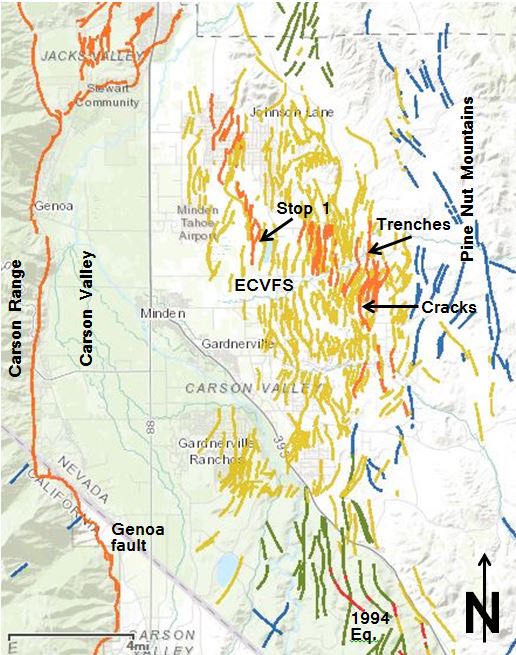
**The Eastern Carson Valley Fault System**

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The Eastern Carson Valley fault system (ECVFS) is a prominent set of Quaternary faults extending 21 to 26 km, the entire length of eastern Carson Valley. The system is made up of over 200 fault traces and is 8-10 km wide, about a third of the width Carson Valley. The ECVFS is a complex zone of subparallel, anastomosing, nested, and generally east-dipping faults (although there are some west-dipping faults). Individual faults are commonly 1 to 2 km long, but some are as much as 4 km long. Cross-strike distances between the fault traces are commonly 100 to 300 m, and as much as 1 km. The pattern of faulting may be inherited from Miocene extensional faults, such as exists in the Singatse Range to the east. The fault system has normal dip-slip displacement and probable right-lateral strike-slip movement as well (oblique slip or bi-slip – alternating preference). Faults of the ECVFS have been mapped by Moore (1969), Dohrenwend (1981), dePolo and others (2000), and the younger ruptures were mapped by dePolo and Ramelli (2005 – *in* dePolo and Sawyer, 2005). Scientists from the Nevada Bureau of Mines and Geology (NBMG) have investigated a few interesting aspects the ECVFS, including documenting aseismic slip along one of the fault traces, mapping the geology of the area, mapping out the youngest rupture, and conducting exploratory trenching.

**Figure 1.** East Carson Valley fault system (ECVFS) and other faults mapped in the Carson Valley area. Orange faults have moved in the last 15 ka, yellow in the last 130 ka, and green and blue are earlier Quaternary. Note the younger rupture crossing through the ECVFS. Also indicated are STOP 1, the location of the aseismic cracks, the location of the trenches, and the location of the 1994 Double Spring Flat earthquake (Mw 5.8) cracks.

**Local Geologic Setting**

The local setting is one of small northerly striking fault-bounded hills and flats, with local streams flowing westward, transverse to the faults. These streams generally down cut through the hills, spill into the flats, and have small fans as they approach and spread out on the Carson Valley floor. The hills are mostly made up of Pliocene and Quaternary sediments, with some Mesozoic rocks exposed in the southern portion of the fault system, near the southern end of the valley. Mammal and fish fossils have been found in these sediments, including rhinoceros bones and horse teeth (Kelly, 1994; Kelly 1997), and the boundary between the Hemphillian and Blancan land mammal ages has been documented using fossils, Ar/Ar dates, and magnetostratigraphy (Lindsay and others, 2002).

Some of the folks that have done research on these Neogene sediments include Don C. Noble (1962 Stanford Dissertation on the geology of the southern Pine Nut Range), Thomas S, Kelly (e.g., 1997 PaleoBios, paleontologist Museum of Los Angeles who studied the mammalian fossils), Tom Muntean (2001 Master’s Thesis on the stratigraphy of the Gardnerville basin), and and Chris D. Henry (~2000, Nevada Bureau of Mines and Geology scientist who sampled interbedded volcanic ash beds and developed Ar/Ar dates for them). The following paragraphs below from Tom Muntean’s Master’s Thesis (2001) give a short summary of the Sunrise Pass Formation:

Neogene sedimentary rocks are exposed on the western flank of the Pine Nut Mountains in western Nevada. The sedimentary rocks, previously unnamed, have been defined in this study as a new formation, the Sunrise Pass Formation. The rocks of the Sunrise Pass Formation were deposited in a separate and unique basin, the Gardnerville Sedimentary Basin, and record the evolution of the Sierra Nevada - Basin and Range transition zone during the time period from >7.02 Ma to <1.9 Ma (based on age control from 40Ar/39Ar isotopic dates, mammal fossils, and a single tephra correlation).

The Sunrise Pass Formation, ~3500 meters thick, is comprised of fluvial, deltaic, and lacustrine sediments. The rocks are conglomerate, sandstone, siltstone, and diatomite. Volcanic ash beds are frequently interbedded within fine-grained sediments.

The Sunrise Pass Formation unconformably overlies Mesozoic granite in numerous locations. The sediment overlying granite is different ages in different places, and the ages young westward. From east to west, unconformity ages are: >7.02 Ma, -6.5 Ma, ~5 Ma, and ~2.5 Ma. There is no evidence of unconformities within the Neogene section.

