Road Log

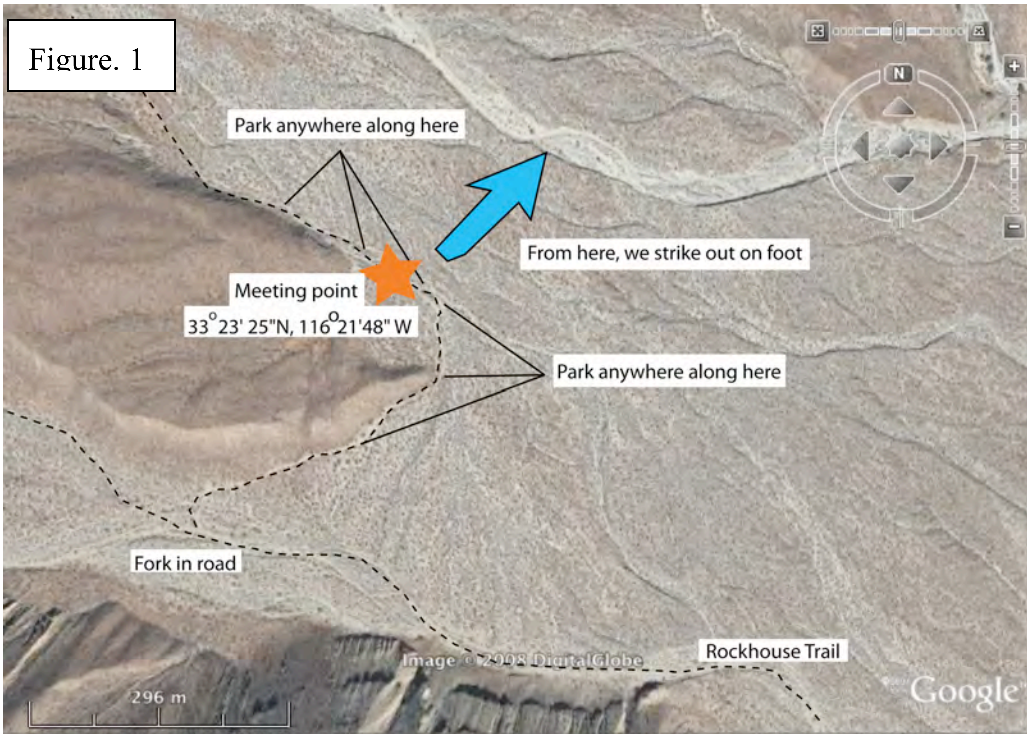
Day 1 November 14th (Friday): Clark fault

Muster at 7:30 am. We will line up along the camp road and head east.

Stop 1. Rockhouse Canyon

Turn **left** (north) on **Yaqui Pass Road** (S3) and proceed for about **6.7** miles to **Borrego Springs Road** - turn **left** (which is to the west at this point) and proceed **5.4** miles (road will bend to the north) to the *circle at Borrego Springs* and turn **right** (to the east) onto **Palm Canyon Drive**. Proceed east past the airport (which is at about 3 miles) and continue for about **7.5** miles to **Rockhouse Trail** (just past the nose of Coyote Ridge). Turn **left** onto **Rockhouse Trail**. From here the road is *unpaved*.

Figure. 1



DO NOT GET STUCK IN THE SAND!

Drive for about **1.5** miles until the road forks and keep left on Rockhouse Trail **(Figure 1).** At another **~2.1** miles, the road bends sharply to the right near the entrance to a small quarry. Continue on Rockhouse Trail (to the right). In another 3.05 miles, the road essentially enters a wash bottom. Continue on Rockhouse Trail for another **~2.7** miles up the wash to a fork in the road near the entrance to a canyon (on your left-straight). You will turn **right** here and go around the nose of the hill about **0.4** miles and park for the long hike. At this point, you are at about 9.75 miles from pavement.

You must park off of the road (i.e., other off-roaders need to have passage). This means that you may end up parking somewhere near the nose of the hill. We will set out on foot from here. See the map detail - the GPS coordinate for the orange star is: **33° 23' 25"N, 116° 21'48" W**. If you have 4WD, take the tougher spots to park - let the 2-wheelers have the hard ground.

