4, that varies between a Bw and Btj horizon. Both Units 6 and 7 are cut by fractures and warped, but we observed no discrete fault offsets in these units. In the deformation zone, both Units 6 and 7 are overprinted, in angular discordance, by carbonate from the overlying buried soil horizon, S_5, developed in Unit 8. We believe this angular discordance was created by a small warping event, Event Y(?), as S_5 appears to have formed on a slope that was steeper and higher than the slope where Units 6 and 7 were deposited. Regardless, it is likely that Unit 8 in the hanging wall includes Units 6 and 7 near its base but stratigraphic characteristics and contacts are obscured by soil formation in S_5.

Indeed, Unit 8 is entirely characterized by a buried K horizon, S_5, that obscured most of the original depositional characteristics of this pinkish-white, silty sand with clay that is likely primarily an eolian deposit. It is present in the footwall and hanging wall but locally missing below the crest of the scarp, from about st. 17 to 28 m, probably due to stripping. Although Unit 8 is cut by fractures, warped down to the west with a total apparent throw of 2.1 ± 0.5 m, and the top appears backtilted in the hanging wall and locally deformed adjacent to FZ5, no through-going faults with definitive discrete slip were discernible in this unit. This is somewhat surprising as the abrupt upper contact with the overlying Unit 9 makes a distinct marker that does not show discrete slip on FZ5, even though Unit 10 above is clearly offset by FZ5. Unit 8 varies from a stage II to III+ carbonate morphology, but is dominantly a stage III. It is also more than double in thickness in the hanging wall (over 1 m), where it appeared more disseminated than in the footwall and contained large zones that were punky and friable in texture. It also contains irregular shaped carbonate nodules, some as large as cobbles, that weathered out of the trench wall easily in places due to apparent partial dissolution of carbonate in the surrounding matrix. We believe Unit 8 has been extensively affected by ground water and/or spring water upwelling along the faults and fractures in the deformation zone. This would not only explain the unusual textures, but also the apparently incongruous large amount of carbonate accumulation in a horizon that is younger than 30 ka, as indicated by luminescence ages from Unit 6.

Unit 9 is a silty clayey sand that is locally present only on the downthrown side of the deformation zone between st. 32 and 56 m. It is characterized by a buried soil, S_6, that consists of a mottled, friable, Btk horizon, with a stage II- to III-carbonate morphology. However, similar to Unit 8, we believe the carbonate in Unit 9 may not all be pedogenic, and thus the morphology is not a reliable indicator of age. Unit 9 contains reworked carbonate nodules, apparently from Unit 8, which generally decrease downslope. Based on these characteristics and its limited extent on the downthrown side of the deformation zone, we interpret Unit 9 to have been scarp-derived colluvium and eolian material deposited after the warping event Y. Unfortunately due to the extensive carbonate accumulation and soil development, Unit 9 was not a good candidate for luminescence age analyses. Unit 9 was also cut by faults of FZ5 during the most recent event, Event Z. Additionally, Unit 9 shows weak planar laminations in places and these are tilted and warped on the downthrown side of FZ5.

Unit 10 is a silty sand with clay that is characterized by the youngest buried soil in the trench, S_7. This soil is a stage II- nodular carbonate horizon that extends the full length of the trench except where it was broken up by faults of FZ5 during Event Z and disturbed by krotovina between st. 39.5 and 41.5 m. Additionally, Unit 10 appears slightly backtilted toward the east on the downthrown side of FZ5. The total apparent throw on S_7 is about 1.7 ± 0.3 m down to the west. Similar to Unit 9, the carbonate accumulation and soil development in Unit 10 prevented luminescence age analyses.

Unit 11 is a light brown silty sand that contained blocks of Unit 10 and reworked carbonate nodules. It is a wedge-shaped deposit that unconformably overlies the buried soil on Unit 10. It is not offset by any faults, and is present only on the downthrown side of FZ5. Based on these characteristics, we interpret Unit 11 to be primarily fault-scarp derived colluvium with minor eolian material deposited after the youngest faulting event, Event Z. An IRSL sample (CHSF02-8 on Figure 6b) yielded an age of 5.5 ± 0.4 ka for the distal and eolian dominated portion of Unit 11.

Units 12 and 13 are respectively silty and coarse sand deposits that are dominantly eolian sediments with some slopewash. These lenticular-shaped deposits are cut by open fractures, but did not appear faulted or warped. They conformably overlie Unit 11 and appear to be filling the topographic depression that was likely created during faulting Event Z, although, it is possible that deposition of Units 12 and 13 was related to another younger, minor warping event that could have occurred subsequent to Event Z and deposition of Unit 11. However, given the lack of any other evidence for this hypothetical event, we believe it is much more likely that the open fractures were related to non-tectonic processes (such as settlement, bioturbation, freeze-thaw, etc.) and that the deposition of distinct eolian packages was related to non-tectonic causes, such as climate change. An IRSL sample (CHSF02-10 on Figure 6b) yielded an age of 6.0 ± 0.4 ka, which is stratigraphically consistent (within 1 σ error) with the age for the underlying Unit 11 and the overall lack of soil development in Units 11 through 13. Finally, Unit 14 is a loose, tan, fine sand that drapes the scarp. This eolian sand includes the modern soil, which is characterized by roots in a weakly developed B_W horizon.

2.2.1.2 Structure

The broad deformation zone exposed in the trench is characterized by: (1) a zone of warping down to the west, that is coincident with the scarp face; (2) a narrower zone of near vertical and bedding parallel fractures, between st. 28 m and st. 41 m, that does not show discernible discrete slip (shown in black on Figures 6a and 6b); and (3) a series of five west-dipping to subvertical fault zones (FZ1 through FZ5, shown in red on Figures 6a through 6b) that offset strata down to the west, and are roughly coincident with the zone of fractures, the maximum zone of warping, and the maximum slope angle on the scarp.

Although warping appears to have deformed Units 1 through 10 in a broad zone (i.e., from the crest of the scarp westward), there is a more concentrated zone of warping between st. 28 and 42 m that is coincident with faulting and the maximum scarp angle. Within this zone, older units are generally warped more than younger units but differential warping and distinct events are much more difficult to distinguish than differential offsets and events on faults. However, a progression of warping (and faulting) events is still evident from: the overall thickening of many units and soils in the hanging wall, the erosion of several units and soils in the zone of maximum deformation, and the angular discordances between some units and overlying units and soils, as discussed in the previous section. Based on these relations and total differential offsets on buried soils (S_1, S_2, S_3, S_5, and S_7) (discussed in Section 2.2.4), it is evident that warping occurred during all of the deformation events on the CHSF, albeit to various degrees.

Fault terminations at the top of buried soils and differential offsets on faults provide evidence for 3 separate faulting events. Fault zone orientations and dip-slip measurements are shown on the trench log (Figure 6b). Faults FZ1 and FZ2 both cut Units 1 and 3, terminating at the top of Unit 3a, the stratigraphic equivalent to the top of the buried soil S_2 and the event horizon for Event W. Differential offset between Units 1 and 3 suggest that FZ1 and FZ2 were both active during Events V and W. However, given the uncertainties in measurement, larger offsets of Unit 1 may be partially due to the listric geometry of FZ1. Similar to FZ1 and FZ2, FZ3 cut Units 1 and 3, terminating at the top of Unit 3, although fractures (without offset) extended into Unit 4. Small differential offsets between Units 1 and 3 were apparent but not definitive on FZ3, given the warping and complex fault geometry of this zone. FZ4 also cut Units 1 through 3 terminating at the top of Unit 3, with associated fractures that extended upward into Unit 5. However, no differential offsets were observed on FZ4, suggesting this fault was only active during Event W. FZ5 is somewhat unusual in that it definitively offsets Units 9 and 10 but does not appear to offset underlying units. However, the top and bottom of Unit 8 are clearly warped and deformed near this fault (at st. 39.5), and may have even been faulted, with slip transferring to the east on FZ4 in underlying units and any fault or fractures in Unit 8 having been obscured by carbonate accumulation and overprinting of S_5 soil development. The upward termination of FZ5 is at the top of the buried soil S_7 in Unit 10, the event horizon for Event Z, with open fractures extending into Units 11 and 12. No differential offsets were observed on FZ5.

2.2.2 Soil Pit

The soil pit exposed an extensively bioturbated package of dominantly eolian sand with minor alluvium that included three buried soils underlying the modern soil on loose eolian sand (Figure 7). The lowermost soil is a disseminated K horizon developed on a sandy silt to silty sand with gravel. It contains the most carbonate (stage II to III) and lacks the clay, mottling, and peds that were characteristic of S_3 in the trench. Therefore, we think this soil most likely correlates to S_5 in the trench.

Overlying the K horizon is a mottled, silty very fine sand with a buried disseminated Bk horizon. This soil may correlate to S_7 on Unit 10 in the trench, although it was much more disseminated. Overlying the Bk horizon is sandy alluvium with a thin Btjk horizon that does not appear to correlate to any units in the trench. It appears to be the deposit of a small drainage that incises the fault scarp north of the trench.

Due to the extensive bioturbation and more disseminated character of the buried soils exposed in the soil pit, correlations to soils in the trench were slightly ambiguous. However, it is clear that neither of the buried soils, S_2 or S_1, nor the channel gravels of Unit 1 were exposed in the soil pit, and presumably these soils and deposits are at a greater depth below the pit exposure. Indeed, as discussed in the next section, S_1 and S_2 were observed at greater depths in the drill holes.

2.2.3 Boreholes

The locations of the three drill holes projected onto the scarp profile are shown on the inset of Figure 6a. Logs of borings are included in Appendix B. Boring B1 was located just south of the st. 60 m at the west end of the trench. It was the deepest hole (total depth 10.39 m) and provided relatively good correlations to stratigraphy exposed in the trench, except for some uncertainties due to sloughing at depths around 1.5 and 2.5 m.

At a depth of 5.6 m, boring B1 encountered a buried carbonate soil horizon that was mottled and appeared nodular. It was developed on a gravelly sand that coarsened downward to a clean sandy gravel with clasts of gneiss, quartzite, and other dark metamorphic rocks. Based on these characteristics, we correlate these sandy gravels to the channel deposits of Unit 1 in the trench, and the soil to S_1 in the trench. At a shallower depth of 3.85 m, boring B1 encountered another mottled carbonate soil horizon that appeared nodular. Our preferred interpretation is that this soil correlates to S_2 in the trench. Alternatively a thin, clayier mottled carbonate horizon encountered at 4.5 m depth possibly correlates to S_2.

Boring B2 was located 46 m southwest of B1 and was 7.22 m deep. B2 encountered a mottled carbonate soil horizon at 2.53 m depth that we believe correlates to S_2 in the trench. Underlying that was another mottled carbonate horizon at 4.76 m depth that we correlate to S_1 in the trench. Underlying S_1 in both B1 and B2, was a thick (> 1 m) pinkish well-sorted silty fine sand. Borehole B3 was located between B1 and B2. Samples from the upper 2 m of B3 were disturbed due to drilling problems. However, a carbonate soil horizon developed on a sandy gravel with metamorphic clasts was encountered at a depth of 4.95 m and we correlate this soil and gravel to S_1 and Unit 1 in the trench. At a shallower depth of 3.7 m, another carbonate soil horizon was encountered in B3, which we tentatively correlate to S_2 in the trench. Unfortunately, at the bottom of B3, we could not punch through Unit 1 and presumably into the underlying pinkish silty fine sand that was encountered in boreholes B1 and B2.

2.2.4 Deformation Event Summary and Chronology

This section summarizes the evidence for, and timing constraints on, the faulting and warping events at the Carrizo Spring Trench site. Differential offsets provide important evidence for identifying events and information about event size. Due to the extensive warping at the Carrizo Spring site, we knew that we needed to look beyond just differential offsets on individual faults and compare the total down to the west throw (including fault slip and warping) between event horizons. Using observations from both the trench and boreholes, we were able to measure the apparent total throw on key marker horizons, buried soils: S_1, S_2, S_3, S_5, and S_7. The tops of these buried soils are the respective event horizons for Events V, W, X, Y(?), and Z. We refer to these total throw measurements as "apparent" because our correlations of units across the deformation zone rely heavily on pedogenic characteristics and soils can form on pre-existing slopes such that all of the vertical relief we measured may not be related to offset that occurred after the soil formed. However, given the nature of the channel gravels comprising Unit 1a, it's likely that these streams beveled off any pre-existing scarp before S_1 formed. Given this, and that the vertical relief measured on each event horizon is progressively larger for each older event, we infer that this vertical relief was all tectonically created as we see no other likely cause for repeatedly creating new relief on a north-trending scarp at this location, especially given the nature of all the overlying deposits, which are all fine-grained eolian and slopewash sediments. This interpretation is supported by the independent stratigraphic, pedologic, and other structural evidence for the occurrence of each of the deformation events.

Table 2 summarizes the total apparent throw on the tops of the buried soils (S_1, S_2, S_3, S_5, and S_7) respectively forming the event horizons for Events V, W, X, Y(?), and Z. The resulting differential offsets can be used to estimate the net vertical tectonic displacements (NVTD) per event. The NVTD is the measure of vertical slip at the fault that accounts for backtilting and antithetic faulting that is common along normal faults (Swan *et al.*, 1980). Although some minor backtilting was apparent for a couple of events, more importantly at the Carrizo Spring site, this measure also includes the effects of warping. Preferred estimates of NVTD per event range from 0.4 to 3.7 m (Table 2), indicating highly variable and non-characteristic behavior (discussed further in Section 3.1). The displacements are smallest for the two warping events, X and Y(?). Indeed, due to the small preferred offset for Event Y(?), and because independent stratigraphic and pedologic evidence is not as strong for this event, we recognize the uncertainty in the occurrence of this probable warping event by explicitly using a query in referring to it. Except for the youngest event, Z, uncertainties for displacements per event are large due to the difficulties in projecting horizons across the broad deformation zone, and the cumulative effect for calculating differential offsets. This results in a minimum estimate of 0 m for three of these events (V, X, and Y[?]). However, with the possible exception of Event Y(?), we believe that the independent evidence for the occurrence of Events V and X argues for some minimum offset larger than 0 m for these events.

It is also worth pointing out here that the cumulative throw on S_1 is 7.3 ± 0.5 m, similar to the 7.5 $\pm$ 1.0 m of NVTD measured across the Llano de Manzano surface on the scarp profile. At first glance this seems somewhat surprising in that offsets measured from scarp profiles on normal faults might be considered minimums due to expected post-faulting erosion of the footwall and deposition in the hanging wall. However, the stratigraphic record preserved in the Carrizo Spring trench shows little evidence for preferential erosion of the footwall aside from at the crest of the deformation zone. Additionally, although fault scarps provide excellent local sediment traps for eolian sands in the region (*eg*., Personius and Mahan, 2003; McCalpin *et al.*, in press), deposits can also blanket scarps, so that sediment is not only accumulating in the hanging wall but in the footwall too (*eg*., Units 4, 5, 6, and 7). These types of cover sands and intervening buried soils are likely present elsewhere on the Llano de Manzano surface and would provide excellent stratigraphic markers for paleoseismic studies of other faults scarps. The "down" side of these deposits is that they mute the geomorphic expression and can even bury faults, making fault scarps appear much more discontinuous and difficult to map. However, in retrospect, the geomorphic expression of the central HSF at the Carrizo Spring trench site is very consistent with the paleoseismic record exposed in the trench, with a very broad scarp resulting from a broad deformation zone of faulting and warping. Additionally, the maximum scarp angle was located at the zone of most concentrated faulting and warping. Scarp heights appear subdued due to little backtilting and a "bulge" of eolian deposits at the scarp base. The low maximum scarp angle and single bevel on the scarp profile may at first seem inconsistent with the 4 to 5 late Pleistocene events observed in the trench, but the single bevel is actually consistent with the dominant deformation style of warping and the small maximum slope-angle of 12° is likely more related to the angle of repose for deposition of eolian sand on the scarp rather than degradation of an older fault scarp. Thus, using morphometric comparisons of scarp height and maximum slope angle (*eg*., Bucknam and Anderson, 1979) do not appear to be reliable indicators of fault-scarp age in this environment. However, our observations also suggest that scarp profiles can still provide useful slip estimates despite the extensive eolian deposition.

A summary discussion of the structural, stratigraphic, and pedologic evidence for each surface-faulting/deformation event and the timing of events follows.

Event Z – Compelling structural, stratigraphic and pedologic evidence for this youngest surface-faulting event includes: (1) offset (including discrete slip on fault FZ5 and warping) of the top of Unit 10, and the buried soil S_7, 1.7 ± 0.3 m down-to-the-west; (2) fault terminations at the top of S_7; (3) an overlying unfaulted, colluvial-wedge deposit (Unit 11) adjacent to the maximum zone of faulting, which contained reworked carbonated nodules from Unit 10, blocks of Unit 10, as well as eolian sediment banked against the scarp created by Event Z; and (4) slight backtilting of Unit 10 to the east toward fault FZ5. Event Z occurred sometime before deposition of the distal portion of Unit 11 about 5 to 6 ka, and well after Unit 6 was deposited 24 to 29 ka, as not only were Units 7 through 10 deposited subsequently, but three intervening buried soils (S_4, S_5, and S_6) formed. However, as previously discussed some of the carbonate accumulation observed in S_5 and S_6 may be related to non-pedogenic processes, and so unfortunately the carbonate morphology of these soils are likely not reliable indicators of their age. Regardless, the general lack of soil development in Units 11 through 14 also suggest that Event Z occurred closer to 6 ka than 24 ka and is likely less than 15 ka.