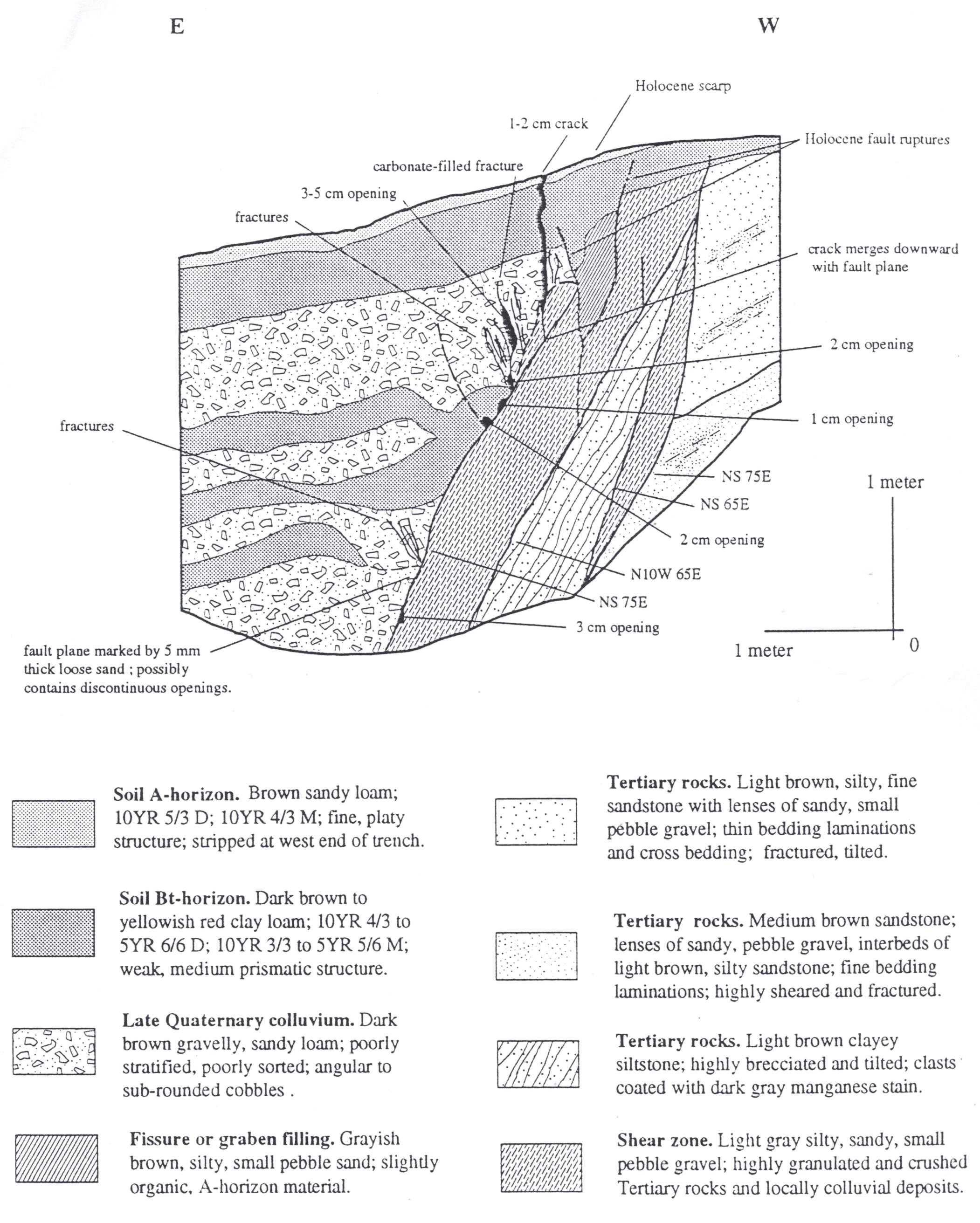
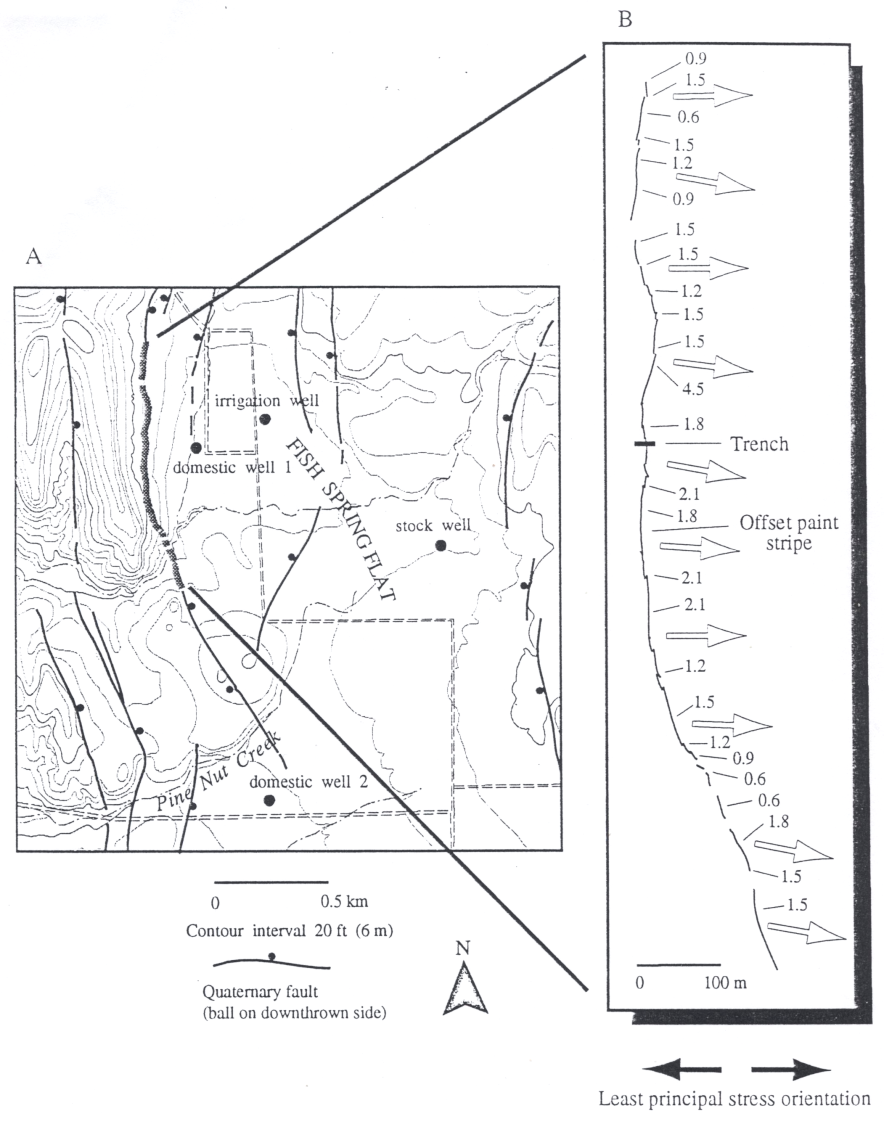
The fanning of dips in the Sunrise Pass Formation records