The hike is about 4.5 miles overall as the crow flies (see **figure 2**), but there will be elevation change. Plus, there is no trail, so the actual hike will likely be 5-6 miles. We start at ~380 m elevation and will climb to ~650 m elevation (that's ~900 feet of total elevation change, both ways). We will have lunch on the fault, so bring all the food and water you need for the next few hours.

On this trek, we will examine two channels that have been beheaded by the Clark fault. Within the channels are debris flow boulder deposits that we dated with ^{10}Be dating (see Le et al. in prep. guidebook article) to resolve slip rates over two periods of time. We will discuss problems with inheritance of ^{10}Be concentrations, look at fault geomorphology, discuss stream capture models and uncertainties on our estimates of displacement. This is just a spectacular section of the Clark fault!

We will plan to spend as much as 5 hours for this hike, as needed.

Upon returning to the vehicles, turn around and head back to the highway and wait for the lead vehicle. We will proceed east on for about 7.5 miles and park on the side of the highway in a large pull-out area **(Figure**

Figure. 2

3). From here, we will proceed on foot for our second (shorter) hike to the fault - **STOP 2**.

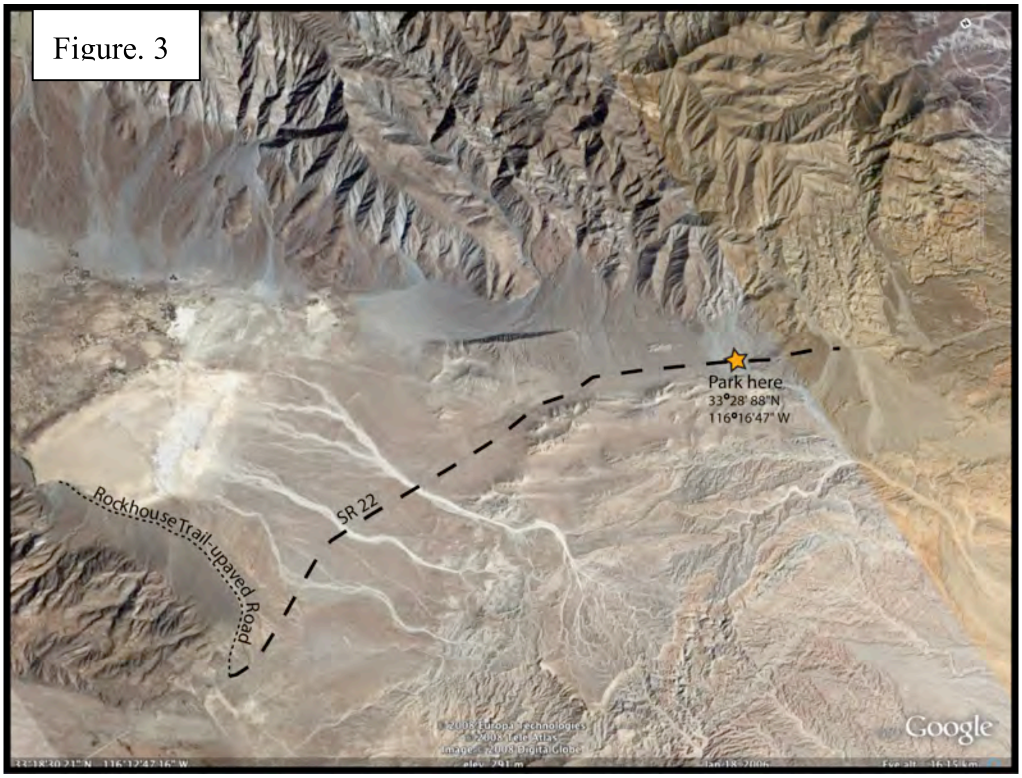
Stop 2. Southern Santa Rosa Mountains

GPS 33° 17' 28.88"N, 116° 10'16.47" W

From the car, we will walk towards the southern Santa Rosa Mountains and across a Holocene alluvial fan surface with well-preserved bar and swale topography. Two sets of Pleistocene alluvial fan deposits are exposed at this location, Qg and Q2b. The oldest deposit, Qg, is an erosional remnant that appears as high rounded mound-like outcrop. These deposits consist of variably weathered pebbles to boulders exposed on a coarse pebbly sand matrix. The Q2b alluvial fan, exposed just northwest of Smoke Tree Canyon, is inset into the Qg deposits. Q2b fans are characterized by relatively smooth to slightly undulating surface morphology. Q2b fan surfaces exhibit strong desert pavement and varnish development, moderate to strong rubification of surface clasts, and very subdued remnant bar and swale microtopograghy.