Event Y(?) – The evidence for the penultimate event, Event Y(?), is strong but not conclusive as the apparent deformation associated with this event was limited to minor warping of Unit 8 and the buried soil, S_5 about 0.4 m down-to-the-west (Table 2). No discrete slip on any faults was observed. However, the angular relation between the buried soil S_5 and the underlying Units 6 and 7 suggest that this soil formed on a slope that was steeper than the one Units 6 and 7 were originally deposited on. This, and the apparent increased differential offset between S_7 and S_5 strongly suggests that this deformation event occurred after S_5 formed, but before Unit 9 was deposited. Indeed, Unit 9 appears to be a mix of scarp-derived colluvium (including reworked carbonate nodules) and eolian sediment banked up against the scarp after Event Y(?) occurred. The timing for Event Y(?) is very poorly constrained. The Btk horizon of S_6 formed on Unit 9 suggests that Event Y(?) was somewhat older than Holocene, and of course it is younger than deposition of Unit 6 about 24 to 29 ka.

Event X – Although Event X did not result in any apparent discrete slip on faults, fracturing and warping of Units 1 through 5 did result in 0.7 m of overall differential down-to-the-west NVTD between the tops of buried soils S_3 and S_5 (Table 2). Additionally, stripping of S_3 and the top of Unit 5 locally at the crest of the zone of maximum warping, along with the angular discordance between the base of Unit 5 and the overlying stratigraphic and pedologic horizons, also indicates that erosion occurred after a warping event of Unit 5 and S_3, but before deposition of Unit 6.

Based on previously discussed luminescence ages for Units 4 and 6 (Table 1), Event X occurred between 26.8 ± 2.4 ka and 30.2 ± 2.4 ka.

Event W – Compelling stratigraphic and structural evidence for Event W includes: (1) discrete offset of Units 1 through 3 along faults FZ1 through FZ3 along faults FZ1 through FZ4 with multiple fault terminations at the base of Unit 4 (the stratigraphic equivalent to the top of the buried soil S_2); (2) warping and faulting resulting in large differential down-to-the-west offset of 3.7 m between the top of buried soils S_2 and S_3 (Table 2); and (3) thickening and coarsening of Unit 4 on the downthrown side of faults FZ1, FZ2, and FZ3. Despite the large NVTD indicated for Event W, displacements on individual faults are small and distributed across multiple splays forming wide zones. Additionally, similar to other events, warping is also evident across a wide zone. One somewhat anomalous stratigraphic relation is the apparent thinning of Unit 4 west of st. 38 m, on the downthrown side of FZ4. This may be due to the presence of buried faults west of st. 43 that were not exposed in the trench. Alternatively, it may be due to stratigraphic uncertainties as the contact between Units 4 and 5 becomes more diffuse and affected by overprinting of soil carbonate west of st. 37 m. Regardless, our estimated 3.7 m of NVTD for Event W based on drill hole and trench data includes any offset on those potential buried faults. The timing of Event W is not tightly constrained, but it occurred sometime before deposition of Unit 4 (about 30.2 ± 2.2 ka), but well after deposition of Unit 2 (65 ± 6 ka), and after subsequent deposition of Unit 3 and formation of the Stage II carbonate horizon of S_2 on Unit 3.

Event V – Stratigraphic, structural, and pedologic evidence from the trench and boreholes indicates that the oldest event, Event V, resulted in about 0.8 m of NVTD of the top of S_1, the buried soil developed on Unit 1. Deformation is characterized by warping fracturing and discrete normal slip on FZ1, FZ2, and possibly FZ3. In addition to differential offsets, a slight thickening of Unit 3a on the downthrown side of faults FZ1 and FZ2 also supports minor slip on these faults during Event V. However, much of the deformation associated with Event V appears to have been accommodated by warping of Unit 1 and S_1, creating a depression at the base of the scarp where a sag pond deposited Unit 2. The timing of Event V is constrained to be well after Unit 1 was deposited (about 84 ± 6 ka), and the S_1 soil subsequently formed, but likely shortly before deposition of Unit 2 about 65.2 ± 5.6 ka.

Table 1
Infrared Stimulated Luminescence (IRSL)[1] Age Data for the Carrizo Spring Trench Across the Central Hubbell Spring Fault

Field No.[2]	Lab Sample No.	Stratigraphic Unit	U (ppm)	Th (ppm)	K_2O (%)	Polymineral IRSL 4-11 μ De (Grays)	Moisture Content (%)	Dose Rate (Grays)[3]	IRSL Age (ka)[4]	Comments
CHSF02-11	Not Analyzed	Unit 14 Eolian sand	—	—	—	—	—	—	—	Post-dates Event Z
CHSF02-10	UIC1088	Unit 13 Eolian sand	2.55 ± 0.41	8.08 ± 1.16	2.16 ± 0.02	24.30 ± 0.18	5 ± 2	4.02 ± 0.19	**6.0 ± 0.4**	Post-dates Event Z
CHSF02-8	UIC1056	Unit 11 Scarp-derived slopewash colluvium	3.53 ± 0.40	6.42 ± 0.75	2.13 ± 0.02	22.66 ± 0.24	5 ± 2	3.66 ± 0.17	**5.5 ± 0.4**	Post-dates Event Z
CHSF02-9	Not Analyzed	Unit 11 Scarp-derived slopewash colluvium	—	—	—	—	—	—	—	Post-dates Event Z
CHSF02-5	UIC1054	Unit 6 Loess	6.14 ± 0.59	9.64 ± 1.31	1.98 ± 0.02	124.84 ± 0.82	5 ± 2	4.47 ± 0.20	**24.9 ± 1.7**	Post-dates Event X and pre-dates Event Y(?)
CHSF02-7	UIC1089	Unit 6 Loess	5.76 ± 0.76	11.29 ± 2.06	2.05 ± 0.02	158.90 ± 1.12	5 ± 2	5.44 ± 0.22	**28.7 ± 2.4**	Post-dates Event X and pre-dates Event Y(?)
CHSF02-6	UIC1055	Unit 4 Eolian sand	3.09 ± 0.43	7.78 ± 1.19	1.93 ± 0.02	122.12 ± 0.48	5 ± 2	3.60 ± 0.16	**30.2 ± 2.2**	Post-dates Event W
CHSF02-1	UIC1091	Unit 2 Sag pond deposit	5.58 ± 0.75	11.29 ± 2.09	2.46 ± 0.02	362.43 ± 1.12	10 ± 3	5.56 ± 0.23	**65.2 ± 5.6**	Post-dates Event V and pre-dates Event W
CHSF02-2	Not Analyzed	Unit 2 Playa	—	—	—	—	—	—	—	Post-dates Event V
CHSF02-3	UIC1090	Unit 1b Eolian sand	3.10 ± 0.36	5.00 ± 0.91	2.02 ± 0.02	300.34 ± 2.97	10 ± 3	3.56 ± 0.16	**84.6 ± 6.0**	Pre-dates Event V and buried soil, S_l, on Llano de Manzano
CHSF02-4	UIC1053	Unit 1b Slopewash	2.86 ± 0.38	7.21 ± 1.09	2.14 ± 0.02	315.00 ± 1.16	10 ± 3	3.60 ± 0.17	**82.5 ± 6.0**	Pre-dates Event V and and S_l on Llano de Manzano

[1] All IRSL measurements were made using a multiple aliquot additive dose (MAAD) method, measuring blue emissions on the 4 to 11 micron polymineral fraction.
[2] Sample locations shown on Figures 6a and 6b.
[3] All errors are at one sigma and calculated by averaging the errors across the temperature range.
[4] Ages are rounded to the nearest 100 years and all errors are at one sigma.

Table 2
Estimates of Displacements Per Event on the Central Hubbell Spring Fault*

Surface Deformation Event	Event Horizon	Estimated Net Vertical Tectonic Displacement (m)	Basis for Estimate	Style of Deformation
Event Z	Top of buried soil S_7 (on Unit 10)	1.7 (1.4, 2.0)	Total apparent throw on top of S_7 (1.7 ± 0.3 m)	• Normal slip on FZ5 • Warping • Fracturing (?) • Backtilting (in FZ5 hanging wall)
Event Y(?)	Top of buried soil S_5 (on Unit 8)	0.4 (0, 1.2)	Differential offset between total apparent throw on top of S_5 (2.1 ± 0.5 m) and top of S_7	• Warping • Fracturing • Backtilting (?)
Event X	Top of buried soil S_3 (on Unit 5)	0.7 (> 0**, 1.8)	Differential offset between total apparent throw on top of S_3 (2.8 ± 0.6 m) and top of S_5	• Warping • Fracturing
Event W	Top of buried soil S_2 (on Unit 3)	3.7 (2.6, 4.8)	Differential offset between total apparent throw on top of S_2 (6.5 ± 0.5 m) and top of S_3	• Normal slip on FZ1 through FZ4 (and buried faults west of st. 43 m?) • Warping • Fracturing
Event V	Top of buried soil S_1 (on Unit 1)	0.8 (> 0**, 1.6)	Differential offset between total apparent throw on top of S_1 (7.3 ± 0.3 m) and top of S_2	• Normal slip on FZ1, FZ2, and possibly FZ3 (and buried faults west of st. 43 m?) • Warping • Fracturing

* All displacements are down to the west.
** See text for discussion.

3.1 RUPTURE HISTORY AND BEHAVIOR

The paleoseismic record of surface faulting and warping events that we deciphered for the central HSF at the Carrizo Spring site is summarized in Figure 8, including timing constraints and preferred NVTDs per event. We found stratigraphic, structural, and pedologic evidence that indicates at least 4, probably 5, surface-deforming earthquakes (Events V through Z) occurred since a stage II buried soil carbonate horizon formed on sediments that were deposited on the Llano de Manzano about 84 ± 6 ka. Also summarized on Figure 8 is the record of surface-faulting events deciphered by Personius *et al.* (2001) and Personius and Mahan (2003) for the western HSF at the Hubbell Spring site. They found evidence for 4 surface-faulting events that occurred after carbonate rinds formed on fan gravels about 92 ± 7 ka.

The available paleoseismic data for the HSF suggests complex rupture behavior that includes both independent rupture of the central HSF and coseismic rupture of the central and western splays of the HSF. Although the timing constraints are poor for the 1st Event on the western HSF and Events Y(?) and W on the central HSF, comparison of the paleoseismic records (Figure 8) indicates that the timing of the four largest events on the central HSF (Events Z, X, W, and V) overlaps with the timing of the past four events on the western HSF (4th through 1st Events, respectively), suggesting coseismic rupture of the western and central splays during larger events. The relatively large displacements for these events (1 to 2 m on the western HSF and 0.7 to 3.7 m on the central HSF), and the similar amounts of total throw since the oldest event (5 to 8 m on the western HSF versus 7.3 ± 0.5 m on the central HSF) also supports coseismic rupture of the two splays. Additionally, the buried soils that formed before each surface-deforming event appear to correlate between sites (e.g., our soil S_1 correlates to the buried soil on Unit 2 at the Hubbell Spring site, etc.), which also supports coseismic rupture. However, given the resolution of ages, even for the events with better age constraints (e.g., Event X on the central HSF and the 3rd Event on the western HSF), we acknowledge that we cannot preclude the possibility that the events on each splay may have occurred separately. Regardless, the smallest event on the central HSF, Event Y(?) does not appear to correlate to any events on the western HSF. Assuming that this event did indeed occur and that the record deciphered for the western HSF is complete, this indicates that the central HSF also does occasionally rupture independently from the western HSF in smaller events.

Further comparison of the two sites also reveals additional similarities and differences in the paleoseismic records that warrant discussion. Some of the more significant stratigraphic and structural similarities between the sites are: (1) the domination of eolian sedimentation along the scarps; (2) the wide distributed deformation zone of many faults across a single scarp; and (3) the box-like network of slope-parallel and subvertical carbonate-filled veins within the deformation zones. In regard to the first similarity, this study adds to a growing body of evidence (e.g., McCalpin *et al.*, in press; Personius and Mahan, 2003) for a stratigraphic signature along normal-slip intrabasin faults in the Rio Grande rift that is different than typical range-bounding normal faults. That is, deposits along intrabasin rift faults generally: (1) lack debris facies that are typically proximal to scarps of normal, range-bounding faults; (2) are dominated by eolian sediments banking up against the scarp rather than colluvial sediments derived from the scarp; and (3) are more lenticular-shaped and can extend completely across the scarp as compared to the classic triangular, colluvial wedge deposit that is primarily limited to the downthrown side of the fault. The success of luminescence dating the eolian and colluvial sediments at both HSF trench sites is promising for applications elsewhere in the Albuquerque basin, not only for fault studies but for all types of Quaternary studies, particularly where additional absolute age constraints are sorely needed to understand complex diachronous surfaces.

There are also important stratigraphic, pedologic and structural differences between the two HSF trench sites. One such difference is the greater degree of warping, including events that were solely characterized by warping (Events X and Y), at the Carrizo Spring site. These warping events have smaller displacements, suggesting smaller associated paleomagnitudes (discussed in Section 3.3).

Another important related structural difference between the two sites is in the displacements per event. Estimated displacements per event for the western HSF ranged between 1 and 2 m (Personius and Mahon, 2003). In contrast, displacements per event on the central HSF showed much more variability, ranging from 0.4 to 3.7 m (Figure 8). This indicates non-characteristic behavior for the central HSF and likely for the HSF overall, which has important implications for recurrence models used in probabilistic hazard analyses (Wong *et al.*, in press).

As originally defined by Schwartz and Coppersmith (1984), the characteristic recurrence model was based on paleoseismic observations along the San Andreas and Wasatch faults of similar-sized displacements per event. The characteristic model predicts fewer moderate-size events and generally results in lower hazard estimates than the traditional Gutenberg-Richter exponential frequency-magnitude relationship. Thus, the large variability in displacements for the central HSF implies non-characteristic behavior and higher associated hazard. We recognize that it is also possible that along-strike variations in displacement on the western HSF are such that a trench on this splay *at the same latitude* as the Carrizo Spring site would reveal complimentary displacements per event that would result in total displacements per event for both splays that were more similar in size. However, observed variations between displacements per event are so large that non-characteristic behavior is still strongly suggested regardless of possible along-strike displacement variations. For example, 2.6 m is an absolute minimum estimate for Event W (see Table 2, and assuming the 3rd Event shows little or no displacement on the western HSF at the latitude of the Carrizo Spring site). In contrast, assuming Event Y(?) did not occur on the western splay, 1.2 m is a maximum estimate for this event (Table 2), which still implies non-characteristic behavior for the fault zone overall.

Another difference between the sites that is worth noting is that since the youngest event occurred, sedimentation appears to have been more continuous and greater at the Carrizo Spring site. In contrast, the surface stabilized for some time at the Hubbell Spring site, allowing a stage I to II carbonate soil to form on Unit 6. We observed very little soil development since the youngest event occurred at the Carrizo Spring site and a more continuous rate of eolian sedimentation.

Finally, the most striking difference between the two sites is the probable occurrence of an additional event (Event Y) on the central HSF, and the more complex stratigraphic and pedologic sequence that predates and postdates this small warping event at the Carrizo Spring site. This highlights the long-recognized complex seismogenic relation between faults in the rift and the need for additional paleoseismic studies so that we can compare fault behavior both across transects and along strike in the rift. We need these coordinated studies to better understand rupture patterns for more accurate modeling in hazard evaluations, which presently use very simplistic rupture models due to the lack of data (Wong *et al.*, in press).

3.2 RECURRENCE AND SLIP RATES

Since we believe that the central HSF has ruptured both coseismically with, and independently from the western HSF, ideally we should calculate rates of activity for both types of behavior. First, we calculate recurrence intervals between coseismic rupture events. As timing constraints are best from the Hubbell Spring site for the youngest three events and from the Carrizo Spring site for the oldest event, we use this combination of data to determine the following intervals. Assuming a preferred age of 70 ka for Event V at the Carrizo Spring site, we calculate a preferred average recurrence interval between the past 4 coseismic ruptures of about 19 ky $\left(\frac{70\,\text{ky}-12\,\text{ky}}{3\,\text{intervals}}=19.3\,\text{ky}\right)$, with a range of 15 ky $\left(\frac{59\,\text{ky}-13\,\text{ky}}{3\,\text{intervals}}=15.3\,\text{ky}\right)$ to 24 ky $\left(\frac{84\,\text{ky}-11\,\text{ky}}{3\,\text{intervals}}=24.3\,\text{ky}\right)$. For individual recurrence intervals we cannot improve on the original estimates of 17 and 27 ky by Personius and Mahan (2003) for the two youngest intervals (Figure 8). For the interval between the 1st (= Event V) and 2nd (= Event W) Events, we estimate a preferred recurrence interval of 14 ky, assuming Event V occurred 70 ka and Event W occurred 56 ka (Figure 8).