progressive westward tilting throughout its depositional history.

Local 1:24,000 geologic mapping was done by Garside and Rigby (2009; Geol. Map McTarnahan Hill Quad.) and dePolo and others (2000; Preliminary geol. map Gardnerville Quad.). Locally, the Neogene sediments dip around 25° to 30° W in the eastern part of the area, and shallow to around 15° W near the valley floor.

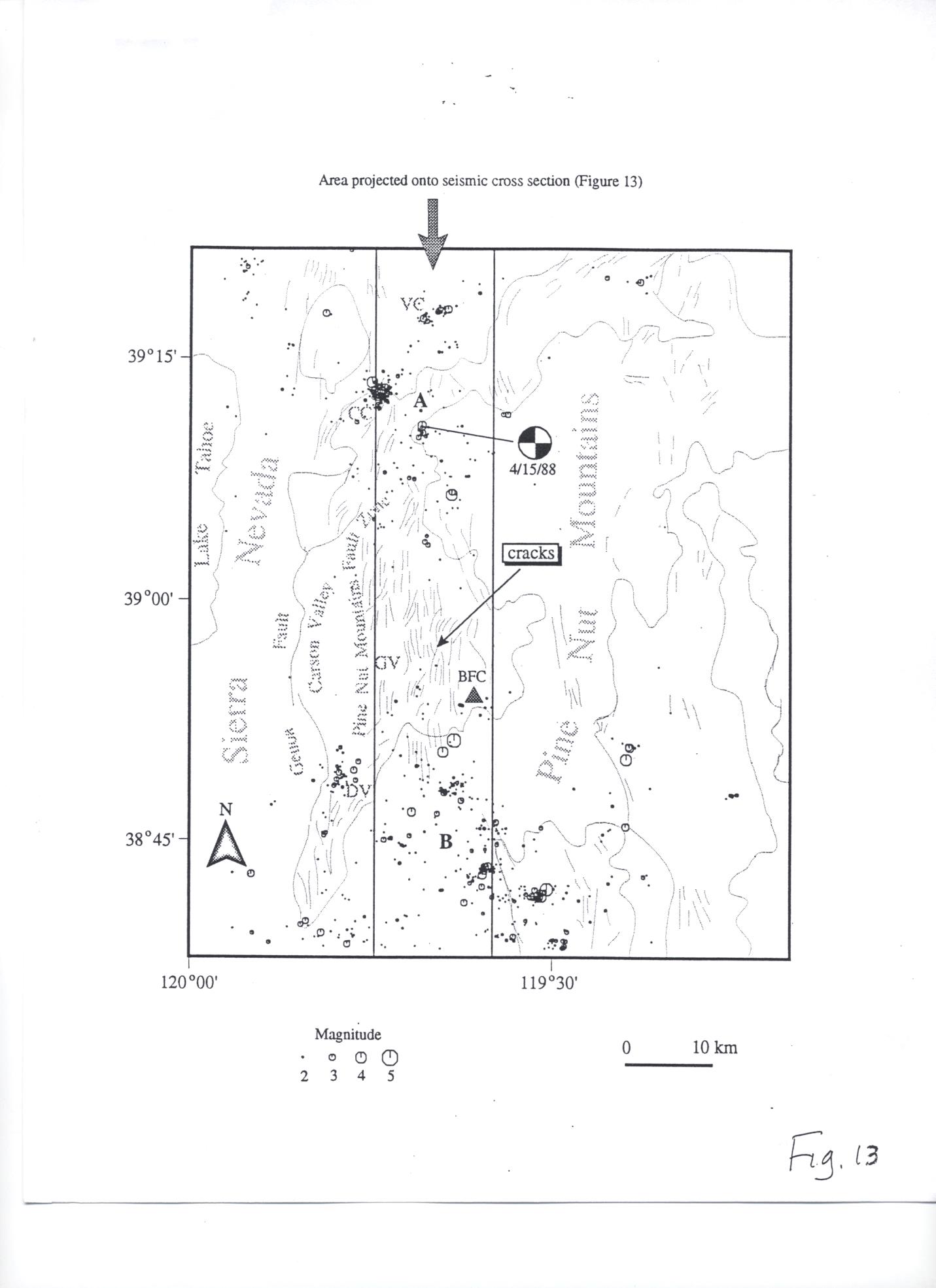
**Aseismic Cracking**

During the summer of 1988 John Bell of NBMG was informed that a fault within the ECVFS (the Fish Springs Flat fault zone) had a 1-km-long crack along it (Bell and others, 1993, unpublished; Bell and Helm, 1998). John led the investigation of this feature and this summary is extracted from the Bell and others (1983, unpublished) and Bell and Helm (1998) papers. Upon inspection it was observed that the crack was along what looked to be the youngest rupture on a compound fault scarp (an inflection in the scarp slope). The crack was 0.6- to 4.5-cm wide; the northern 2/3rds was northerly striking whereas the southern third had a NNW strike; and the indicated an extension direction across the crack was 90° to 101° (fig. 2). John Bell trenched the crack and found it was directly connected to the fault forming the scarp (fig. 2). He also found openings as wide as 3 cm along the fault and splay faults, evidence of prior cracks, and evidence of discrete displacement deposits, including the most recent event. Thus, the fault appears to have two modes of displacement, cracking and larger offsets likely formed during earthquakes. We could not detect progressive slip with time along the crack although one of our paint stripes across the fault showed 1-2 cm of right slip in March 1989. Three main hypotheses were entertained at the time for the 1-km-long crack: 1) the crack was related to a small earthquake, 2) the crack was related to local groundwater withdrawal, or 3) the crack was related to aseismic movement of the fault. A seismometer from the Nevada Seismological Laboratory was located in Buffalo Canyon at the south end of the ECVFS. We were able to examine helicorder records from this station for a month prior to the report of the cracking (discovered by local residents shortly after it formed) and there were no local earthquakes that could have been related to the crack (fig. 3). Don Helm, a hydrologist for the NBMG, modeled the hydrology of Fish Springs Flat using the dimensions of the basin, estimated/known alluvial fill, and pumping rates from local water well data and concluded it was unlikely that the cracking was due to local groundwater pumping; groundwater levels had been stable for at least five years prior to the cracking. That left the aseismic movement hypothesis for the formation of the crack (Bell and others, 1993 unpublished). Desiccation cracking (too low clay content – generally gravelly loam) and a landslide hypothesis (crack crossed flat lying sediments in places, no previous landslide scars) were also considered but were ruled out. In 1994, a magnitude 5.8 earthquake (Double Springs Flat earthquake) occurred just south of the ECVFS (fig. 1). Another crack formed over the same section of Fish Springs Flat fault zone, this time as triggered or sympathetic slip related to a nearby regional earthquake. These cracks did not result in significant displacement on this fault, which appears to mostly occur during larger coseismic events. In the summer or fall of 2004, another crack was reported to have formed under a reservoir about 3 km NNW of Fish Springs Flat. Trenching of that crack by consultants indicated that it was not along a discrete fault and carbonate-filled fractures indicated there were previous cracking episodes in that area.