Starting at the northwestern end of the fault, multiple fault strands horizontally and vertically offset the Q2b surface into a positive flower structure. The Clark fault continues to the south as a single strand. Post Q2b displacement of 51 ± 5 m along the Clark fault is constrained by two deflected channels and at least one beheaded channel. A cosmogenic depth profile was

Figure. 3



collected from a natural exposure of the Q2b deposit (see Le et al., in prep). This yielded a surface exposure age of 35 ± 7 ka. If we assume no erosion of the surface, this yields a slip rate of 1.5 ± 0.3 mm/yr. Erosion of the surface would make the age older, resulting in a slower slip rate. Please see Le et al., in prep in the field book for more details.

Day 2 - Saturday, November 15th. Age of the San Jacinto Fault, Basin History, Long-Term Slip. Rate See Fig. 4 for general location of stops.

Stop 1: Borrego Springs Airport (33° 15.447' N, 116° 19.532' W)(see road directions from Day 1). **Overview and introduction**. (NOTE: we may drive a short north on a dirt road located about 0.4 mi. west of the airport, in order to get a better view). From here we can see the SW edge of Coyote Mountain and the SW side of the Santa Rosa Mountains (see photos in the guidebook). Figure 5 shows the points of interest on the north edge of San Isidro Mountains (likely not in view), SW edge of Coyote Mountain (CM) and the SW part of the Santa Rosa Mountains. Look for the white marble-rich intervals between the biotite and hornblende-bearing tonalite to the west and the dark weathering biotite-rich migmatite to the east (figs 5 and 6). These units correlate across the fault zones. Table 2 (in Janecke et al guidebook article) shows the displacement estimates from this analysis as well as the lifetime slip rates. (See Figures 1 to 10 and Appendix figure 1, 2 of the associated guidebook articles.)

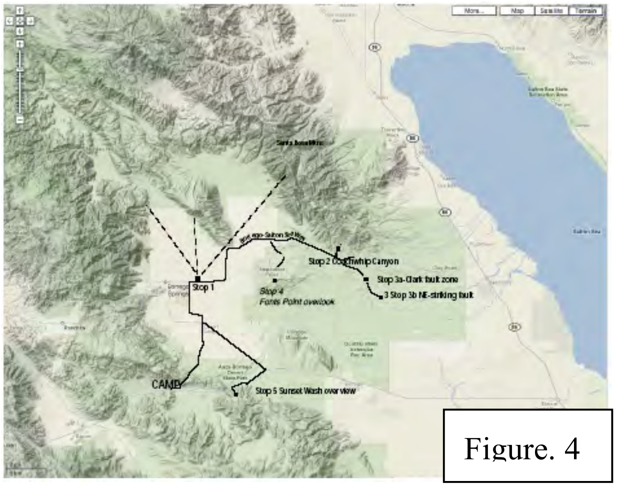


Figure. 4

Figure. 5

Figure. 6

Drive NE from stop 1 along the Borrego-Salton Seaway highway toward Salton City. About 8.5 miles from the airport is Lute Ridge to the north. This prominent hill has an escarpment on its far, NE side that coincides with the main trace of the Clark fault. Numerous smaller scarps displacement the pediment that lies in angular unconformity on folded older Quaternary conglomerate. Figure 10 in the associated guidebook article shows a new interpretation of the uplift in Lute Ridge and the folding in low hills a few kilometers to the NW. We interpret this area as preserving extensional and contractional steps between subparallel strands of the dextral Clark fault zone. See Belgarde (2007) for details.

Continue driving east to the turn-off into Coachwhip Canyon on the left/north side of the road. The turn off is not all that well marked. Drive about 0.5 miles to stop 2.

STOP 2. STOP 2: Coachwhip Canyon (33° 17.428' N, 116° 8.949' W). Figure A3, A4 and A5. Figure 9, 10, 12, 13. Park and examine the multiple strands of the Clark fault that parallel bedding in pebbly sandstone of the fine Canebrake and coarse Olla formations. The beds dip south and the faults do too. Microseismicity shows that at least one strand of the Clark fault about 0.5 km farther up the canyon dips steeply to the SE at depth (Fig. 17)(Belgarde, 2007). This requires a bend in the fault plane and reversal of the dip direction.