Although there is evidence for temporal clustering of surface-faulting events on many faults in the Rio Grande rift (e.g., Foley *et al.*, 1988; Machette, 1998), we see no evidence for clustering of coseismic rupture events along the HSF. Individual recurrence interval estimates of 14 to 27 ky are similar to average intervals of 19 (+5, -4) ky, and soils developed between events are consistent with these intervals.

Given only one observation for an independent event on the central HSF, we cannot calculate recurrence intervals for this type of behavior. However, we can provide some constraints and insights into the frequency of these events. The occurrence of independent events on the central HSF is obviously less frequent than coseismic ruptures of the western and central splays, with recurrence intervals apparently having exceeded 60 ky based on the minimum amount of time for the open interval before the occurrence of Event Y(?).

For comparison, and because seismic hazard analyses often do not consider rupture behavior alternatives (e.g., Frankel *et al.*, 2002), we also calculate the average recurrence interval between all surface-deforming events on the entire HSF, regardless of the type of behavior. For this estimate, we simply include Event Y(?), which adds another interval. This yields a preferred average recurrence interval between all surface-deforming events of 15 ky, with a range of 12 ky to 18 ky. These recurrence interval estimates are not significantly shorter than those between coseismic rupture events, especially given the uncertainties.

Calculating cumulative slip rates for the HSF is complicated by the fact that the two trench sites are located over 18 km apart along-strike, and displacements on a fault can vary significantly along strike. Assuming that the displacements measured at each trench site are representative averages for each fault splay, we can simply add displacements from each site to estimate cumulative slip rates for the entire HSF. However, another complication arises from the lack of data on the eastern HSF. Although this splay shows no evidence of late Quaternary offset at the latitude of the Carrizo Spring site, this is not necessarily the case further north, at the latitude of the Hubbell Spring site. Therefore, all of our cumulative slip rate estimates should be considered minimums, pending further investigation, as our estimates do not consider late Quaternary slip on the eastern HSF.

First, we estimate the average vertical slip rate over the past 4 complete seismic cycles for the entire HSF. Again, assuming the oldest event (Event V) occurred 70 ka, we estimate a preferred rate of 0.18 mm/yr for the HSF overall $\left(\frac{4.7\,\mathrm{m}+1.7\,\mathrm{m}+0.4\,\mathrm{m}+3.7\,\mathrm{m}}{70\,\mathrm{ky}-12\,\mathrm{ky}}\right)$. Of the 10.5 m of vertical slip associated with these complete seismic cycles, over 96% (10.1 m) occurred as coseismic rupture of the western and central splays, yielding an average slip rate of 0.21 mm/yr for the past 3 complete seismic cycles of coseismic rupture.

Next, we can calculate slip rates for individual seismic cycles. These rates for the past 4 complete seismic cycles are shown in the slip rate diagram in Figure 9. Note that we consider a complete seismic cycle to include the time interval of strain build-up preceding an event with the strain release (or displacement) for that event. This is consistent with Reid's model of elastic rebound theory for earthquake occurrence on faults. Note that since we do not know the time interval of strain build-up associated with the 2.8 m of displacement in the oldest event (0.8 m on the central HSF and 2 m on the western HSF), this is not a complete seismic cycle and we do not calculate an associated slip rate. Thus, the first (and oldest) complete seismic cycle is the 14 ky interval of strain-build associated with 4.7 m of strain release, the combined displacements for Event W on the central HSF and the 2nd Event on the western HSF. The preferred slip rate for this seismic cycle is 0.34 mm/yr $\left(\frac{4.7\,\mathrm{m}}{70\,\mathrm{ky}-56\,\mathrm{ky}}\right)$. This is nearly double the average rate but is still not as high as the preferred rate calculated for the youngest (4th) complete seismic cycle, which is 0.46 mm/yr $\left(\frac{3.7\,\mathrm{m}}{20\,\mathrm{ky}-12\,\mathrm{ky}}\right)$. In contrast, preferred rates for the 2nd and 3rd complete seismic cycles are as much as an order of magnitude lower at 0.063 $\left(\frac{1.7\,\mathrm{m}}{56\,\mathrm{ky}-29\,\mathrm{ky}}\right)$ and 0.044 $\left(\frac{0.4\,\mathrm{m}}{29\,\mathrm{ky}-20\,\mathrm{ky}}\right)$ mm/yr, respectively. We note that low slip rates are associated with both types of rupture behavior (independent and coseismic) and result regardless of the timing uncertainties for Event Y(?). Thus, although recurrence intervals have remained relatively consistent through time, cumulative slip rates for the HSF appear to have varied significantly due to large variations in displacements per event, or non-characteristic behavior. This may have important implications for hazard evaluations in the rift.

Interestingly, order of magnitude variations in slip rates through time have been observed on many faults throughout the Rio Grande rift (McCalpin, 1995; Machette, 1998). McCalpin (1995) observed that short-term slip rates are generally much higher than long-term rates for dozens of faults. These variations have possibly been attributed to variations in the frequency of occurrence of earthquake events (i.e., temporal clustering) or even variation in the quality or type of data being used (e.g., Wong and Olig, 1998; Machette, 1998). Results from this study indicate that non-characteristic fault behavior can also cause order-of-magnitude variations in slip rates through time. Perhaps other faults in the rift also show large slip-rate variations through time due to non-characteristic behavior. If so, we are underestimating the hazard along these faults as recurrence models used in hazard analyses typically favor characteristic behavior (e.g., Wong *et al.*, in press) or even exclude non-characteristic models altogether for individual faults (Frankel *et al.*, 2002).

3.3 PALEOMAGNITUDE ESTIMATES

Many empirical relations have been developed to estimate paleomagnitudes from various fault parameters, such as length and displacement per event (see for example, dePolo and Slemmons, 1990 for discussion). Table 3 shows paleomagnitude estimates for the HSF using various recent empirical relations based on surface-rupture length (L), average (AD) or maximum (MD) along-strike displacement per event, and slip rate (SR). Paleomagnitude estimates for ruptures of the entire HSF vary from M_w 7.0 to 7.5, whereas estimates for independent rupture of the central HSF alone vary from M_w 6.6 to 7.0.

The estimates for rupture of the entire HSF are slightly higher than previous M_s or M_w estimates of 6.8 to 7.1 by Personius and Mahan (2003). This is due to our results suggesting coseismic rupture of the western and eastern splays, which generally results in larger displacements depending on how site data are considered. This is discussed further below, but first we note a caveat on paleomagnitude estimates based on length. Recent mapping (Maldonado *et al.*, 1999) and geophysical studies (e.g., Grauch, 2001) suggest that the western and central plays of the HSF may be longer than previously recognized (see Section 1.2 for discussion). This implies that our paleomagnitude estimate of M_w 7.0 based on surface rupture length alone (Table 3) may be best considered as a minimum, especially for coseismic rupture events.

Development of empirical relations used to estimate paleomagnitudes from displacements did not explicitly consider or account for zones of subparallel faults with multiple splays, such as the HSF. Therefore, it is not clear whether adding displacements per event for each splay is appropriate or not, but it does seem the most logical approach to estimating paleomagnitudes for coseismic rupture of the western and central HSF. Cumulative displacements for the four coseismic ruptures are (oldest to youngest): 2.8 m, 4.7 m, 1.7 m, and 3.7 m. Assuming 1.7 m is a minimum estimate and 4.7 m is a maximum estimate for the cumulative AD for the entire fault zone results in paleomagnitudes of M_w of 7.1 to 7.5, respectively (Table 3). Assuming a MD of 4.7 m yields an estimated M_w of 7.2. In comparison, assuming an AD of 0.4 m yields an estimated M_w of 6.6 for independent rupture of the central HSF alone.

Table 3

Paleomagnitude Estimates for Surface-Faulting Earthquakes on the HSF

Fault Parameter[1]	**Moment Magnitude (M_w)**	
	Wells and Coppersmith(1994)[2]	**Anderson et al. (1996)**[3]
L=43 km[4]	7.0	
L=43 km, SR=0.2 mm/yr[5]		7.2
MD=4.7 m[6]	7.2	
AD=1.7 m[7]	7.1	
AD=4.7 m[8]	7.5	
AD=0.4 m[9]	6.6	

1 All surface rupture lengths (L) measured straight line, end to end. Slip rate (SR) is average vertical rate.

2 Relations for all type of slip: Mw=5.08+1.16*log (L)σ, σ=0.28; Mw=6.93+0.82*log (AD), σ=0.39; Mw=6.69+0.74*log (MD), σ=0.04.

3 Mw=5.12+1.16*log (L)-0.20 log (SR).

4 Based on mapping by Machette and McGimsey (1983) and is applicable for both the entire HSF and central HSF.

5 Based on data in Section 3.2.

6 Maximum observed displacement for coseismic rupture of the western and central HSF; here assumed to be representative of the maximum along-strike displacement.

7 Minimum observed displacement of coseismic rupture of the western and central HSF; here assumed to provide a lower bound of AD.

8 Maximum observed displacement for coseismic rupture of the western and central HSF; here assumed to provide an upper bound of AD.

9 Preferred displacement for Event Y(?); applies to independent rupture of central HSF only.

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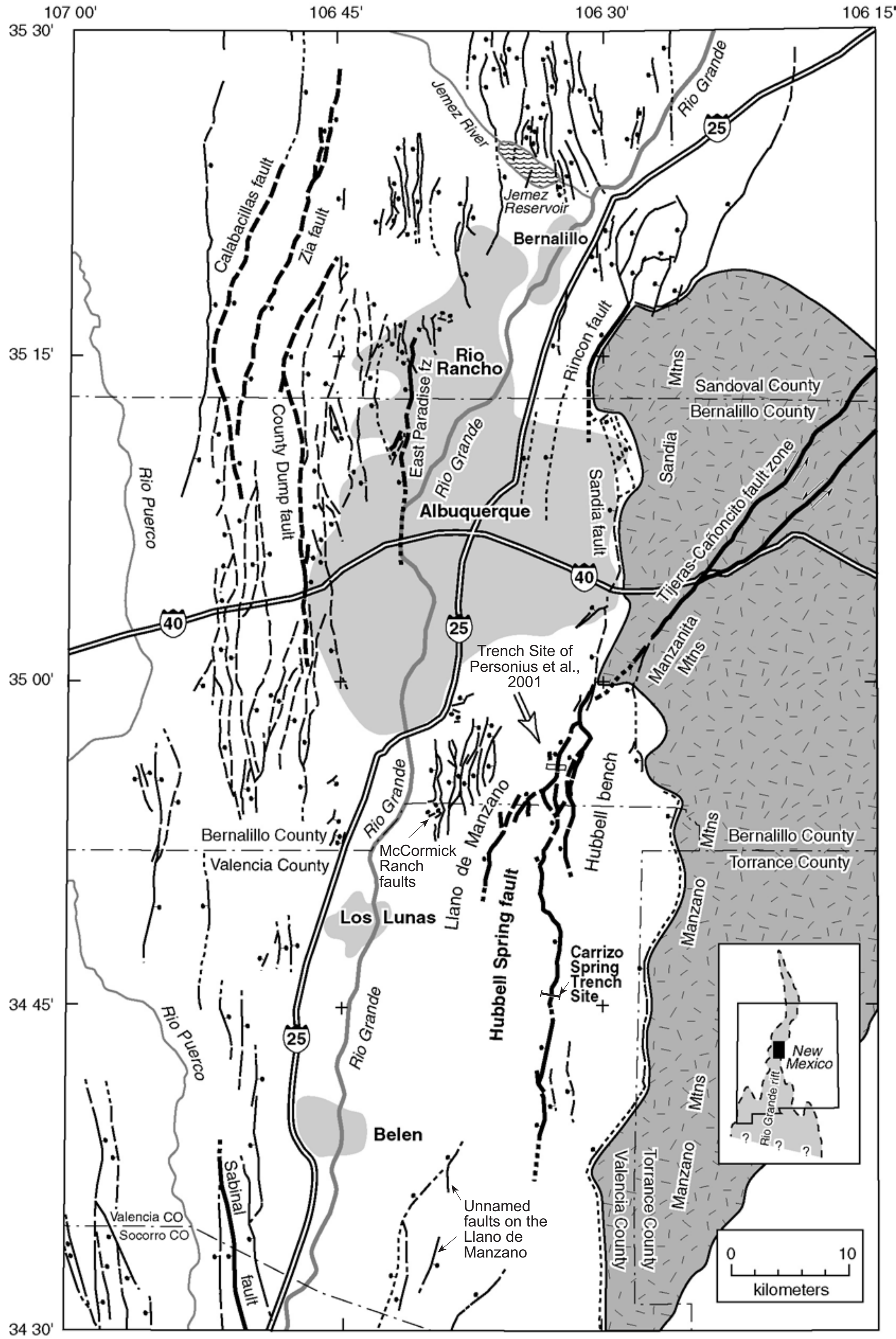
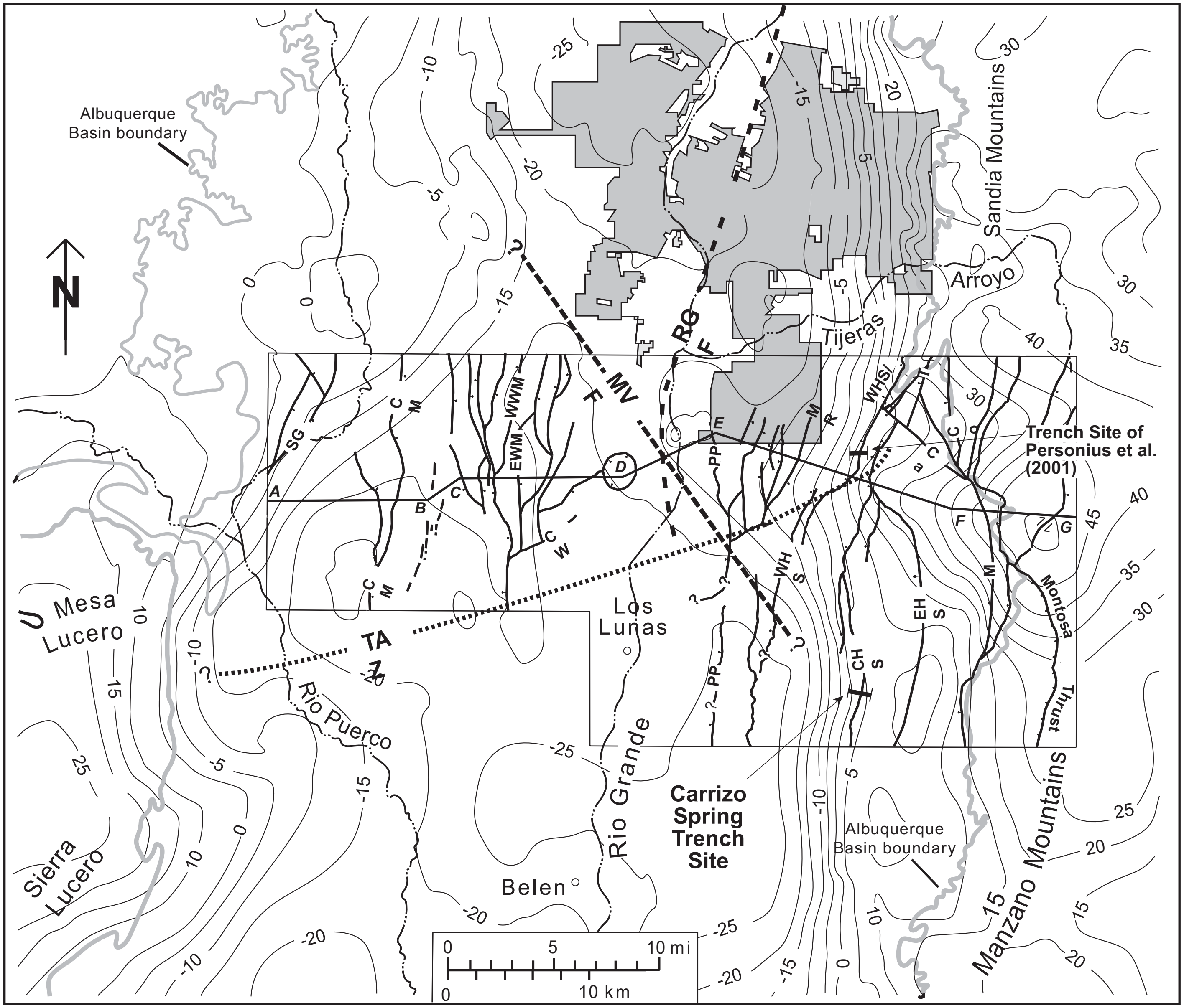


Source: Personius and Mahan (2003)

Note: Heavier lines distinguish faults with known late Quaternary offset.