**Figure 2.** These figures are from John Bell and others (1993, unpublished). Above is the cross-crack trench. Lower left are a map of the crack area and crack extension directions.





**Figure 3.** These figures are from John Bell and others (1993, unpublished). Above left is a section of the crack (center of photo). Lower right is seismicity 1983 through 1992. The strike-slip focal mechanism is from a small earthquake near Carson City that occurred in 1988. Although this event was very small this mechanism shows right-lateral strike-slip movement along a north-south nodal plane, possibly similar to events along the ECVFS.

**Geomorphic Expression from Paleoseismic Ruptures**

The main geomorphic expressions of paleoseismic activity, young scarps, inflections on hillslopes, and a set of tectonically offset stream terrace remnants. The youngest rupture showed up distinctly on low-sun-angle photography taken by Dr. Burt Slemmons of the University of Nevada, Reno (figs. 4 and 5) and was visible to us in Fish Springs Flat when we studied the aseismic crack. Using the fault map created by dePolo and others (2000) Alan Ramelli and I mapped out the extent of the youngest ruptures (example shown in fig. 5). Although there is a central rupture in the middle, there are numerous young breaks off to the sides that also appear to be young ruptures and appear to all be about the same age. Young ruptures were also discovered just south of Hot Springs Mountain and were trenched by Gary Luce for an engineering project. One trench exposed the young rupture as a fault and colluvial wedge deposit. Within this deposit was a piece of charcoal that yielded a radiocarbon age of 302-905 cal ybp; this date would postdate the most recent event. There is a small gap with a cross-strike distance of 2 km between the two groups of young ruptures, where surface breaks either weren’t present or were too small and/or eroded away to be detected. The fault pattern is less dense in this area as well. The zone of young ruptures has an end-to-end length of about 17 km and a width of 4 to 7 km. Overall the ruptures have a northwest trend and a crude left-stepping nature (this is complicated by a large amount of overlap between adjacent fault traces). The heights of the fault scarps are variable but are as much as 1 m.

A possible explanation for these young ruptures is that an earthquake with a significant right-lateral strike-slip component created them. This paleoearthquake may have been made up of two subevents or had two areas of larger displacements. The ECVFS appears to be made up of normal faults that accommodate extension and there is no reason not to expect that normal dip-slip earthquakes occur along the system. This brings up the possibility of a bi-slip fault system that can accommodate both extensional and translational events as the conditions dictate. Additional support for a strike-slip component on the ECVFS are slickenlines from on fault that indicated a lateral component, apparent reverse slip on faults in trenches, steeply dipping faults that have potential flower structure, and juxtaposition of thickness of some units across faults.



**Figure 4.** In the stone-age days before LiDAR early humans still had some tools at their disposal. Dr. David “Burt” Slemmons (Univ. of Nevada, Reno) and Lloyd Cluff (PG&E Co.) pioneered a technique that used actual sunlight grazing the Earth as a low angle to shadow or highlight fault scarps as small as 30 cm high. This was called low-sun-angle photography. The above low-sun-angle aerial photograph of the ECVFS shows tectonogeomorphic features including the youngest surface breaks along the system.**Figure 5.** Enlargement of a faulted horst from Figure 4. These shadowed and highlighted scarps are the most recent surface rupture (PE1).