Notice the well-developed clay gouge in excellent exposures of the fault. Other parts of the fault have almost no gouge and could be mistaken for intact bedding planes, particularly in areas of typical exposure. This exposure of the fault is along strike of a scarp in late Pleistocene pediment deposits. Refer to figures 5, 6, 11, 12 and 13. OSL ages range from 21.72 ± 1.19 to 62.26 ± 4.05 ka in these pediment deposits (Rittenhour, Janecke and Belgarde, unpublished).

Coachwhip Canyon illustrates the character of the Clark fault zone in moderately well-lithified units like the Canebrake Formation. Faults dominate in these settings. Where mud becomes a major constituent, folding becomes much more common in the fault zone and the Clark fault broadens (Fig. 15). The Clark fault zone is up to 18 km wide in map view in the Arroyo Salada and Tarantula Wash segments (Belgarde, 2007) (Fig. 13).

Exit Coachwhip Canyon. Drive east on the paved highway to the turn-around and pull-out at 33° 17.044'N 116° 7.788'W. This is about 1.5 miles to the east. The scarp that coincides with the fault exposed at stop 2 is located about 2/3 of the way from Coachwhip Canyon to the turn around. On the way to the turn-around notice the numerous SW-facing fault scarps on the pediment surface. Each of these scarps is along strike of a bedding parallel fault strand of the Clark fault zone in Coachwhip Canyon. We dated this pediment deposit in an exposure about 1 km SSE of the turn around. From the turn-around it is about 1 km SSE to the location of a dated portion of this pediment surface. A fine-grained sand-bearing bed near the base of the pediment deposit produced a late Pleistocene OSL age of 30.71 ±2.34 ka OSL age (Rittenhour, Belgarde, and Janecke, unpublished data).

Turn around and drive back to Arroyo Salada. Turn south opposite Coachwhip Canyon and drive ESE down Arroyo Salada, past the primitive campground, for about 3.5 miles. Two wheel drive is adequate unless it has rained.

Stop 3a: Clark fault zone in Arroyo Salada (33° 15.363' N, 116° 6.559' W). A wide steep fault zone is exposed in the west wall of Arroyo Salada (Belgarde, 2007). This is one of the main strands of the Clark fault zone in the Arroyo Salada segment. Note how the main fault planes parallel bedding planes and are very thin. Prior to a fortuitous rock fall, this fault zone looked like it was intact stratigraphic section. Slickenlines range in direction and include an important population of strike-slip slickenlines. If stop 3a is poorly exposed due to weathering, continue SE to stop 3b. This stop further illustrates the hidden faulting in the sedimentary units. This fault was mapped as a minor thrust fault by Jarg Pettinga but the horizontal slickenlines show that it is instead a major central strand of the Clark fault zone. At least half a dozen similar strands parallel this one, and there is significant deformation dispersed across a region ~18 km wide perpendicular to the fault zone at this spot (Figs. 10, 11, 12, 14,16).

Stop 3b: alternate to stop 3a (33° 14.305' N, 116° 5.804' W). If stop 3a has been covered over by gully wash or we are running ahead of time, continue to stop 3b another 1.7 to 2 miles to the SSE. Drive SE past the turn-off to 17 Palms and turn right into a narrow track leading to Tule Wash. Whenever the road splits turn left or follow any signs to Tule Wash, and drive to the fault exposed at stop 3b. This smaller fault has a NE strike and is a left-oblique strike-slip fault. It is exciting because it is one of a large population of NE– to E-striking left-oblique faults that dominate the SW 40% of the Clark fault's damage zone in the Arroyo Salada and Tarantula Wash fault segment (Fig. 12). The deep structure beneath these left-oblique faults is completely different, however, and consists of a 6-13 km deep planar fault, which is called the Tule Wash fault (Belgarde, 2007)(Fig. 17 and 18). The Tule Wash fault dips steeply NE and passes beneath the shallow and subvertical NE-striking faults exposed at the surface. A decollement surface must separate the incompatible structures at the shallow and deep levels. We envision a left-oblique fault array on an "overpass" and a steeply NE-dipping dextral fault on an "underpass" (Janecke and Belgarde, 2007, 2008)(Figs. 12, 17, 18). Decollements and pitchfork fault structures, like those modeled by Le Guerroué and Cobbold in Figure 19 E, may facilitate this behavior.