URS	Project No. 26813901 Hubbell Spring Fault	KNOWN AND SUSPECTED QUATERNARY FAULTS NEAR ALBUQUERQUE	Figure 1

26813901.00000/042503/gos



LEGEND

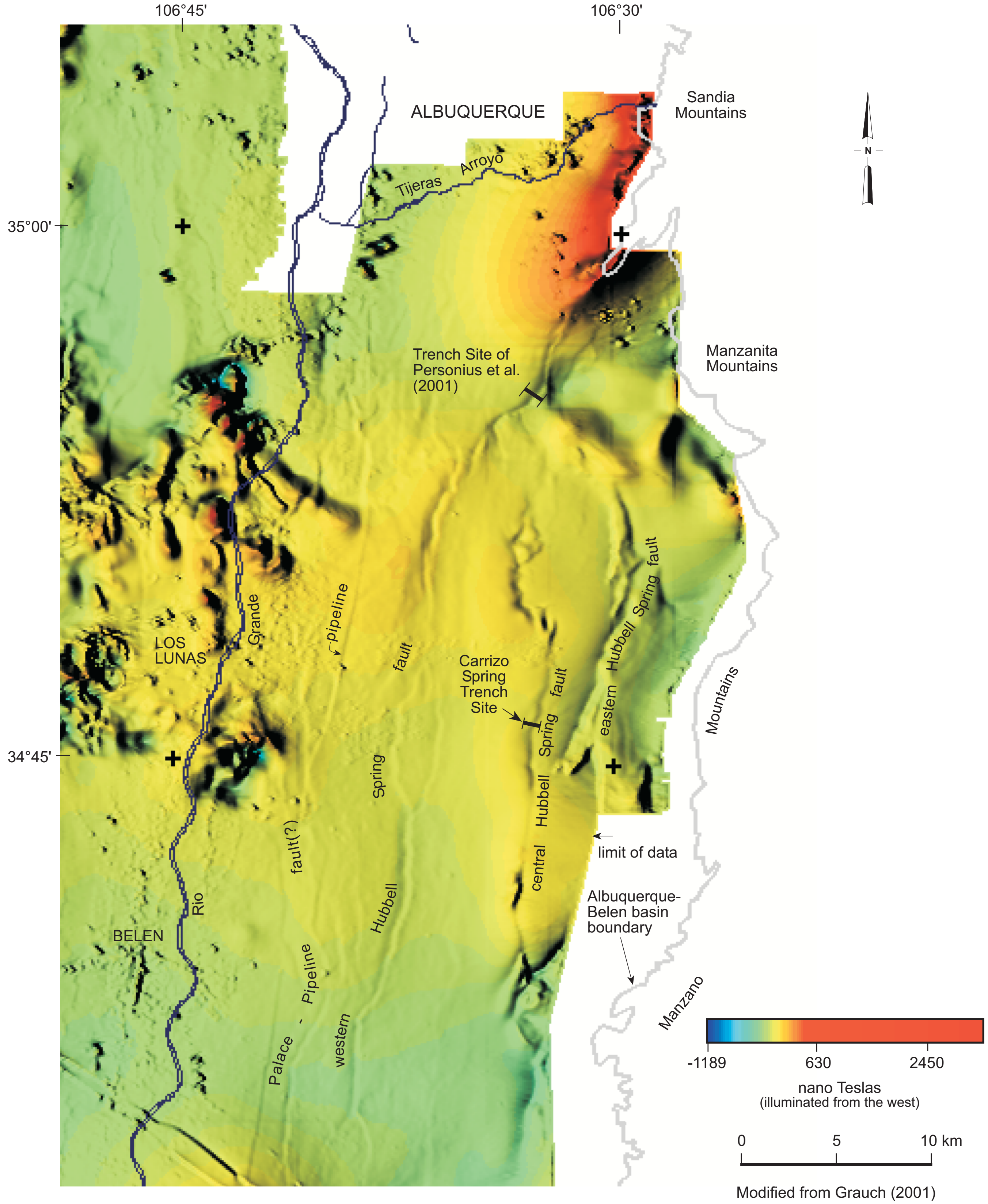
WHS - Western Hubbell Spring fault
CHS - Central Hubbell Spring fault
EHS - Eastern Hubbell Spring fault
PP - Palace-Pipeline fault
MR - McCormick Ranch faults
M - Manzano fault

5 Contours are 5 mgals

Modified from Maldonado et al. (1998). See their Figure 9 for complete explanation.

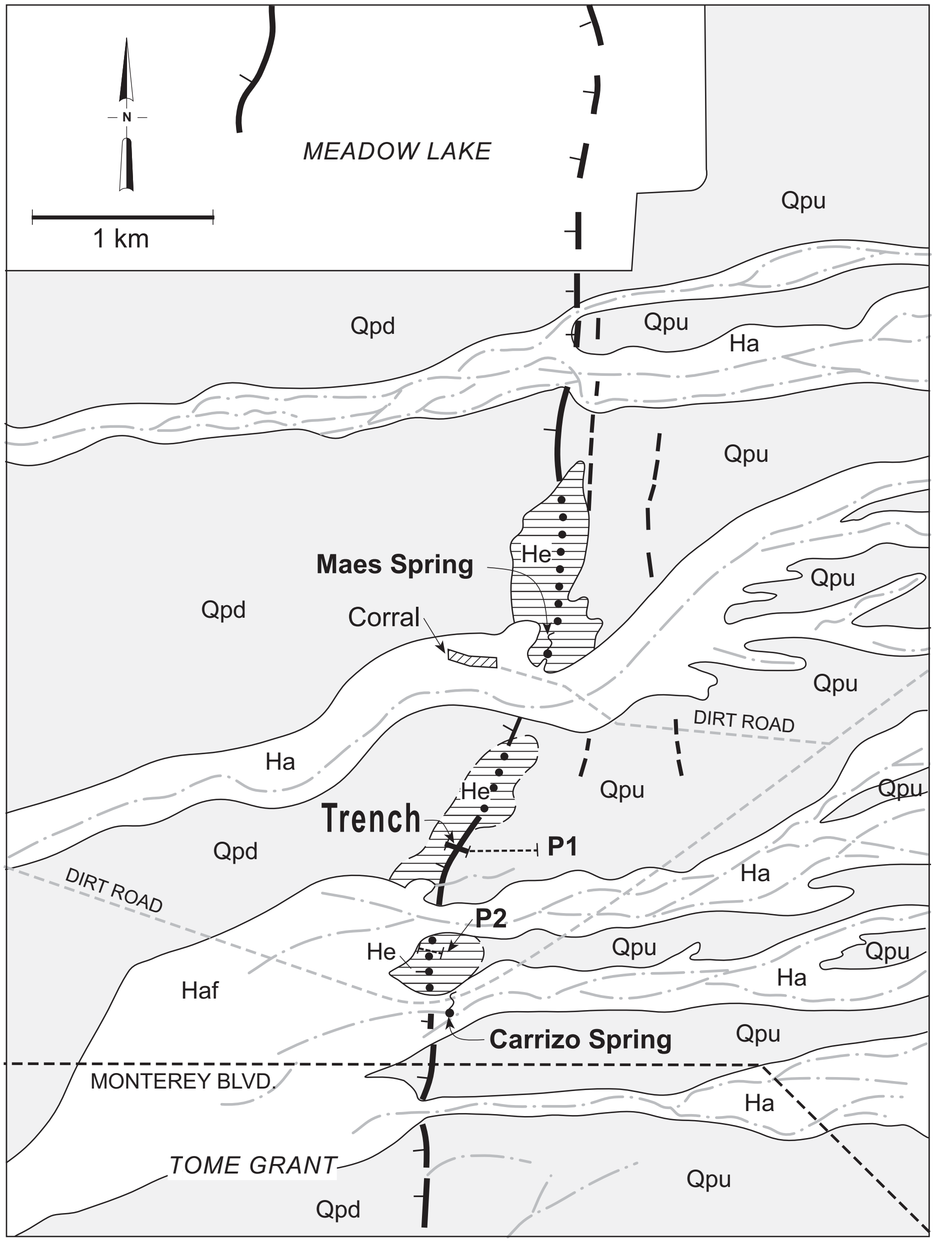
URS	Project No.26813901 / Hubbell Spring Fault	ISOSTATIC RESIDUAL GRAVITY ANOMALY MAP OF THE HUBBELL SPRING FAULT	Figure 2

26813901.00000/050203/gos



URS	Project No. 26813901 Hubbell Spring Fault	SHADED-RELIEF AEROMAGNETIC MAP OF THE HUBBELL SPRING FAULT AREA	Figure 3

26813901.00000/050203/gos



EXPLANATION

Fault scarp, bar on downthrown side, dotted where partially buried

Tonal lineament

Ephemeral drainage

Ha/Haf — Holocene channel and fan alluvium

He — Holocene eolian sand

Qp — Piedmont deposits of the Llano de Manzano (part of the Sierra Ladrones Formation)

d - on downthrown side of central Hubbell Spring fault (with thicker eolian cover sand)

u - on upthrown side of central Hubbell Spring fault (more dissected and with thinner eolian cover sand)

P1 — Scarp Profile

URS

Project No. 26813901

Hubbell Spring Fault

SURFICIAL GEOLOGY OF THE CARRIZO SPRING TRENCH SITE CENTRAL HUBBELL SPRING FAULT

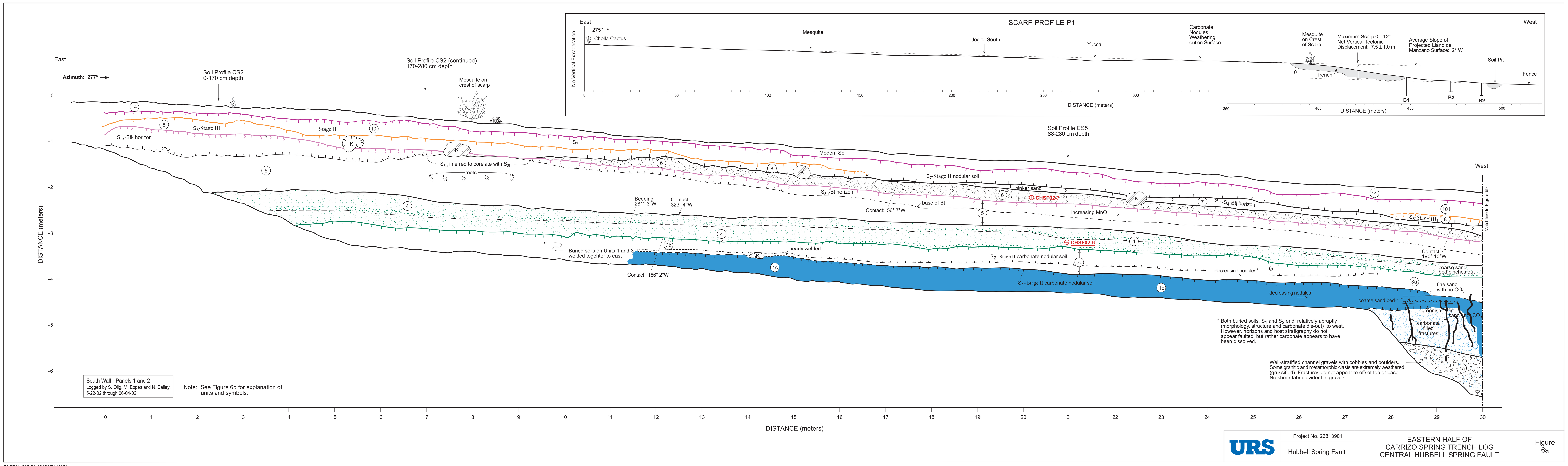
Figure 4

(a) Looking Southeast

(b) South Wall,
Zone of Warping

(c) South Wall, Fault FZ1

URS	Project No. 26813901 Hubbell Spring Fault	PHOTOGRAPHS OF THE CARRIZO SPRING TRENCH	Figure 5



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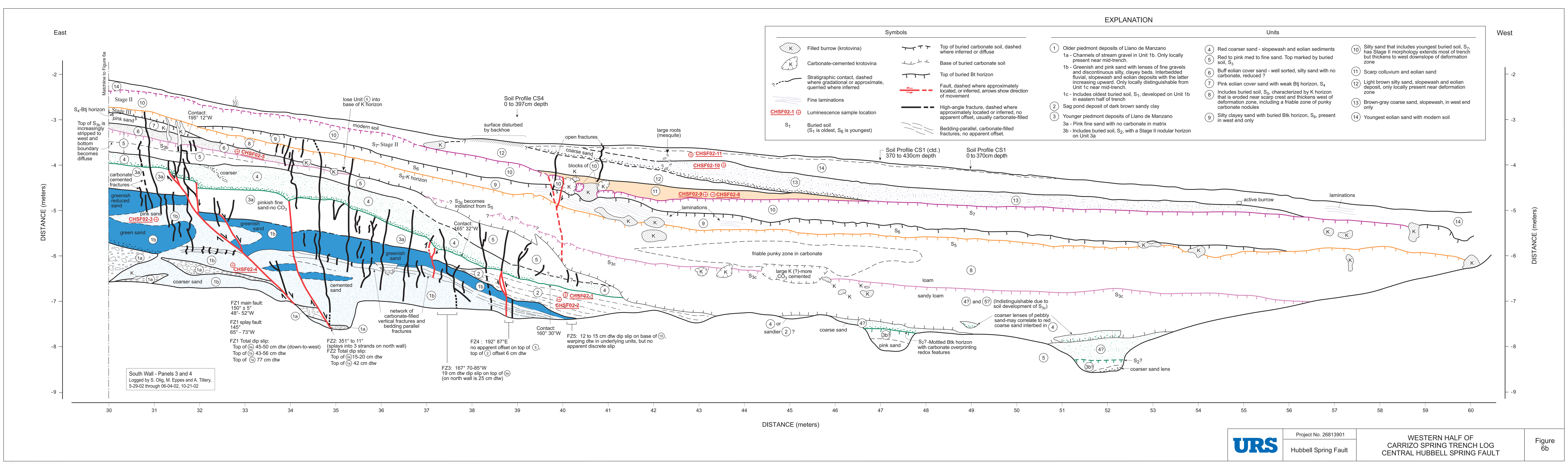

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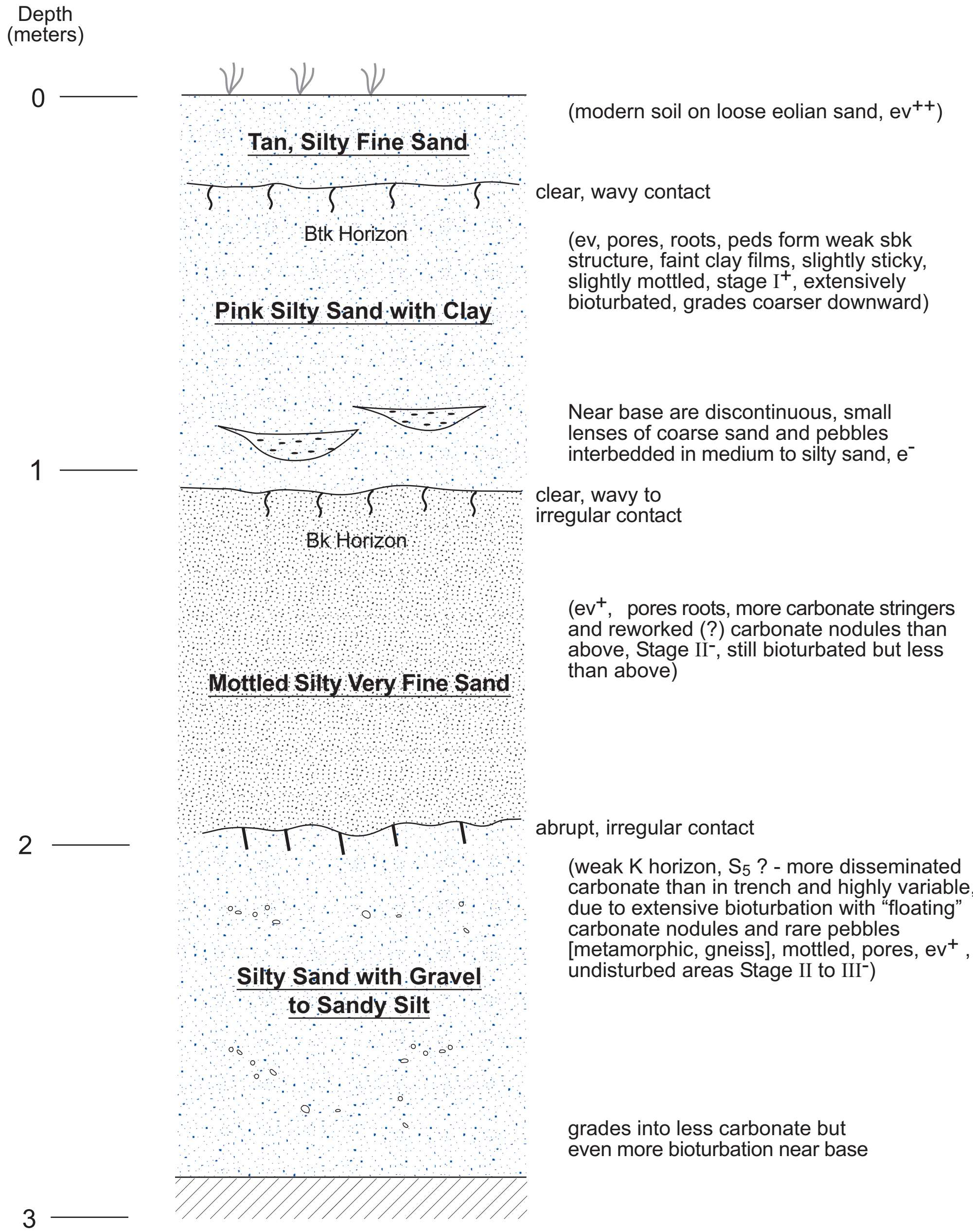