**Trenching Studies**

Tom Sawyer and I had three trenches excavated in the area of tectonically offset stream terrace remnants, one on each terrace (fig. 5). We chose this location because of the strong geomorphic expression of paleoearthquakes, but also because this was a first order fault in the system (Fish Springs Flat fault zone) and the site included the youngest rupture (so we could get a relatively complete history of back in time). The fault zone was clearly exposed in all three trenches and the geologic units were distinct.

**Trench 1**

Trench 1 was through the fault scarp on the lowest terrace remnant (figs. 5 and 6). The scarp trends N5°E and has about 80 cm of vertical offset across it. A sequence of four Holocene fluvial, alluvial, and eolian deposits were exposed throughout the trench. Units 2 through 4 were offset by the fault in a single event. Unit 1a is an actively forming colluvial wedge deposit that is buttressed against the fault scarp. The fault zone is made up of many near vertical fault traces forming a 2.3-m-wide zone that can be divided into a distributed eastern zone of fractures and faults, and an intense 30- to 50-cm-wide western fault zone where most of the 82-90 cm vertical displacement occurred (consistent with surface offset). The faults all strike N10°E, a very clean pattern that is consistent with offset from a single event. There is some juxtaposition of facies and unit thickness across some faults that likely indicate some strike-slip offset. The faults in the trench all strike 5° more easterly than the fault scarp. This is consistent with these faults being in a wrenching, left-stepping pattern.

**Trench 2**

Trench 2 was across a 2-m-high fault scarp in the face of the second highest stream terrace remnant, about 30 m south of Trench 1 (figs. 5 and 7). The scarp trends N15°E and has a vertical surface offset of ~2 m. Trench 2 exposes a 3-m-thick stack of colluvial, alluvial, and fluvial deposits in the hanging wall, and mostly Plio-Pleistocene alluvium in the footwall, covered by some alluvium and with an argillic soil where it forms the terrace surface. The Plio-Pleistocene deposits are thinly bedded to massive sands and silts that have some fluvial structures, including cross-laminations. With exception of a few faults and fractures, the Plio-Pleistocene sediments are relatively undisturbed. In the hanging wall, units 6 and 7 are massive colluvial gravelly sands that include significant amounts of the Plio-Pleistocene sediments making them grayish; unit 6 grades into an alluvial deposit in its western part and lower part. Unit 5 is discontinuous and is made up of fluvial gravelly sands and sandy gravels. Unit 5 may have formed when the hanging wall was at the intermediate terrace level. Units 1-4 are dominated by poorly sorted, matrix-supported colluvium. These sediment packages tend to thicken towards the fault scarp and are involved in the damage zone of the main fault. Unit 4 is a gravelly, clayey, fine to very fine sand that has some alluvial parts (units 4a and 4b) away from the scarp. Unit 3 is a very well-developed colluvial wedge deposit that is a cobbly, gravelly, clayey coarse to very fine sand. Unit 2 grades westward from colluvial to alluvial deposits. Near the scarp, the deposit Unit 2b is a poorly sorted, matrix supported gravelly, clayey fine sand, and has a well-developed proximal facies and stone line at its base. Unit 2a has a large eolian input and forms an Av horizon. Unit 2 has a well-developed polygenetic Bt horizon in the western part of the trench that may correlate with the soil on the intermediate terrace surface (we call this polygenetic because there appears to be input from the argillic soil on the terrace that is washing down the slope). Unit 1 is a poorly sorted, matric supported, cobbly, gravelly, silty, clayey, fine to very fine sand and is an actively forming colluvial wedge deposit.