Crossing strike-slip faults also interfere with one another at the same structural level in other parts of the field area (Fig. 11). Mutual interference and mutual bending developed in these situations.

Turn around and return to pavement. Drive west on the Borrego-Salton Seaway Highway for about 5.5 miles. Turn SW (left) into Fonts Wash and follow the signs and track up to Fonts Point in the south.

Stop 4: Fonts Point (33° 15.454' N, 116° 13.958' W). The view looking south from Fonts Point provides a breath-taking vista of the Borrego and Ocotillo formations exposed in the southern Borrego Badlands, as well as other features including Borrego Mountain which is cut by strands of the Coyote Creek fault, the complexly faulted eastern of the Peninsular Ranges, and low-lying sedimentary rocks of the western Salton Trough. Here we are standing at the top of a precipitous erosional escarpment that is currently retreating to the north as a result of ongoing uplift and erosion in the Borrego Badlands. Figure A11.

The Ocotillo Formation is exposed beneath and east of Fonts Point in the erosional escarpment. Using magnetostratigraphy calibrated with the 0.76-Ma Bishop Ash, the sharp base of the Ocotillo Formation was dated at 1.05 ± 0.03 Ma (Lutz, 2005; Lutz et al., 2006). This contact records abrupt expansion of alluvial-fan and fluvial systems that prograded rapidly into and across the former Borrego lake depocenter at this time. Paleocurrent data show that coarse sediment entered the basin from multiple newly emergent sources located south and SW (Vallecito Mts.), west and NW (San Ysidro Mts.), north (Coyote Mt.), and NE (southern Santa Rosa Mts.) of the Borrego Badlands depocenter (Lutz et al., 2006). A systematic up-section increase in C-suite sandstone clasts recycled from the Arroyo Diablo Formation provides evidence for uplift and exhumation of the former hangingwall basin of the WSDF (ibid). Isopach and facies patterns record syn-basinal titling to the NE in response to growth of the San Felipe anticline and oblique slip on the Clark fault (ibid). Based on this and companion studies by Kirby et al. (2007) and Steely et al. (in press), we conclude that rapid progradation of the Ocotillo and Brawley formations across the western Salton Trough was driven by a dramatic increase in sediment flux from the eastern Peninsular Ranges at ~1.1 Ma. This marks a major, tectonically controlled basin reorganization that resulted from initiation of the San Jacinto and San Felipe fault zones and related onset of uplift and erosion in the former hangingwall of the Late Cenozoic West Salton detachment fault.

The Fonts Point Sandstone (FPS) is a thin, well-cemented, widespread sandstone characterized by a stripped calcic paleosol with deep calcite-filled fissures, which in this area rests on the Ocotillo Formation. Lutz et al. (2006) inferred that deposition of the FPS began at ~0.60 ± .02 Ma based on: (1) presence of the 740-ka Thermal Canyon ash in the upper Ocotillo Formation, 49 m below the contact with the FPS; (2) a likely range of sediment-accumulation rates based on correlation to the nearby, well dated Beckman Wash section; and (3) detailed mapping and visual inspection of the contact which indicate that the Ocotillo-FPS contact in this area (from Fonts Point to Inspiration Point) is concordant and conformable. Subsequent mapping by Dorsey around Inspiration Point supports this interpretation. Farther to the north and south, the base of the FPS is clearly an angular unconformity that truncates early folds and faults in the western Borrego Badlands. Our preferred age for the FPS is not 100% confident and deserves to be further tested. Recent dating of nearby Quaternary terraces and pediment deposits using cosmogenic isotopes (Le et al, this volume) and OSL (T. Rittenour, Janecke and Belgarde) reveals that many terrace deposits that superficially resemble the mesa-capping FPS have much younger ages ranging from about 20 to 60 Ka. Although the deep, stripped nature of calcic paleosols in the FPS suggests that it probably is much older than most of the Late Quaternary pediment deposits, we cannot be certain there was no break between deposition of the uppermost Ocotillo Formation and the basal FPS, even where the contact is concordant and appears conformable. New data are needed to resolve existing uncertainty in the age of the FPS and the depositional - deformational events that it brackets.