URS

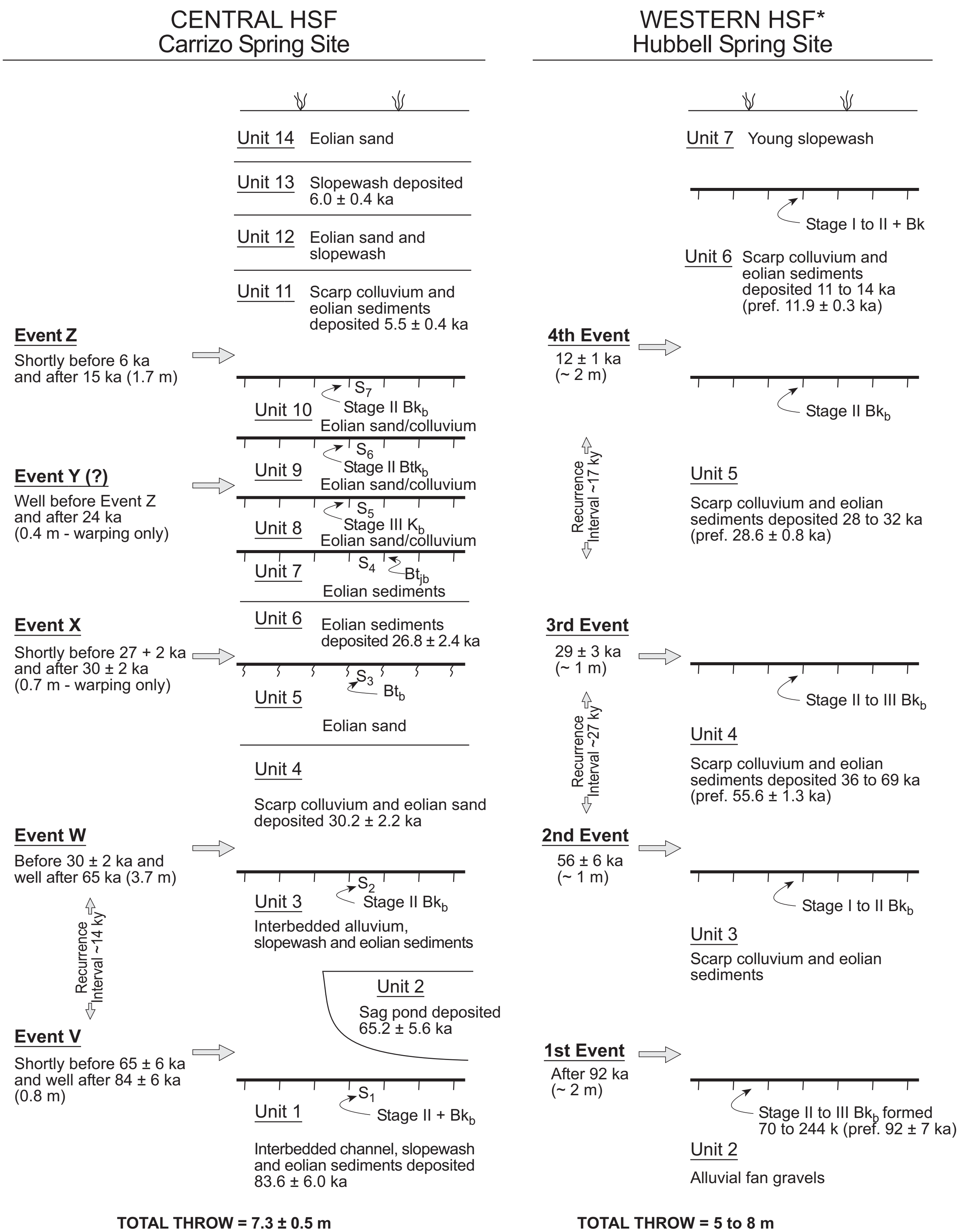
Project No. 26813901

Hubbell Spring Fault

SOIL PIT LOG
CARRIZO SPRING TRENCH SITE
SOUTH WALL

Figure 7

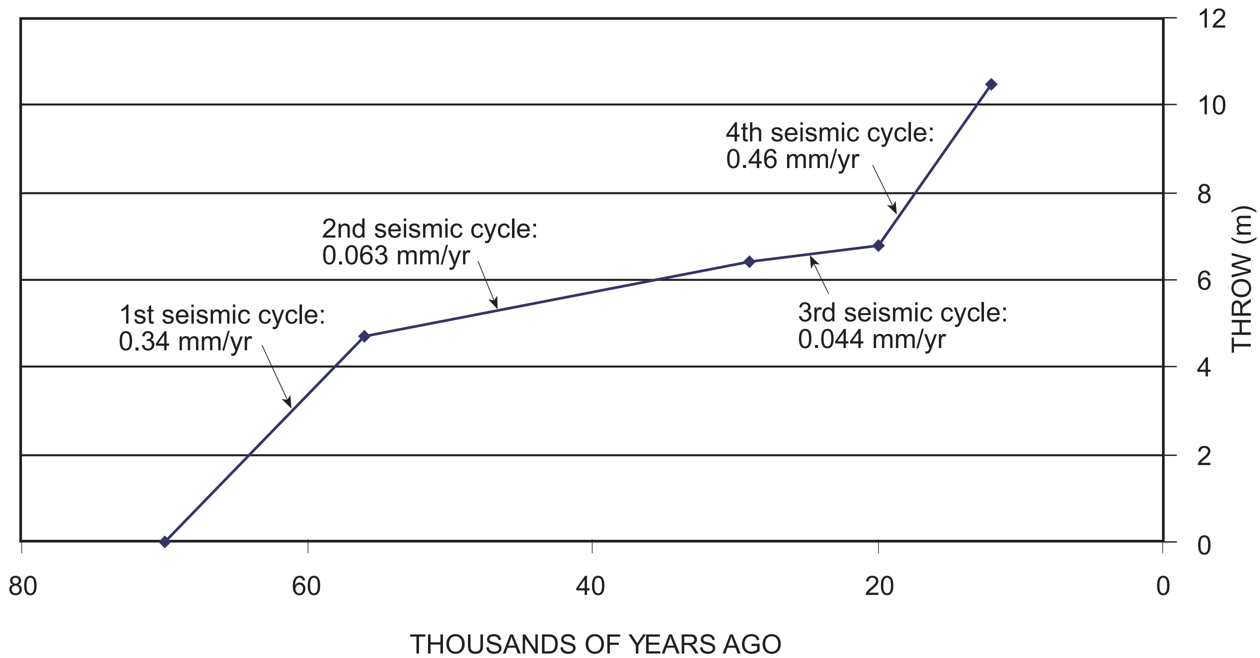
26813901.00000/041103/gos



* Data Sources: Personius *et al*., 2001; and Personius and Mahan, 2003

URS	Project No. 26813901 Hubbell Spring Fault	COMPARISON OF THE PALEOSEISMIC RECORDS OF THE CENTRAL AND WESTERN HSF	Figure 8

26813901.00000/111903/gos



URS	Project No. 26813901	CUMMULATIVE VERTICAL SLIP RATES FOR THE HSF	Figure 9
	Hubbell Spring Fault		

Appendix A

Lithologic Unit Descriptions

UNIT DESCRIPTION

Initials: SSO/AT

USGS NEHRP 51-F011035.00 00000

Project: Central Hubbell Spring fault

Date: 6-3-02

Location: Carrizo Spring Trench

Depth: st # 29

Unit: 1a

Genetic Name: Fluvial Channel Gravels interbedded in Unit 1b

PSA:		**% Total**	**Rounding**	**Composition**
>20cm	Boulders	0 to 5	rounded	~~pre cambrian~~ gneiss/greenstone/granite
	Cobbles	5 to 15	sub-r	" "
	Gravel	55	sub-ang	felspar/qtz/lithics/carbonate fragments
	Sand	20-25	sub-r	matrix (<2mm) is sandy loam to loamy sand
	Silt	5-10		
	Clay			

Max. Size: 32 cm **Average Size:** med. pebbles

USCS: cobbly sandy gravel with boulders to sandy gravel with cobbles

	Dry		**Wet**	
Color:	7.5YR 6/6	reddish yellow	7.5YR 5/6	Strong brown

Plasticity: none **Dry Strength:** so **Dilatency:** none

Bedding: weak imbrication of coarse gravels + cobble to NE Well-stratified, lenses + top of channels dip 15° to 18° W

Sorting: moderate to good **Clast or Matrix Supported**

Contacts: clear

Thickness: 0 to 80 cm (min. - lower contact not exposed)

Cementation: poorly cemented **HCl rx:** mod-weak

Carbonate: some zones of intergranular carbonate

Other: Roots Rootlets Root Pores Organics Staining

Vesicles Pedogenic Horizons Fe Mg

- lense shape, upper contact is buried under bench - lower contact pinches out @ st 31
- Entire unit dips down to west (apparent dip = 12°)
- slightly interfingered w/ sandy unit 1b (some laminated sand lenses)
- metamorphic + granitic clasts highly weathered
- weak imbrication of clasts suggests flow to SW
- 1a does not appear offset where S_1 and S_2 die out (between st. 28 and 31 m).

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UNIT DESCRIPTION

Initials: AT

Project: Central Hubbell Spring fault

Date: 6-3-02

Location: Carrizo Spring Trend

Depth:

st # 31

Unit: 1b (below dk blue dots w/ white)

Genetic Name: Greenish and pinkish interbedded fluvial and eolian sand

PSA:		% Total	Rounding	Composition
	Boulders	0		
	Cobbles	0		
	Gravel	trace	rd to sub. rd	floaters of qtzite + carbonate nodules
	Sand	75-85	sub-R	~~qtz/kspar/oxides/mica~~ matrix is loam to sandy loam (generally)
	Silt	15-25		
	Clay			

Max. Size: ~~fkskrsnop~~ to mU (2 cm) **Average Size:** lower fine sand

USCS: silty sand with clay to sand

horizon:		Dry		Wet	
greenish	**Color:**	10YR 7-3	Very pale brown	10YR 6/3	pale brown
pinkish		7.5YR 6/6	reddish yellow	7.5YR 5/6	strong brown

Plasticity: ps **Dry Strength:** sh **Dilatency:** medium

Bedding: flat lams visible in some sandy sections, occassional clay rich lenses (5-10 cm thick, x ~20-40 cm long) that are wavy or deformed

Sorting: overall very well sorted but some beds less so **Clast or Matrix Supported**

Contacts: lower-clear to gradual with 1a; upper-clear to gradual

Thickness: 2 m (min. - base not exposed)

Cementation: cw **HCl rx:** matrix: none to moderate (decreases ↓ & →W); carbonate filled fractures - strong

Carbonate: filling fractures & localized pockets of mottling near top

Other: Roots Rootlets Root Pores (in fractures) Organics Staining + some limited staining near st. 39

Vesicles Pedogenic Horizons Fe/Mg

carbonate nodules of S_1 that are in 1c appear dissolved from 1b (some ghost nodules near st. 29 to 30 m)

- very gradational contact w/ Unit 1c at st. 28 to 29 m
- reduced (green) sand
- includes many horizontal & vertical $CaCO_3$ filled fractures
- includes horizontal ribbon (10 cm) zone of dense horizontal fractures
- includes several small (gravelly) channel deposits ~15 cm thick + 60 cm long
- re-dox red-green color variations - redder in lower section
- clearly offset by faults FZ1 through FZ4
- overall fines upward

UNIT DESCRIPTION

Initials: AT

Project: Central Hubbel Spring fault

Date: 6.3.02

Location: Carrizo Spring Trench

Depth:

Unit: 1c (below dk blue dots - East of deformation zone) st # 21

Genetic Name: lower nodular soil; S_1; on eolian sand and slopewash

PSA:	% Total	Rounding	Composition
Boulders	0		
Cobbles	0		
Gravel	trace		occ. floaters
Sand	65-70		qtz, kspar, oxides, mica
Silt	30-35		matrix (<2mm) is loam to sandy loam
Clay			

Max. Size: 1.5cm **Average Size:** very fine sand

USCS: clayey silty sand

.62mm - 100mm - sandy loam

	Dry	Wet
Color:	10YR 8/3 very pale brown	10YR 6/4 light yellowish brown

Plasticity: ps **Dry Strength:** h **Dilatency:** medium

Bedding: - none apparent thru overprinting of soil development

Sorting: very-well sorted **Clast or Matrix Supported**

Contacts: upper - clear, wavy; lower - not exposed

Thickness: 40 - 50cm (min? - base not exposed where best developed)

Cementation: cw - carbonate **HCl rx:** very strong ev+

Carbonate: nodules stage II+

Other: Roots Rootlets Root Pores common Organics Staining

Vesicles common Pedogenic Horizons = S_1 Fe Mg

- S_1 - stage II+* buried soil w/ carbonate nodules in fine grained parent material
- occaissional narrow lenses (<5cm thick) of course sand/gravel
- carbonate nodules are completely disolved away by st. #29 (becomes unit 1b to W) however "ghost" nodules remain visible for ½ meter - (grey stain)
- sticky to slightly sticky
- rare verticle fractures that cut unit.

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* Note where S_1 is welded w/ overlying S_2 east of st. 11.5 m, becomes stage III (K horizon)

UNIT DESCRIPTION

Initials: SSO & ACT

Project: Central Hubbell Spring fault **Date:** 6-3

Location: Carrizo Spring Trench **Depth:**

Unit: 2

Genetic Name: Small playa (at base of scarp)

PSA:	% Total	Rounding	Composition
Boulders	0	—	
Cobbles	0	—	
Gravel	0	—	
Sand	10-15		
Silt	40		
Clay	55		

Max. Size: v. fine sand **Average Size:** silt → clay

USCS: Sandy silty clay (silty clay loam)

Color: Dry: 7.5 YR 6/4 light brown Wet: 7.5 YR 5/6 strong brown

Plasticity: plastic **Dry Strength:** =Consitence extremely hard **Dilatency:** slow

Bedding: Weakly thinly bedded with v. fine sand partings

Sorting: Very well sorted Clast or Matrix Supported

Contacts: bottom clear and interfingers with underlying sand (1b)
upper clear but gradational with both (4) and (5).

Thickness: Varies from 0 to 60 cm

Cementation: very well cemented **HCl rx:** matrix none

Carbonate: matrix none, a few nodules, coats on some veins & pores

Other: Roots, some Rootlets, Root Pores, Organics ?, Staining, Vesicles, wthd* Pedogenic Horizons ? no obvious carbonate soil - what happened to S_2? Dissolved? Appears so. Fe Mg

slightly mottled w/ MnO and rare carbonate

Bedding at st. 38.5: 333° 37°W

*sticky; weak clay films and sbk structure.

pinches out in both directions (st. 37 - 43? Western contact not completely exposed)

appears warped down to west

very cracked unit - dessication cracks

UNIT DESCRIPTION

Initials: SSO

Project: Central Hubbell Spring fault

Date: 6-3-02

Location: Carrizo Spring Trench

Depth:

Unit: 3a

Genetic Name: Eolian sand and slopewash

PSA:		**% Total**	**Rounding**	**Composition**
	Boulders	0		
	Cobbles	0		
	Gravel	Rare	Rd.-Sub Angular	Carbonate nodules Qtzte ("floating")
	Sand	70-80		
	Silt	15-20		
	Clay	5-10		

Max. Size: 15mm **Average Size:** med. to fine sand

USCS: Silty sand w/ clay to silty sand

	Dry	**Wet**
Color:	"Red" (coarser beds) 7.5 YR 6/4 light brown	7.5 YR 5/3
	"Green" (finer beds) 10 YR 7/3 very pale brown	2.5 Y 6/2 Light brownish gray

Plasticity: slightly plastic to non-plastic **Dry Strength:** moderate **Dilatency:** rapid

Bedding: weak to none, pockets and thin beds of coarser sand (usually pink), thin to thick beds of finer sand & silt (usually greenish)

Sorting: well sorted to very well sorted **Clast or Matrix Supported**

lower **Contacts:** distinct w/ Unit 12 ("cow wallow"); highly variable w/ Unit 1b (distinct to unclear)

Thickness: Thickest near FZ 2 (60cm); thinnest near st. 28½m (30cm)

Cementation: CSt **HCl rx:** none (matrix)

Carbonate: filled fractures near faults; some nodules near top (others are floater clasts) lots of gyp near fault

Other: Roots Rootlets Root Pores Organics nodules & Staining and to E limonitic along top

Vesicles Pedogenic Horizons Fe Mg

- Intraclasts and floating clasts (gravel to coarse sand)
- Gravel lens offset on FZ 1 38 to 40 cm, dtw (cf 39 cm dtw offset of cemented green sand dip slip bed in Unit 1b)
- Same strat. unit as 3b but lacking soil (stripped & dissolved near FZ1 and to W →)
- Fracture + fault terminations at top. Clearly faulted and warped.