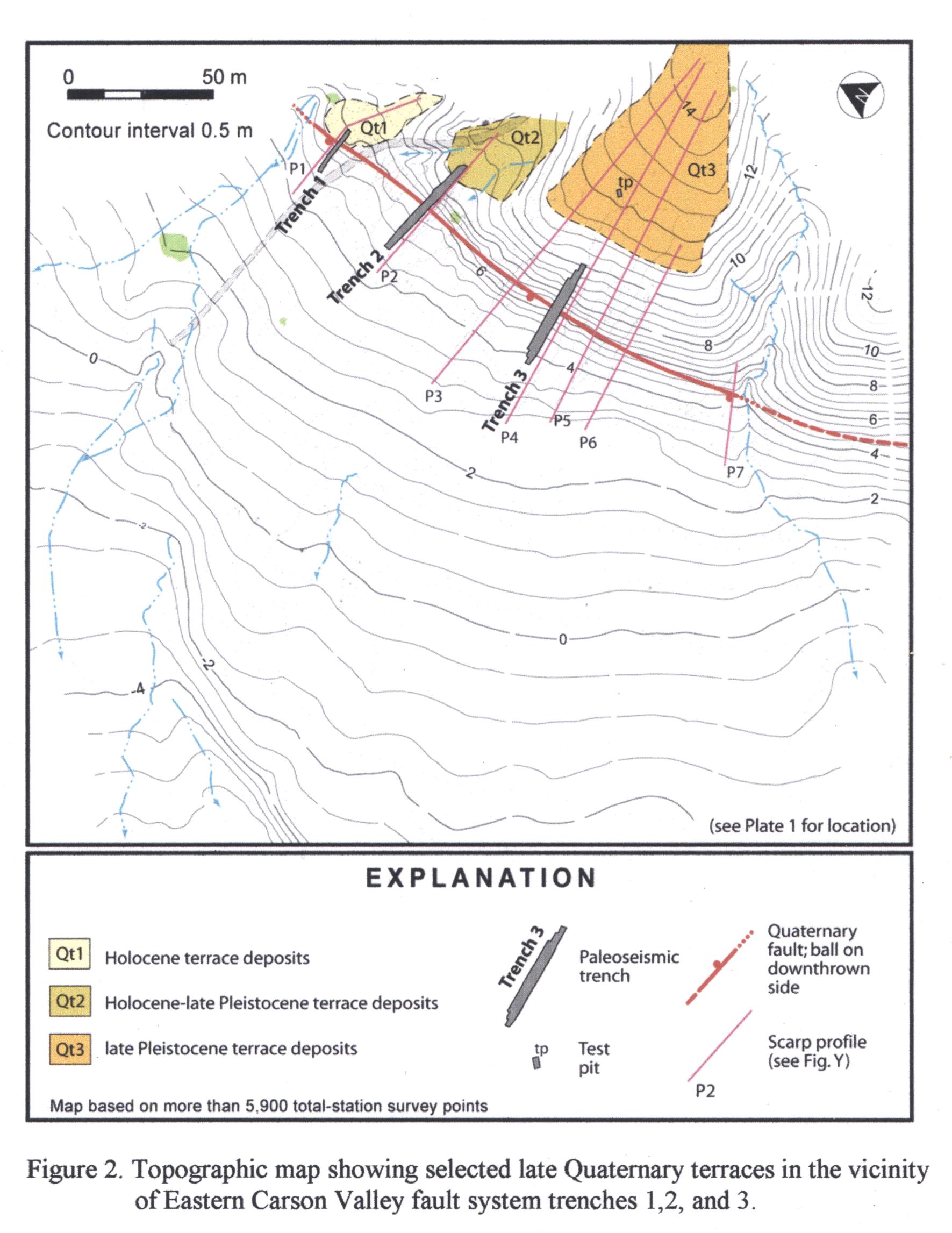
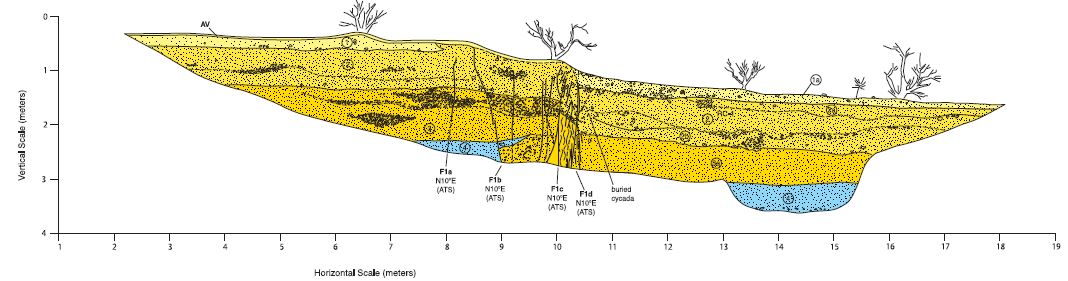
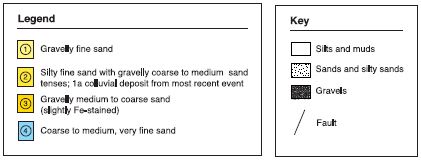
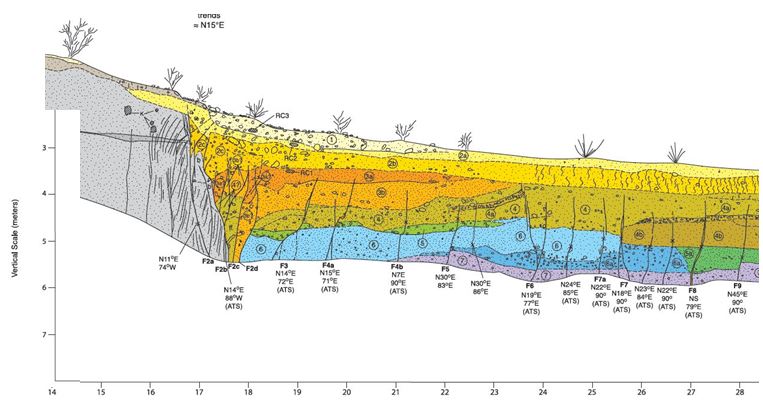
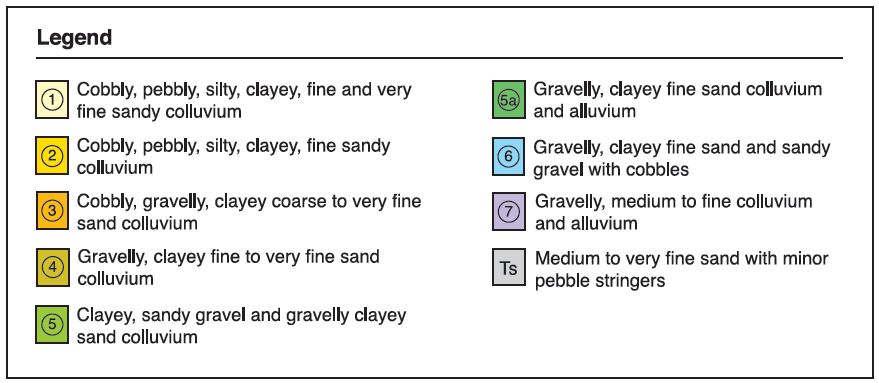
**Figure 5.** Trench location map showing terrace remnants

Figure made by Tom Sawyer with robotic total station and mountain bike.

**Figure 6.** Trench 1. dePolo and Sawyer (2005)



**Figure 7.** Partial log of Trench 2. dePolo and Sawyer (2005).

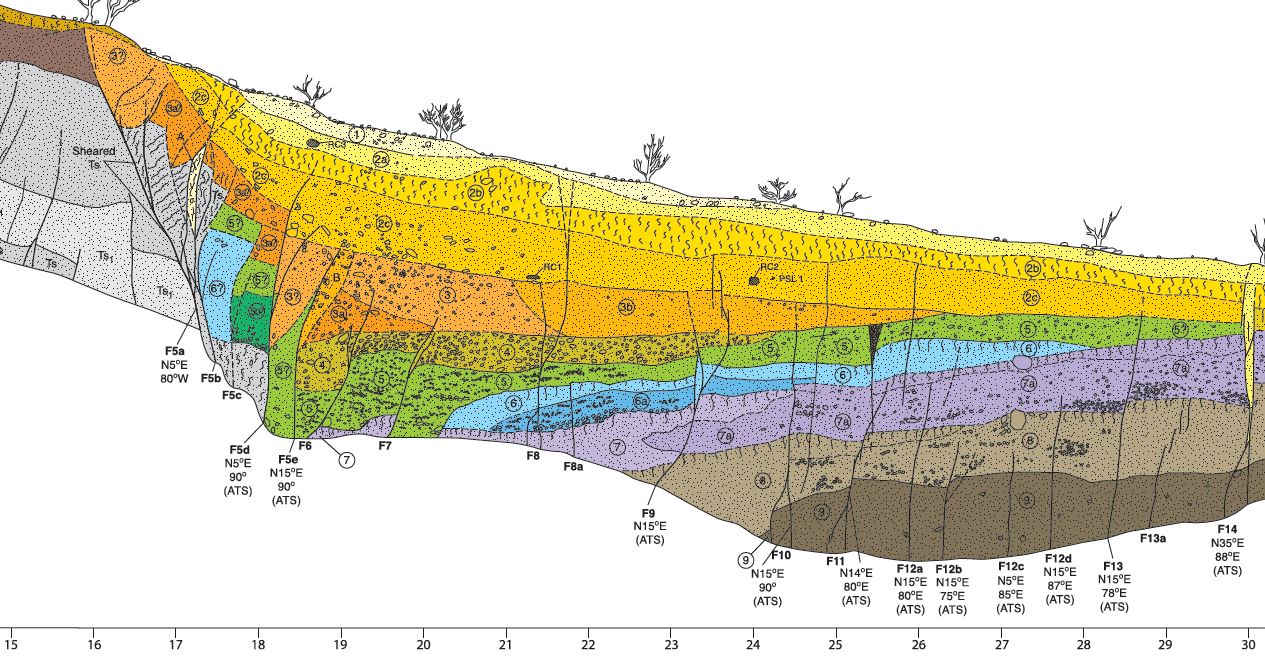
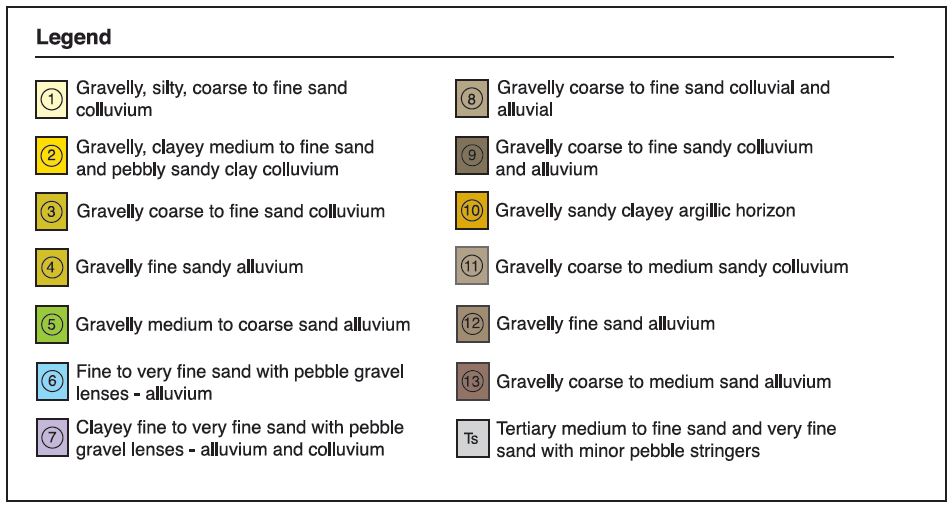
A 17-m-wide fault zone was exposed in Trench 2 (fig. 7). The main fault between the Plio-Pleistocene sediments and the colluvium has a N15°E strike, the same as the orientation of the fault scarp. The zone has an anastomosing character and dips 88° to the west. Within about 4 m of the main fault, faults are parallel to the scarp as well. In contrast, most faults that are greater than 4 m away from the main fault have 15° to 20° more easterly strikes, consistent with a left-stepping, wrenching pattern of faulting. Between 6 and 8 m west of the main fault is a second fault zone (F6, F7, & F8) that is a little more easterly striking than the scarp and exhibits unit truncations and thickness juxtapositions that would be consistent with strike-slip movement. This secondary fault zone also has about 40 cm of apparent down-to-the west displacement across it. It seems like the juxtaposition of units indicates greater lateral offset than the apparent vertical displacement – if so, this would be a dominantly strike-slip fault trace. Fault F11 formed a fissure and has an apparent reverse offset; this is also a candidate for a strike-slip component.