UNIT DESCRIPTION

Initials: SSO

Project: Central Hubbell Spring fault **Date:** 6-3-02

Location: Carrizo Spring Trench **Depth:** St. 24.5m

Unit: 3b (between dk green & blue)

Genetic Name: Eolian sand and slopewash with buried soil, S_2

PSA:		**% Total**	**Rounding**	**Composition**
	Boulders	0		
	Cobbles	0		
	Gravel	Trace	sub.rd-sub.ang.	carbonate nodules
	Sand	60-75	subrd-subang.	
	Silt	20-25		
	Clay	5-15		

Max. Size: fine gravel **Average Size:** v. fine sand

USCS: clayey silty sand (sandy loam to loam)

Dry very mottled **Wet**

Color: 7.5YR 7/3 to 6/4 pink to brown 7.5YR 5/3 brown

Plasticity: plastic **Dry Strength:** medium (hard) **Dilatency:** rapid to slow

Bedding: homogeneous to weakly bedded with coarser pockets and discontinous beds

Sorting: very-well sorted/fines grossly upward **Clast or Matrix Supported**

Contacts: lower w/ Unit 1c: abrupt to distinct; irregular flat to slightly W dipping

Thickness: Very uniform; in E end of trench only 50-60cm

Cementation: CS **HCl rx:** strong

Carbonate: lots of nodules

Other: Roots some Rootlets Root Pores Organics Staining Vesicles Pedogenic Horizons Stage II Bk in upper 40 cm Fe Mg

Bkb-sticky to slightly sticky (underlying sand)

Top of soil is eroded & carbonate morphology dies out between station 25 and st 28½ (before break in slope or upslope of faults) and likely is below floor of trench in HW W of Unit; except near st. 47 where dug out

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UNIT DESCRIPTION

Initials: AT

Project: Central Hubbell Springs Fault

Date: 6.3.02

Location: Carrizo Springs Trench

Depth:

st # 22

Unit: 4 (below light blue dots - above green)

Genetic Name: reddish ~~orange~~ fine sand with coarse interbeds; slopewash & eolian deposit

PSA:		**% Total**	**Rounding**	**Composition**
	Boulders	0		
	Cobbles	0		
	Gravel	trace		
	Sand	90		qtz / K-spar / plag? / some oxides
	Silt	10		
	Clay			

Max. Size: floaters 7 vcU 1.8 cm **Average Size:** bimodal: (1-2 mm) coarse & fine sand

USCS: sand <2mm = Sandy loam

	Dry	**Wet**
Color:	7.5 YR 6/6 reddish yellow	7.5 YR 5/6 Strong brown

Plasticity: very slight **Dry Strength:** h **Dilatency:** rapid

Bedding: faint flat laminations; discontinous coarser beds (distribution shown on log)

Sorting: moderate **Clast or Matrix Supported**

Contacts: clear - wavy

ck log → **Thickness:** 20 to 60 cm (thickest in HW of FZ2)

Cementation: CW - weathers out from wall easier than over & underlying units **HCl rx:** none

Carbonate: none

Other: Roots Rootlets Root Pores Organics **Staining** lots limonitic

Vesicles Pedogenic Horizons **Fe** Mg

- coarser zones w/ more & larger "Floaters" near upper & lower contacts;
- ~10 cm thick horizon of yellow limonite staining above lower contact, becomes more apparent near cw wallow unit
- stickiness = none - slight
- top of 4 does not appear faulted
- thickens on downthrown-side of faults

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UNIT DESCRIPTION

Initials: AT

Project: Central Hubble Springs Fault

Date: 6.2.03

Location: Carrizo Springs Trench

Depth:

st # 24

Unit: 5 (light blue to yellow dots)

Genetic Name: red eolian sand w/ soil, S_3 (description is of Parent material)

		% Total	Rounding	Composition
PSA:	Boulders	0		
	Cobbles	0		
	Gravel	0		
	Sand	60-95	rd	qtz
	Silt	5-30		
	Clay			

Max. Size: mU occ. coarse sand **Average Size:** very fine sand

USCS: Sand (pm) to silty clayey sand loam

	Dry	Wet
Color:	7.5 YR 6/4 light brown	7.5 YR 5/4 m Brown

Plasticity: ps **Dry Strength:** h **Dilatency:** rapid

Bedding: faint flat lams

Sorting: very well sorted **Clast or Matrix Supported**

Contacts: upper: flat, wavy to smooth, distinct to abrupt; lower: gradational

Thickness:

Cementation: CW **HCl rx:** none (lower horizon)

Carbonate: occasional floater small carbonate nodules

Other: Roots Rootlets Root Pores Organics **Staining** lots MnO

Vesicles **Pedogenic Horizons** Btk - S_{3a}; Bt - S_{3b}; Btk S_{3c} **Fe** **Mg** (more disseminated)

- Unit is divided into two horizons - upper Bt ~ 15cm thick
  - lower sandy parent material
- some mottled limonite staining along top of lower horizon
- occasional zones of Mg rust staining in upper horizon
- occasional vertical fractures throughout
- slightly sticky
- rare gran >2mm.

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UNIT DESCRIPTION

Initials: AC

Project: Central Hubble Springs Fault

Date: 6.3.02

Location: Carrizo Springs Trench

Depth:

Unit: 6 (above yellow dots)

SE#25

Genetic Name: Buff reduced (?) very fine coversand

PSA:		% Total	Rounding	Composition
	Boulders	—0		
	Cobbles	—0		
	Gravel	—0		
	Sand	60	sub rd	qtz/some oxides
	Silt	35		
	Clay	5		

Max. Size: coarse sand

Average Size: vfL very fine sand

USCS: silty sand loam

	Dry	Wet
Color:	10YR 7/4 very pale brown	10YR 4/6 dk yellowish brown

Plasticity: ps

Dry Strength: so

Dilatency: med-rapid

Bedding: faint flat lams - mainly homogeneous unit
weather out in wind

Sorting: very well sorted

Clast or Matrix Supported

Contacts: abrupt / smooth

Thickness: thicker at east end of trench - thins, then pinches out toward scarp

Cementation: cw -

HCl rx: none

Carbonate: rare carbonate tubule (<2mm diameter)

Other: Roots Rootlets Root Pores rare Organics Staining

Vesicles occasional Pedogenic Horizons Fe Mg

- common horizontal cracks + fractures
- occasional Mg Staining
- very homogeneous almost "ashy" grey unit
- slightly sticky

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M0715941410

UNIT DESCRIPTION

Initials: AT

Project: Central Hubble Springs Fault

Date: 6.3.02

Location: Corrizzo Springs Trench

Depth:

Unit: 7 (below purple w/white dots

#24

Genetic Name: pinkish tan eolian cover sand with weak buried soil (Btj) horizon

PSA:		**% Total**	**Rounding**	**Composition**
	Boulders	0		
	Cobbles	0		
	Gravel	0		
	Sand	55		qtz / some opaques
	Silt	35		
	Clay	15		

Max. Size: coarse sand **Average Size:** very fine sand

USCS: clayey silty sand (coarse silty clay loam)

	Dry	**Wet**
Color:	7.5YR 6/4 light brown	10 YR 5/8 yellowish brown

Plasticity: ps **Dry Strength:** so **Dilatency:** med - slow

Bedding: none

Sorting: very well sorted **Clast or Matrix Supported**

Contacts: clear - smooth

Thickness: lose it to east (eroded away?) and near warp to west

Cementation: CW- **HCl rx:** mod - strong *

*Carbonate: occasional small xtline carbonate nodules

Other: Roots Rootlets Root Pores occasional Organics fine roots Staining

Vesicles occasional/common Pedogenic Horizons S_4 Fe Mg

• rare fine roots

• sticky

• weakly developed buried 1... Btj horizon (Unit 6 is PM)

*• ceases to fizz further up slope

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UNIT DESCRIPTION

Initials: SSO

Project: Central Hubbell Spring fault **Date:** 10-20-02

Location: Carrizo Spring Trench **Depth:**

Unit: 8 (marked by orange dots)

Genetic Name: Buried K horizon (S5)

		% Total	Rounding	Composition
PSA:	Boulders	0		
	Cobbles	0		
	Gravel	0		
	Sand	60		qtz. & oxides (?)
	Silt	40		
	Clay			

Max. Size: **Average Size:** v. fine sand

USCS: silty sand with clay (sandy loam)

Color: Dry: mottled block from FW: 10 YR 8/2 to 8/3 pale brown 7.5YR 8/3 pink Wet: 7.5 YR 7/3 pink

Plasticity: p **Dry Strength:** h to vh **Dilatency:** slow

Bedding: none apparent

Sorting: well-sorted **Clast or Matrix Supported**

Contacts: Upper: irregular to wavy; Lower: gradational

Thickness: 0 to 1.2 m

Cementation: CW+ to CS **HCl rx:** ev+

Carbonate: Stage III to III+

Other: Roots Rootlets lots Root Pores lots Organics Staining
Vesicles Pedogenic Horizons K S5 Fe Mg

- Present in FW & HW but locally eroded from below scarp crest
- Thickens noteably in HW, includes pinkish punky channel-shaped nodular zone, spring-related?
- & relation with base & underlying Units 5, 6 & 7 @ deformation zone (between st. 31 and 37)

UNIT DESCRIPTION

Initials: AT

Project: Central Hubble Springs Fault **Date:** 6.3.02

Location: Carrizo Springs Trench **Depth:**

Unit: 9 - (below Spruce green markers) St #44

Genetic Name: Buried soil in HW (S6) on eolian and colluvial sand

PSA:		% Total	Rounding	Composition
	Boulders			
	Cobbles			
	Gravel	1-5	sub-ang	quartzite
	Sand	55-60		
	Silt	35-40		
	Clay			

Max. Size: 15mm **Average Size:** vfL (range ≥vfL-vcU) somewhat bimodal

USCS: silty clayey sand

	Dry	Wet
Color:	mottled 7.5 YR 7/3 pink	7.5YR 6/4

Plasticity: p (sticky to very sticky) **Dry Strength:** sh **Dilatency:**

Bedding: flat lams on side of warp that are // to warp slope, downslope flat (// to upper contact)

Sorting: moderate **Clast or Matrix Supported**

Contacts: clear smooth except near FZ-5

Thickness: thickest in colluvial wedge area - thins to west.

Cementation: CW **HCl rx:** e+ to ev (e with just H_2O!)

Carbonate: Stage II+ carbonate on clay film coated grains / few very xtline nodules (up to 15mm) calcite, maybe gypsum too

Other: Roots **Rootlets** some **Root Pores** Organics Staining

Vesicles - some - lg - irregular **Pedogenic Horizons** Btk = S_6 Fe Mg

- flat lams in coluvial wedge position // to warp surface
- unit not present in footwall - "merges" w/ big K in scarp (S_5)
- debatable spring deposit punkyness
- slight pink/greenish mottling? not real obvious
- reworked nodules (up to 2 cm)
- worm burrows

UNIT DESCRIPTION

Initials: AT

Project: Central Hubbel Springs Fault **Date:** 6.4.02

Location: Carrizo Springs Trench **Depth:**

Unit: 10 (top marked by black)

Genetic Name: Buried Soil S_7 on eolian sand

		% Total	Rounding	Composition
PSA:	Boulders	0		
	Cobbles	0		
	Gravel	trace		
	Sand	75		qtz, feldspars, oxides
	Silt	25		
	Clay			

Max. Size: **Average Size:** Very fine sand

USCS: silty sand with clay

	Dry	Wet
Color:	7.5 YR 6/4 light brown	7.5 YR 5/4 brown

Plasticity: p (sticky) **Dry Strength:** h to vh **Dilatency:**

Bedding: none apparent - overprinted by pedogenesis

Sorting: well sorted **Clast or Matrix Supported**

Contacts:

Thickness: thickens slightly to east but is eroded slightly by modern soil at west edge

Cementation: CW **HCl rx:** ev+

Carbonate: nodular stage II; carbonate on clay films

Other: Roots Rootlets Root Pores Organics Staining

Vesicles see soil desc. Pedogenic Horizons S_7 Bk Fe Mg

- Present in FW & HW (looks slighty backtilted in HW)
- well developed soil - original stratigraphy overprinted -

see soil description for details

UNIT DESCRIPTION

Initials: AT

Project: Central Hubble Springs Fault

Date: 6.4.02

Location: Carrizo Springs Trench

Depth:

Unit: 11 (below white)

described @ st 43

Genetic Name: Fault scarp colluvium and eolian sand

PSA:	% Total	Rounding	Composition
Boulders			
Cobbles	trace		CO_3 nodules near warp
Gravel	15% near warp; W of st 42: trace		carbonate nodules (near warp) some chert clasts (.5cm)
Sand	55-65		mostly qtz, some mica, femg,
Silt	25-30		
Clay			

Max. Size: 7cm **Average Size:** very fine sand

USCS: silty sand with gravel to silty sand

	Dry	Wet
Color:	7.5 YR 6/4 light brown	7.5 YR 5/4 brown

Plasticity: ps (slightly sticky) **Dry Strength:** sh **Dilatency:**

Bedding: faint, tiny flat laminations to west

Sorting: very poorly sorted toward E possible blocks of Unit 10 Clast or Matrix Supported

Contacts: abrupt irregular

Thickness: wedges out @ st 46, thickest @ 42, pinches out against block @ st 36

Cementation: very weak **HCl rx:** very strong

Carbonate: some small nodules + coated grains

Other: Roots Rootlets Root Pores Organics some carb. Staining Fe Mg

Vesicles Pedogenic Horizons

- weak buried soil → see soil description
- note – between st 41 + 42 – this unit suddenly contains many large (2-3cm) reworked carbonate nodules (reworked from Unit 10) which decrease in size + distribution down the slope (toward west) (ie. fines downslope)

lots of krotovina toward E near warp

UNIT DESCRIPTION

Initials: AT

Project: Central Hubble Springs Fault

Date: 6-4-02

Location: Carrizo Spring Trench

Depth:

Unit: 12 (below dk green)

Genetic Name: eolian sand

PSA:	% Total	Rounding	Composition
Boulders	0		
Cobbles	0		
Gravel	0		
Sand	70		cl coats = mica, carbonate nodules, qtz
Silt	>30		
Clay			

Max. Size:

Average Size: bimodal cL + fL (coarse sand in fine sand matrix

USCS: silty sand with clay   Sandy loam

	Dry	Wet
Color:	10YR 6/6 brownish yellow	10 YR 4/4 dk yellowish brown

Plasticity: po **Dry Strength:** sh **Dilatency:** med - rapid

Bedding: faint baby flat lams - dipping west. Apparent dip = 26°

Sorting: bimodal sands. cL + fL   Clast or Matrix Supported

Contacts: Upper: clear + smooth (lower gradational + conformable)

Thickness: Daylights near st 39, Thickest there, wedges out near 47

Cementation: cw – **HCl rx:** very strong

Carbonate: some grain coatings + small (cL) nodules

Other: Roots Rootlets rare Root Pores Organics Staining

Vesicles - rare/poorly formed Pedogenic Horizons Fe Mg

Only in HW, lenticular shape at base of scarp

slightly sticky

slightly more coarse grains near base of unit

UNIT DESCRIPTION

Initials: AT & SSO

Project: Central Hubble Springs Fault

Date: 6.4.02

Location: Corizzo Spring Trench

Depth:

Unit: 13 (below neon and above dk green)

Genetic Name: Slopewash and eolian sand

PSA:	% Total	Rounding	Composition
Boulders	0		
Cobbles	0		
Gravel	0-trace (upper) 5% (base)	angular to sub rd	Chert, Qtz, Qtzte, CO_3 nod. reworked
Sand	75-85	ang. to sub rd	Chert, Qtz, some mica, mets and FeMg
Silt	10-15		
Clay	5-10		

Max. Size: fine gravel (4mm) **Average Size:** med. sand

USCS: sand (base) to silty sand

Color: Dry: 7.5 YR 5/4 brown Wet: 7.5 YR 4/4 - 4/6 brown to strong brown

Plasticity: none to slightly **Dry Strength:** weak **Dilatency:** very rapid

Bedding: stratified into 3 subunits that parallel base

Sorting: moderately sorted (best in mid subunit) Clast or Matrix Supported

Contacts: lower (dk green) clear smooth slopes W 10-12° over Unit 11 flattens to hor. over Unit 1

Thickness: Daylights around st. 42 (against Unit 11) Wedges out near st 52 (against unit 10.) Thickest toward scarp

Cementation: cw (massive) **HCl rx:** strong

Carbonate: disseminated (no veins but some fine nodules)

Other: Roots Rootlets (abundant, increase upslope) Root Pores Organics Staining Vesicles Pedogenic Horizons Bk massive Fe Mg

Grades upward from coarser sand at base, to fine to med sand with coarse floaters, to med sand with more coarse floaters than middle subunit. some intraclasts in lower portion; long lenticular wedge shape (only in HW at base of scarp - similar to Unit 12)

UNIT DESCRIPTION

Initials: AT

Project: Central Hubble Springs Fault

Date: 6.4.02

Location: Carrizo Spring Trench

Depth:

Unit: 14 Above neon green

Genetic Name: Weak Bw or Br soil on eolian sand

		% Total	Rounding	Composition
PSA:	Boulders	0		
	Cobbles	0		
	Gravel	trace		carbonate nodules
	Sand	80		qtz, micas, oxides
	Silt	15		
	Clay	5		

Max. Size: vcL (very coarse sand) **Average Size:** fU (fine sand)

USCS: silty sand Sandy loam

	Dry	Wet
Color:	7.5 YR 6/4 light brown	10YR 5/8 yellowish brown

Plasticity: ps **Dry Strength:** sh **Dilatency:** rapid

Bedding: Faint 'baby' flat lams

Sorting: medium **Clast or Matrix Supported**

Contacts: gradual / wavy

Thickness: Thickest near st 46 - daylights near station 43, pinches out at st 52

Cementation: cw **HCl rx:** strong rxn

Carbonate: small nodules / grain coatings

Other: **Roots** several **Rootlets** several **Root Pores** some **Organics** **Staining**

Vesicles many **Pedogenic Horizons** **Fe Mg**

this unit is mantled by modern "duff"

sticky

occasional larger (2cm) nodules near base of soil

many larger crotovena coming down from modern surface

Appendix B

Soil Profile Descriptions

Soil Profile Description CS1

~~Table A-2.~~—Work sheet for recording soil properties in the field
[In the note column, one can record properties not universal to all soils. Courtesy of D. Jorgenson, 1989]

P. 1 of 2

Soil Description: Location Marker 49 Carrizo Spring trench **CS1**
Site No. ____ Date ____ Time ____ Vegetation ____
Elevation ____ Slope ____ Aspect ____ Geomorphic Surface Hanging wall
Parent Material(s) aeolian sand / slope wash Described by M Eppes A Tilley

Trench Strat.	Depth (cm)	Horizon	Color moist	Color dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes	Roots	Pores
UNIT ABOVE	0-5	A/C **CS1-1**	7.5yr 4/3	10yr 5/4	vf 1 sbk	<5%	ss ps		so	SL			a s	gravels are 90% carbonate nodules <5mm dia.	1c 2m	
NEON YELLOW	5-15	Bw **CS1-2**	7.5yr 5/4	10YR5/4	m 2 sbk	<5%	ss ps		so sh	SL			a w	" see above gravel comment	1c 1m 2f 3vf	1m 2f
	15-30	Ck **CS1-3**	7.5yr 5/4	7.5yr 5/4	m 2 sbk	<5%	ss ps		so sh	SL			a s	gravels ~2mm diam qtz + carb. grains	2m 1f 2vf	1f
	30-50	1Bkb (b1) **CS1-4**	7.5yr 5/4	7.5yr 6/4	m c 2 3 abk sbk	<5%	ss ps		h	SL			a s	same	1m 1f 2vf	2m 2f
NEON YELLOW	50-64	2Bkb **CS1-5**	7.5yr 4.5/4	7.5yr 5/4	m 2 sbk	<5%	ss ps		h	SL			c s	same	1f 1vf	2m 2f
	64-85	2Ck **CS1-6**	7.5yr 4/4	7.5yr 5.5/4	m	<5%	so po		sh	LS			a s	same coarse sand	1f 1vf	1m
Top of black	85-118	3Btkb (b2) **CS1-7**	7.5yr 5/4	7.5yr 6/4	m 3 abk	<1%	s p		vh	SiL		v1 f pf	c s	clay films not obvious; may be over printed with carbonate	1f 1vf	1c 1m 2f 1vf
	110-127	3Bkb2 **CS1-8**	7.5yr 5/4	7.5yr 6/4	m 2 3 abk	<1%	s p		vh	L			g s	xtaline nodules concentrated @ top of horizon	1f	1m 2f
	127-137	3Bkb3 **CS1-9**	7.5yr 5/4	7.5yr 6/4	m 2 abk	<1%	s p		h vh	SiL L			a w		1f	1m 2f
Under sage green	137-143	4Btk (b3) **CS1-10**	7.5yr 7/4	7.5yr 7/3	f 2 sbk	<5%	vs vp		vh	SiC		2 d pf po	c w	Carb. coats on clay films	1vf	2f 1m

— = n/a

M = massive

Soil Profile Description CS1

~~Table A-2.~~—Work sheet for recording soil properties in the field
[In the note column, one can record properties not universal to all soils. Courtesy of D. Jorgenson, 1989]

P. 2 of 2

Trench strat.

Soil Description: Location Marker 49 Carrizo Springs trench - CS1
Site No. ____ Date ________ Time __________ Vegetation ____________
Elevation ________ Slope ________ Aspect ________ Geomorphic Surface ____________
Parent Material(s) ____________ Described by ____________

	Depth (cm)	Horizon	Color moist	Color dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes	roots	pores
Sage green	143-165 CS1-11	5Btk2	7.5yr 7/4	7.5yr 7.5/3	f, 3, sbk	<5%	ss, ps		vh	L		v1, f, pf, po	a, w	~~Xtaline carb~~ S = contains ~~lens of clay in~~ "sage green" deposit. Stage II+-3	none —	2c, 2v, 2f
orange-banded K	165-195 CS1-12	(B4) 6K	7.5yr 8/3	7.5yr 8/1	m, 2, sbk	<1%	s, vs, p		sh, h	CL			c, s	Stage III	1vf	1v, 2
	195-237 CS1-13	6Kz2	7.5yr 7/3	7.5yr 8/2	f, 2, sbk	<1%	ss, s, ps		h, vh	L			c, s	Stage III	—	1c, 3v, 3f
	237-268 CS1-14	6K3	Peds have mottled colors 7.5yr 6/4	7.5yr 7/3	m, 2, sbk	<5%	vs, vp		vh	CL		v1, f, ?, pf, po	c, s	Stage II+-III ↓ 30% of horizon = 3-5cm diam, Carb-cemented irreg. shaped nodules. eh sbk. xtaline carb growing on nodule faces	—	2f, 1m
	268-295 CS1-15	(B5) 6BtKmb	7.5yr 5/4	7.5yr 6/4	m	<1%	ss, ps		vh	SL		v1, f, pf, po	g, s, w	Stage 1-2	—	2m, 3f, 2vf
	295-323 CS1-16	6Bkmb	7.5yr 5/4	7.5yr 7/3	m	<5%	ss, ps		vh	SL			g, s, w	Stage 2	—	1m, 2f
	323-370 CS1-17	7Kmb2	7.5yr 6/4	7.5yr 7/3	m	<5%	~~so~~, s, ps		vh	SL			a, w, i	Stage 2+ grading into Stage III @ bottom of ~~horizon~~ gravels somewhat coarser 2-5mm	—	1c, 2f
Continue description @ marker #47 in pit dug by S. Olig on Jan 2	370-382 (bottom) CS1-18	(B6) 8BtKmott	7.5yr 5/6	7.5yr 6/5	m, pl, m, 2	<1%	ss, ps, s		vh	SL		v1, f, pl, ps	c, s	K overprints redox features Mn coatings no modern roots but traces of roots are visible	—	2v, 2f, 2
	382-402 CS1-19	(B7) BtKmott2	7.5yr 5/6	7.5yr 6/5	m, vf, m, 2, abk	<1%	ss, s, ps, p		h, vh	SL, CL		1, d, pl, po	g, s		—	2m, 2f, 3vf
	402-420 CS1-20	BK	7.5yr 6/5	7.5yr 7/5	m	<1%	ss, s, ps		vh	SL			a, s		—	2m, 2f, 1vf
	420-430 CS1-21	(B8) BK2	10yr 6/4	7.5yr 7/6	M	<1%	SP		vh	L					—	1m, 2f, 1vf

Soil Profile Description CS2

~~Table A-2.~~—Work sheet for recording soil properties in the field
[In the note column, one can record properties not universal to all soils. Courtesy of D. Jorgenson, 1989]

Soil Description: Location Carrizo Spring trench 0-170cm @ 2.5m. mark; 170-280cm @ 7m. mark **CS2**

Site No. _____ Date _________ Time ___________ Vegetation ______________

Elevation __________ Slope ___________ Aspect __________ Geomorphic Surface Footwall

Parent Material(s) ______________________ Described by M. Zipps

TRENCH STRAT.	Depth (cm)	Horizon	Color moist / dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes		ROOTS	PORES
Duff	0-5	A/C **CS2-1**	7.5yr5/4 / 7.5yr6/4	vf sg 1 sbk	20%	ss ps		so	SL			a s	"gravel" is reworked K nodules. real "gravel" % is <1%	Both horizons contain abun. reworked K nodules	1c 2m	
	5-16	Bk **CS2-2**	7.5yr7/4 / 10yr6/3	f m 2 sbk	25	ss ps s		sh	L			a w	ditto on gravels		1c 2m 2f 3vf	
Black	16-39	(b1) Bkb **CS2-3**	7.5yr7/4 / 7.5yr8/3	f m 2 sbk	<1%	s p		vh	L			a w	Stage 2+ abundant carb - cemented kroalinna likely reworking of underlying K		1m 1f 1vf	
orange	39-47	(b2) K **CS2-4**	7.5yr7/3 / 7.5yr8/2	m	<5%	ss ps s		vh	L			c s	Stage 3		1f	
K	47-64	K2 **CS2-5**	7.5yr6/4 / 7.5yr7/3	m m 2 3 sbk	<1%	s p		vh	SiL L			a w	Stage 3 Carb cemented kroalwina		1f 2f 3vf	
purple/orange / orange	64-106	(b3) Kmb **CS2-6**	7.5yr6/4 / 7.5yr7/3	m	<1%	ss ps		vh	SL			g s	STAGE 3 grading into stage 2 @ boundary		0.5 f	
	106-127	Bkmb **CS2-7**	7.5yr5/4 / 7.5yr6/6	m 3 abk	<1%	ss po ps		vh	SL		?	c s	mottles		1f	
	127-170	Bkmb2 **CS2-8**	7.5yr5/5 / 7.5yr6/5	m	<1%	ss po		sh	SL			c s	Many roots are decayed		1f 1m	
Light blue	170-212	2Coxk **CS2-9**	7.5yr5/5 / 7.5yr6/6	m	<5%	ss ps		vh	SL			c s	Stronger mottles		—	
	212-236	3Coxkz **CS2-10**	7.5yr5/6 / 7.5yr6/4	m	<1%	so ss po		vh	LS SL			a w	faint mottling		—	
Dk. Green	236-280 (bottom)	(b4) Kb **CS2-11**	7.5yr6/4 / 7.5yr7/4	m - 3mabk	<1%	ss/s ps		vh	L			—	Sparce mottles nodular stage 1+		—	

Soil Profile Description CS3

Soil Description: Location **CS3** @ marker 42.75m Carrizo Spring Trench

Site No. _____ Date ________ Time ________ Vegetation ________ p. 1 of 1

Elevation ________ Slope ________ Aspect ________ Geomorphic Surface Base of Scarp

Parent Material(s) Duff – Spruce Unit Described by M Epps

Depth (cm)	Horizon	Color moist	Color dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes	Roots	Pores
0–5? CS3-1	AC	7.5yr 4/4	7.5yr 6/4	f, 1, sbk	<10	ss, po		so	SL			?	Scraped away; "gravels" are a mix of fine pebble clasts of rock + reworked K horizon	1c 2m	
5–17 CS3-2	Bw	7.5yr 5/4	7.5yr 6/4	m, c, 2, 3, sbk	<5%	ss, ps		sh	SL			a, w	Top is scraped away; Unit 14	1c 2m 2f 3vf	
17–45 CS3-3	Bwb (b1)	7.5yr 5/4	7.5yr 6/4	f, m, 2, sbk	<5%	ss, ps		sh	SL			c, s	Unit 13	1m	
45–61 CS3-4	Bk	7.5yr 5/4	7.5yr 6/5	m, c, 2, sbk	<5%	ss, po, ps		sh, h	SL			c, s	Unit 13	1c 1m 2f 2vf	
61–70 CS3-5	2Bk	7.5yr 5/4	7.5yr 5/4	f, m, 2, sbk	<10	ss, ps		h	SL			c, s	Coarse unit above "green"; Unit 13	1f 1vf	
70–87 CS3-6	3Bkb (b2)	7.5yr 5/4	7.5yr 6/4	m, 2, abk	<1%	ss, ps		sh	SL			c, s		1m 2f	
87–95 CS3-7	Bkb2	7.5yr 5/4	7.5yr 6/4	f, m, 2, sbk	<1%	ss, ps		so, sh	SL			c, s		1f 2vf	
95–117 CS3-8	Bwb (b3)	7.5yr 5/4	7.5yr 6/4	m, 2, sbk	<5%	ss, ps		sh	SL			a, s, w	"gravels" are reworked carb. nodules 2mm–5mm diameter, likely eroded/reworked from "black" soil – fine sand	1m 2f 2vf	
117–130 CS3-9	Btkb (b4)	7.5yr 5/4	7.5yr 6/4	f, m, 3, sbk	<1%	s, p		h, vh	L		v1, 1, f, pf, po	c, s	– Nodular stage 2; – found a 1cm dia. qtz clast; – Carb on clayfilms	–	
130–148 CS3-10	Bk	7.5yr 6/4	7.5yr 6/4	m, 2, abk	<1%	s, vs, vp		sh	SiCL			c, w		–	
148–165 CS3-11	Btkb (b5)	7.5yr 6/4	7.5yr 7/4	3 f abk sbk	<1%	s p		vh	SiL		1-2 f po pf	cs	– stage 2+; – Carb on clay films; – makes "fiz" in contact w/ H2O	–	
165–195	K	7.5yr [illegible]		3c abk	<1%	s p		vh	SiCL			cw	stage 3-/2+; – slightly salty		

Soil Profile Description CS4

CS4

Soil Description: Location @ MARKER 39 CS4

Site No. ____ Date ________ Time ________ Vegetation ________

Elevation ________ Slope ________ Aspect ________ Geomorphic Surface "warp"

Parent Material(s) ________ Described by M. EPPES

Depth (cm)	Horizon	Color moist	Color dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes	Roots	Pores
0 – ? scraped	AC CS4-1	7.5yr 5/4	7.5yr 6/4	f 1 sbk	<5%	so ps		so	SL			?			
? – 27	Bw CS4-2	7.5yr 5/4	7.5yr 6/4	2 m c sbk	<1	so ss ps		so sh	SL			a w	"baby lams" in bottom of horizon 'gravels' are rework carb. nodules	1c 2m 2f 3vf	1[illegible] 2f
27 – 43	Bwb (b1) CS4-3	7.5yr 5/4	7.5yr 8/4	f m 2 sbk	<1%	ss ps		sh	SL			c s	occasional carb-cemented burroughs gravels are carb nodules + qtzite	1m 2f 2vf	1[illegible] 2[illegible] 2[illegible]
43 – 61	Bkb CS4-4	7.5yr 5/4	7.5yr 5/4	m 2 sbk	<1%	so ss ps		sh	SL			a s	occasional <2mm nodules of carb.	3f 3vf	2[illegible] 2f 1v[illegible]
61 – 70	Bkb2 (b2) CS4-5	7.5yr 6/4	7.5yr 7/4	m 3 sbk	<1%	s ps p		vh	L			c s	STAGE II nodules + carb cemented krot. - difficult to tell if nodules formed in-situ or if they are reworked fm. black unit	2f 2vf	1[illegible] 3f
70 – 93	Bkb3 +? CS4-6	7.5yr 6/4	7.5yr 7.5/4	m c 3 abk	<1%	s p		vh	CL		v1 f pf po ? not obvious	a w	STAGE II+ nodules + carb cemented krot	1m 2f 2vf	2w 3f 3vf 1c
93 – 110	Kb (b3) CS4-7	7.5yr 5/4	7.5yr 8/4	f 2 abk sbk	<1%	s p		so sh	CL			c s	Stage II+ Both "green" horizons have friable/granular appearance in trench wall	1vf	1n 2-3 2v
110 – 122	Kb2 CS4-8	7.5yr 6/4	7.5yr 8/4	f 2 3 sbk	<1%			sh h	CL			a w i	stage 3	1vf	1c 1m 2f
122 – 160	Kb3 (b4) CS4-9	7.5yr 7/4	7.5yr 8/3	m c 3 sbk M in areas	<1%	s p		vh eh	SiCL CL			c s	STAGE 3 +p Stage 2 w/'spring' nodules >5cm diameter irregular morphology	1vf	1c 2m 2f 3vf
160 – 191	Kb4 CS4-10	7.5yr 7/4	7.5yr 8/4	f 3 sbk	4%	s p		vh	SiCL CL			a w i	friable/granular texture in wall	–	2c 2w 3f 3vf

Soil Profile Description

Soil Description: Location CS4 pg 2 of 2

Site No. _____ Date _________ Time ___________ Vegetation ______________________

Elevation __________ Slope ___________ Aspect _________ Geomorphic Surface ______________________