The most recent event (**paleoearthquake 1, PE1**) had a 30 cm apparent vertical offset, down-to-the-west, seen in the offset of the base of unit 2a; this is also the thickness of the associated colluvial wedge, unit 1. The best estimate of the age of PE1 is bracketed between two bulk radiocarbon ages from Trench 2, RC3 from unit 1, 520-726 cal ybp (2 sigma), and sample RC4, which was taken from the north wall in the same position as RC2 in the Trench 2 log. Sample RC4 is from just below the buried surface on unit 2a, and is 678-921 cal ybp. Assuming these dates are representative, PE1 at the trench occurred between 520 and 921 years ago. **PE2** offset the surface and unit 2 formed as a corresponding colluvial deposit. An estimate of the offset of the base of unit 2b is 90 to 110 cm, and subtracting PE1 gives an estimate of 50 to 80 cm of apparent vertical offset for PE2. **PE3** is associated with the deposition of colluvial units 3a and 3b, which show some back-rotation into the fault caused by PE1 and PE2. Apparent vertical offset at the main fault is about 110 cm after removing later offsets, but it is unclear how much of this is related to the depression that is forming immediately adjacent to the main fault. **PE4(?)** is related to a fissure fill deposit along fault F2c that is below unit 4(?); this may indicate that unit 4 may be a colluvial deposit related to an offset event. There may be older events evident in Trench 2 as well. Units 6 and 7 are also colluvial deposits that have large inputs of the Plio-Pleistocene deposits making them gray; these were likely derived from a fault scarp exposing the Plio-Pleistocene sediments.

**Trench 3**

Trench 3 was 50 m south of Trench 2 and exposed stratigraphy that was similar to that trench (figs. 5 and 8). The excavation was across a large 6-m-high compound fault scarp in the highest terrace remnant. Fourteen different units could be identified in Trench 3. Plio-Pleistocene medium to fine sands with pebble stringers; these are identical to those in Trench 2. Three thin alluvial packages overlie the Plio-Pleistocene sediments, and some faults within the footwall offset all these sediments. An argillic horizon as much as 30 cm thick capped the sediments in the footwall. In the hanging wall, the same seven units exposed in Trench 2 were exposed in Trench 3, with the addition of two older alluvial deposits, units 8 and 9.

The trench exposed a 25-m-wide zone of faulting. The main fault (fault F5) has strike of N5°E that is close to the scarp orientation (N2°E), dips 80°W, and has numerous synthetic faults splaying off into the hanging wall. Some of these splays have apparent reverse displacement. There are several secondary faults in the hanging wall with a spacing of 0.5 to 2 m. Most are simple faults with limited offset, and all have more easterly strikes than the main fault, indicating a wrenching pattern. Fault F14 has a filled fissure associated with it and strikes 30° more easterly than the main fault. Between the main fault and fault F14, the deposits appear to be tilted to the east, back rotated into the main fault. Faults in the footwall have N1-3°W strikes and appear to be older than the hanging wall faults.



**Figure 6.** Partial 1:1 log Trench 3. dePolo and Sawyer (2005).

There is evidence for at least three paleoearthquakes in Trench 3, and the possibility of as many as three additional events that have weaker evidence. PE1, PE2, and PE3 are evidenced by the three upper colluvial deposits, units 1, 2, and 3, respectively. Faults that moved during **PE1** include F5a, F5b, F5d, F8, F9, F14, and possibly F11 and F13. **PE2** produced an offset at the main fault of over 1 m as indicated by a colluvial wedge (unit 2a, 2b, 2c) that is 1.4 m thick at the fault. In addition, a 20 cm wide fissure opened on fault F5e. Several faults moved during PE2, including F5c, F5d, F6, F7, F8, F9, F10, and possibly F13 and F14. **PE3** also had almost a meter of offset as indicated by the colluvial wedge unit 3, which tapers to zero thickness 8 m west of the scarp. Unit 3 has well developed colluvial wedge facies with a coarser proximal facies (unit 3a) and a fine grained distal facies with a large eolian input (unit 3b). Faults that moved during PE3 include F5d, F6, F7, and possibly F5e and F11. **PE4(?)** is related to colluvial unit 4. In addition to probable offset at the fault, a small fissure was formed along fault F11, that although not structurally unique to unit 4 (i.e., it could have formed from PE3), it is filled with material that is akin to unit 4 and assigned to that event. Some earlier events may be indicated by upward terminations of faults in the lower part of the trench, but these may have also been limited breaks formed by the younger events.

Unfortunately, there were limited dating funds with this project and although the youngest dates seem reasonable, older bulk radiocarbon dates were somewhat inconsistent with soil features so more work has to be done in understanding the age of these colluvuial packages. I have many additional samples collected than can be dated, but have not been able to get back to this project. At the time of the project many scarps in the eastern part of Carson Valley were being levelled for farming and we used the remaining budget to trench, log, and sample an additional five trenches (some with only an hour or so to work in them). These logs and samples still need to be worked up and may give some insight to the western part of the system.

**Summary**

The late Quaternary ECVFS is a complex system with hundreds of fault traces. As a possible explanation for this complexity, the system may be the reactivation of a complicated pattern of faults inherited from Miocene extension. There are several indications that this system has a right-lateral strike-slip component. Given the range-bounding fault on the west side of Carson Valley, the Genoa fault, has normal dip-slip motion, the ECVFS appears to accommodate some partitioned lateral motion of the Walker Lane belt in this area. The youngest event on the Genoa fault is thought to be about 300 ybp (Ramelli and Bell, 2014). Thus, the most recent event on the ECVFS appears to have occurred a couple to few hundred years before the MRE on the Genoa fault. As far as potential earthquake size, offsets appear to be on the order of 1 m (although potentially more if the strike-slip component is significant) and the length of the recent surface rupture is between 9 km (if the groups of ruptures are independent events) to 17 km. Estimates based on these lengths yield potential moment magnitudes of 6.5 ±0.2 . The complex pattern of faulting will also likely manifest itself in a wide spread surface rupture pattern during the next major earthquake along the system, creating a significant surface rupture hazard for the eastern Carson Valley. Aseismic and sympathetic cracking along faults may also occur.

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