Parent Material(s) ______________________ Described by ______________________

Depth (cm)	Horizon	Color moist / dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes	Roots	Pores
b5 2Kmb CS4-11	191-225	7.5yr 6/6 / 7.5yr 7/4	m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25 <1%	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b	1-5cm spring nodules common nodules are eh. - A 2-5cm thick zone of Stage 3 carb @ bottom of horizon otherwise Stage 2+		
2Ck CS4-12	225-289	7.5yr 5/5 / 7.5yr 6/6	m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25 4%	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b		–	1 2
3Cox k CS4-13	289 312	7.5yr 5/6 / 7.5yr 6/6	m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25 <1%	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b	occ. mottling + Mn coats	–	2
b6 4Btk (cow wallow) CS4-14	312-370	7.5yr 8/6 / 7.5yr 6/5	m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b	effervescent salts "sweating" out of trench walls + clays are prominent b/c of abundance in p.m. no horizonation likely b/c of bioturbation veins + isolated nodules of carb otherwise no fizz		1 3 2
5Cox k CS4-15	370-397 bottom	10yr 5/6 / 10yr 6/6	m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25 <1%	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b	orange mottles carb stringers mottling is greatest @ top of horizon	–	1 2
			m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b			
			m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b			
			m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b			
			m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b			
			m sg 1 2 3 vf f m c vc gr pl pr cpr abk sbk	0 50 <10 75 10 >75 25	so po ss ps s p vs vp	lo vfr fr fi vfi efi	lo so sh h vh eh	S SiCL LS SiL SL Si SCL SiC L C CL SC		v1 f pf 1 po 2 d br 3 co p cobr	a s c w g i d b			

Soil Profile Description

Pg 1 of 1

Soil Description: Location **CS5** @ marker #21m starting @ yellow dot yellow=0cm (82cm above line)

Site No. _____ Date _________ Time ___________ Vegetation ______________________

Elevation __________ Slope ___________ Aspect _________ Geomorphic Surface footwall

Parent Material(s) ______________________ Described by MEpps

Depth (cm)	Horizon	Color moist	Color dry	Structure	Gravel %	Consistence Wet	Consistence Moist	Consistence Dry	Texture	pH	Clay films	Boundaries	notes	Roots	Pores
0-20 CS5-1	Btk	7.5yr 6/6	7.5yr 7/6	2 3 c sbk	<1%	ss ps		vh	SL		v1 f pf po	c s	orange mottles Carb nodules + linings in fractures	1m 1f	2m 2f 2vf
20-36 CS5-2	Bkm	7.5yr 6/6	7.5yr 7/6	m	<1%	ss ps		vh	SL			c s	boundary marked by end of mottling	—	2f
36-52 CS5-3	Ck	7.5yr 6/6	7.5yr 6/6	m	<1%	so ps		vh	SL			c g s		—	1f
52-75 CS5-4	2Ck	7.5yr 5/4	7.5yr 7/6	m	<5%	so po		vh	SL			c s		—	1f
75-97 CS5-5	2Coxk	7.5yr 5/6	7.5yr 6/6	m	<5%	so po		h	SL			a g w	mottled	—	1c 1m 1f
97-112 CS5-6	Kb (b1)	7.5yr 5/5	7.5yr 7/4	m 2 3 abk	<1%	s ps		vh	L		v1 f pf po	c s	mottled nodular Stage II+	—	1m 2f
112-130 CS5-7	Kb2	7.5yr 5/6	7.5yr 7/6	f m 2 3 abk; massive in areas	<1%	ss s ps		h	L		v1 f pf po	c w	more mottled than above nodular stage 2	—	1m 2f
130-149 CS5-8	BKb (b2)	7.5yr 6/6	7.5yr 7/6	m	<1%	s ps		vh	L			c s	overprinted in areas fm. above K	—	2f 2vf
149-167 CS5-9	Kb3	7.5yr 6/4	7.5yr 7/4	m	<1%	s ps		vh	L			c s	nodular stage 2	—	1m 2f 2vf
167-192 bottom CS5-10	Kb4	7.5yr 6/4	7.5yr 8/4	m	<1%	s ps		h	L				nodular stage 2	—	1m 2f

Appendix C
Boring Logs

Project: Hubbell Spring Fault **Project Location:** Carrizo Spring Trench Site **Project Number:** 26813901.00000	**Log of Boring B1** Sheet 1 of 4

Date(s) Drilled	10-22-02	Logged By	S. Olig	Checked By	
Drilling Method	Continuous Auger	Drill Bit Size/Type		Total Depth of Borehole	10.39 m
Drill Rig Type	SIMCO 2800 HS	Drilling Contractor	Bruce Allen & Dave Love NMBM&G	Surface Elevation	
Groundwater Level and Date Measured		Sampling Method(s)	Auger	Hammer Data	NA
Borehole Backfill	Spoil	Location	2.85 m S of St. 60 m @ Carrizo Spring Trench		

Elevation feet	Depth, ~~feet~~ 0.1 m	SAMPLES: ~~Type~~	~~Number~~	# Photos ~~Sampling Resistance, blows/foot~~	Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	0			Depth of sample			Tan silty sand (Unit 14)				
				1 & 2		40	abrupt				
	5				S6		Pink clayey silty sand (S_7 on Unit 10) Btk				
		55									
				3							
1m =	10										
		120	dry	4 & 5		126	* Upper bound Top of S_5 (K horizon on unit 8) Uncertainty due to cave-in while sampling				some rig resistance
	15					163	Lower bound S_5 measured on auger				
						180	Light Pink clayey silty sand (more & whiter nodules than above) — matrix plugged with carbonate				much less resistance
2m =	20	208		7 & 8			Upper bound top of S_4 or S_{3c}^* uncertainty				cleaned hole before next sample
	25					247	* lower bound top S_4 or S_{3c}^* S_5 - Silty clayey sand - Redder than above & more clay (stickier) Sand coarser than above carbonate nodules				
		278									
	30										

Report: GEO_10B1_OAK; File: WC_CORP2.GPJ; 10/16/2001

URS

* Preferred interpretation

Project: Hubbell Spring Fault
Project Location: Carrizo Spring Trench Site
Project Number: 26813901.00000

Log of Boring B1

Sheet 2 of 4

Elevation feet	Depth, ~~feet~~ 0.1 m	Type	Number	Sampling Resistance, blow/foot (photo)	Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	30	olner	9 + 10				Reddish silty clayey sand S_{3c} ctd.				
						330	10YR yellow Fine sand - no carbonate gradational upper contact abrupt lower contact well-sorted (finer, yellower & better sorted than Unit 4; more like unit 6?)	gradational			
	35										
						385	Mottled Pink & White (S_2^* or S_{3c}?) Stage II+ carbonate nodular soil evt silty clayey sand	abrupt			(Pref. S_2)
	40						grades (?) into ← uncertainty due to mix or sloughing				
			430				Mottled reddish & white / sandy clay with gravels (qtzte, ls, meta, carb. nod.) upto 25 mm rounded has much more clay than above (S_2 or colluvial wedge reworked from S_1 and Unit 1?)				
	45		11 + 12			450 BtK?					(Alt. S_2)
						494	— strong resistance — easier — harder > gravels in clayey sand matrix				
	50		533				— — gradational lower boundary of soil				
							coarse orangeish-yellow poorly sorted pebbly sand sub ⅔ to sub rd. (same comp. as below)				
	55	moist	13, 14 & 15			560	mottled pinkish & white (stage I S_1) nodular soil on silty coarse sand with gravel (15%)	abrupt	10% carb. evt		(S_1)
						581	← gradational coarse yellow sand with gravel - mostly qtz & qtzte, some ls, meta, Fe-Mg oxides, mica poorly sorted				(Unit 1)
	60						coarse gravels / clean sand matrix cobbles near bottom of run, some (carbonate-coated metamorphic-greenstone				difficulty pulling stems
			630				↑ gradational boundary (?) pink vf sand				
	65										

Project: Hubbell Spring Fault **Project Location:** Carrizo Spring Trench Site **Project Number:** 26813901.00000	**Log of Boring** B1 Sheet 3 of 4

Date(s) Drilled		Logged By		Checked By	
Drilling Method		Drill Bit Size/Type		Total Depth of Borehole	
Drill Rig Type		Drilling Contractor		Surface Elevation	
Groundwater Level and Date Measured		Sampling Method(s)		Hammer Data	
Borehole Backfill		Location			

Elevation feet	Depth, feet	SAMPLES Type	SAMPLES Number	SAMPLES Sampling Resistance, blow/foot (Photo)	SAMPLES Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
65	~~0~~			16 end of roll**			Pink silty vf sand very well sorted no carbonate no visible bedding slightly more silt & some clay (<10%)				very smooth and easy drilling
			734								
75	~~10~~	moist		none			pebbly silty vf pink sand with coarser and clayer pockets (could be just poorly sorted or interbedded lenses of silt+clay + coarser) gravels are rd to sub rd carb. nodules* up to 25mm + meta with d. to clay (not many - "floating") *matrix doesn't fizz	gradational?			
80	~~15~~										
85	~~20~~					849	Slightly mottled pink and whitish pink stage I+ carbonate soil - clayey silty pink vf sand	abrupt	ev-		
			889				Pink silty vf sand with granules [illegible] & carb. nodules	gradational	e		
90	~~25~~	Sat-urated		New roll #1-4		899	grades coarser with lenses of greenish gray & limonitic yellow-orange coarse sand lenses some pebbles (meta, some completely withd to white clay, greenstone) poorly sorted(?) but stratified - still dominantly pink silty vf sand	gradational		no fizz (matrix) except carbonate nodules + some carb. coats on clasts	moist 7.5YR 5/6 strong brown
95	~~30~~										

**Camera didn't sound like it completely wound off roll - didn't reload

Project: Hubbell Spring Fault
Project Location: Carrizo Spring Trench Site
Project Number: 26813901.00000

Log of Boring B1

Sheet ~~3~~ 4 of 4

Elevation feet	Depth, feet	SAMPLES Type	Number	Sampling Resistance, blow/foot	Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
100	~~30~~	saturated	1039				stratified lenses coarse sand in pink silty vf sand and (ctd) clayey silty vfs clasts up to 30mm qtzte, meta wthd to clays, greenstone				
							Bottom				
105	~~35~~										
110	~~40~~										
115	~~45~~										
120	~~50~~										
125	~~55~~										
130	~~60~~										
	~~65~~										

URS

Project: Hubbell Spring Fault Project Location: Carrizo Spring Trench Site Project Number: 26813901.00000	Log of Boring B2 Sheet 1 of 3

Date(s) Drilled	10-23-02	Logged By	S. Olig	Checked By	
Drilling Method	Continuous Auger	Drill Bit Size/Type		Total Depth of Borehole	7.22 m
Drill Rig Type	SIMCO	Drilling Contractor	Bruce Allen & Dave Love NMBM&G	Surface Elevation	
Groundwater Level and Date Measured		Sampling Method(s)		Hammer Data	NA
Borehole Backfill	Spoil	Location	489 m projected on scarp profile (farthest W)		

Elevation feet	Depth, ~~feet~~ 0.1 m	Type	Number	~~Sampling Resistance, blows/foot~~ Photo #	~~Recovery, %~~	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	0	B2-1 no sample			20		Loose vf sandy silt pinkish white	Dry gradational		ev	modern cover loam
							BK in vf sandy silt w/ gravels (granules of carb. nodules, greenstone, qtzte well rd up to 1/2") whitish pink			ev	(S7 ?)
	5	B2-2 no sample			60			Dry gradational			
							Grades sandier and less white (darker than above) silty vf sand			ev-	
1.0 m =	10	B2-3 no sample 118		lost	118			Dry			
							carbonate cemented sand 7.5 YR 6/4 light brown (dry) Whitish Pink silty vf sand with some clay (< 10%) and granules (up to 1/2" - carb. nodules, qtztes mostly)	Slightly moist		ev+	rig resistance (S5) Stage II-III ? (clasts completely coated w/ carb)
	15	B2-4			158						
		B2-5		Photo #6 + #7			7.5 YR 5/4 brown (dry) silty vf to coarse sand w/ trace fine gravels (redder & darker and than below, some clay)	moister		ev	(S3 ?)
	20										
	25	253 B2-6		Photo #7 & 8	253		7.5 YR 7/3 Pink (dry) mottled-nodular? silty coarse to fine sand moderately sorted, rd to sub rd, occ granule, carb coated grains, lots carbonate nodules, qtz, qtzte	Slightly moist		ev+	Stage II+ (S2)
	30										

Project: Hubbell Spring Fault	Log of Boring B2
Project Location: Carrizo Spring Trench Site	Sheet 2 of 3
Project Number: 26813901.00000	

Elevation feet	Depth, ~~feet~~ 0.1 m	SAMPLES: Type	SAMPLES: Number	SAMPLES: Sampling Resistance, blow/foot	SAMPLES: Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	30				313			gradational			
			B2-7	Photo 7 & 8 & 9			10YR 5/4 (yellowish brown) sand moderately sorted (fine to coarse sand with silt & occ. fine granule)			e	(Unit 2~~X~~) ~~or Unit 1?~~
	35						grades coarser to				
	40										
			421				10YR 5/4 Clean gravelly sand, upto 40mm (rd gneiss), subrd, clast-supported, mod. sorted (fine sand to fine gravel) qtz, qtzite, meta			e-	
	45		B2-8	photo 9 & 10	476						
							Pinker silty sand with fine gravel light brown 10YR 6/4 similar to above w/o as much gravel, & siltier, more carbonate (mottled) and carbonate nodules	Slightly moist		ev+	grades finer w/ more silt (5.0 m Unit 1)
	50		B2-9				some pebbly lenses (meta.)				
	55						grades finer to				
			570								
			B2-10	photo 11 & 12			Pink silty sand (dom. v.fine to med sand but ranges vf → c) w/ gravel occ 7.5YR 5/4 (moist, same as above dry) brown			e-	
	60							moist			
					636		grades cleaner (less silt)	gradational			easy drilling
							lots of Fe & MgO				
	65										

Project: Hubbell Spring Fault
Project Location: Carrizo Spring Trench Site
Project Number: 26813901.00000

Log of Boring B2

Sheet ~~2~~ 3 of 3

Elevation feet	Depth, ~~feet~~ 0.1 m	SAMPLES Type	Number	Sampling Resistance, blow/foot	Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	65 ~~30~~		B2-11	photo 11 & 12			sand with silt and occ. gravel sand ranges f → vc 7.5YR 6/4 (moist) light brown no carb. coating on clasts	moist		no fizz	
	70 ~~35~~										
			722				Bottom = 7.22 m				
	75 ~~40~~										
	80 ~~45~~										
	85 ~~50~~										
	90 ~~55~~										
	95 ~~60~~										
	~~65~~										

Project: Hubbell Spring Fault	Log of Boring B3
Project Location: Carrizo Spring Trench Site	Sheet 1 of 2
Project Number: 26813901.00000	

Date(s) Drilled	10-23-02	Logged By	S.Olig / D. Love	Checked By	
Drilling Method	Continuous Auger	Drill Bit Size/Type		Total Depth of Borehole	5.68 m
Drill Rig Type	SIMCO 2800 HS	Drilling Contractor	Dave Love & Bruce Allen NMBMG	Surface Elevation	
Groundwater Level and Date Measured		Sampling Method(s)		Hammer Data	
Borehole Backfill	spoil	Location	472 m projected on scarp profile (between B1 & B2)		

Elevation feet	Depth, ~~feet~~ 0.1m	SAMPLES Type	Number	~~Sampling Resistance, blow/foot~~ photo	~~Recovery, %~~	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	0	B3-1					Loose light tan vf sandy silt very well sorted 7.5 YR 7/3 Pink	dry		ev+	
					30						gradational
	5			Photo 13			Tan vf sandy silt trace coarse sand 7.5 YR 7/4 Pink	slightly moister but still dry		ev+	
		B3-2									Problems drilling hole straight re-augered
	10	110				?	slightly more orange sand than below 7.5YR 7/6 reddish yellow	slightly moist		ev+	
	15						transition?				disturbed? tried to realign hole changed bit
							pale tan vf sand cohesive enough to form small chunks 5% small granules of P€	dry		ev+	
	20	200		Photo 14			200-211 pale tan (lighter than below) vf sand and silt with 5% granules - smallest pebbles of P€	dry		ev++	
	25						211-261 tan vf sand + silt w/ 5% granules 10YR 7/4	moister		ev+	
		261									
	30										

Project: Hubbell Spring Fault
Project Location: Carrizo Spring Trench Site
Project Number: 26813901.00000

Log of Boring B3
Sheet 2 of 2

Elevation feet	Depth, ~~feet~~ 0.1m	SAMPLES Type	Number	Sampling Resistance, blow/foot	Recovery, %	Graphic Log	MATERIAL DESCRIPTION	Water Content, %	Dry Unit Weight, pcf	Unconfined Compressive Strength, psf	REMARKS AND OTHER TESTS
	30						all same vf sand and silt with 5-10% small pebbles + granules hole still resisting	slightly moist		ev+	
		-327									
	35						all same vf sand and silt with fewer ~~5-10%~~ small pebbles to 1cm granules but pale tan "floury"			ev++	
					S_2?		sample ~370 cm - looks like cc horizon fine to coarse silty sand with granules and carbonate nodules (originally mottled?)				(S_2?)
	40	412		Photo 15							
	45	-458-	468				gradational contact into Pebbly sand, darker tan vf sand and silt 10%-15% pebbles	slightly moist		e+	
	50						Unit 1			ev+	(S_1)
	55						38-76 above base - calcium carbonate accumulation with pebbles to 2cm, 10% hit cobble, could not grind through it	dry		ev++	
		-568					20-30 cm above base darker vf sand w/ 10% pebbles (P-E)	slightly moist		ev++	
	60										
	65										

URS

Report: GEO_10B1_OAK; File: WC_CORP2.GPJ; 10/16/2001