Return to pavement and drive past Borrego Springs to the Yaqui Narrows area. Turn east into Nude Wash north of the Narrows. Park where the wash is no longer drivable and hike SW along the wash for about 0.3 miles. Admire the exceptional exposures of pseudotachylyte and fault rocks

(Kairouz, 2005, Steely, 2006; Janecke et al. (2008)) on the way to an overlook at Stop 5.

Stop 5: Overview of San Felipe fault zone (33° 7.962' N, 116° 17.264' W). This stop (which is based on Steely, 2006 and Steely et al., in press) illustrates the typical relationship between Pleistocene to Recent strike slip faults and Ocotillo Formation. We are located within a double contractional stepover of the San Felipe fault zone. This relatively unknown dextral strike slip fault reaches from the NW Elsinore fault to the SE part of the San Jacinto fault zone. It is about 60 km long from end to end. In the Yaqui Ridge area there is a cross-cutting relationships between the San Felipe fault zone and the older West Salton detachment fault, as well as syntectonic deposits shed from the nascent San Felipe fault zone. Structurally, the San Felipe fault zone steps left from the large fault on the N side of the Fish Creek Mountains and Vallecito Mountains (the Fish Creek Mountains fault) to the San Felipe fault. The San Felipe fault is south of here under San Felipe Wash and at the base of Yaqui Ridge. A small fault called the Sunset fault is parallel to these two larger structures and lies a couple hundred meters NE of our stop. Slip steps from the Fish Creek Mountains fault to the Sunset fault and then SW to the San Felipe fault. A thick section of folded and faulted conglomerate is north of the Sunset fault, whereas the folded West Salton detachment, mylonite and other crystalline rocks lie south of the Sunset fault. See Steely et al. (in press) for an overly long structural discussion of this stepover.

Our purpose today is to illustrate the stratigraphic and sedimentary record of initial slip in the San Felipe fault zone. The conglomerates that we can see from here, on the NE side of Sunset Wash, were correlated to the Pliocene Canebrake Conglomerate by Dibblee (1954). Detailed mapping and analysis by Steely et al. (in press) shows that this conglomerate correlates instead to the early to middle Pleistocene Ocotillo Formation. The Canebrake is derived from the footwall of the West Salton detachment fault (Axen and Fletcher, 1998; Kairouz, 2005; Steely, 2006). The conglomerate along Sunset Wash does not contain a single clast of mylonite derived from the footwall of the detachment fault, despite being located as little a 300 m NE of the detachment fault. Its provenance was exclusively in the hanging wall of the detachment fault and most of the sediment was shed from displaced and uplifted plutonic rocks immediately SW of the Sunset fault (See figures in Steely et al., in press). Paleocurrents show dispersal to the NE, grain size decreases in that direction, and the composition and grain size are perfectly concordant with those in the Ocotillo formation nearby. Boulders up to 4 m across near the Sunset fault attest to active tectonism within the San Felipe fault zone and across the Sunset fault during deposition of the conglomerate. An angular unconformity, missing units beneath the Ocotillo Formation about a km SE of here, and the presence of recycled sandstone clasts derived from the Pliocene Arroyo Diablo Formation further support our interpretation.

Very similar relationships exist adjacent to the San Jacinto fault zone, and show that the Ocotillo formation, and its finer lateral equivalent, the Brawley Formation, were deposited in a new sedimentary basin ringed by brand new dextral oblique strike slip faults. The Ocotillo formation thickens by a factor of ~2 NE toward the Clark fault from a condensed section near Font's Point (Stop 4)(Lutz et al., 2007). The Ocotillo Formation coarsens in that direction and contains distinctive clasts shed from the NE side of the Clark fault. Paleocurrents indicate southward flow. Westward thickening and coarsening, and eastward paleocurrent show that the East Coyote Mountain fault was an active structure within the San Jacinto fault zone starting about 1.05 Ma (Lutz et al., 2006). A disconformity and angular unconformity separate the Ocotillo and Brawley formation from the underlying basin fill, and mark the change from syndetachment to syn-strike slip deposition.

Concluding remarks: Many lines of evidence now show that the San Felipe and San Jacinto fault zone are early Pleistocene dextral faults with high lifetime slip rates. Refined and new displacement estimates, combined with magnetostratigraphic dating of the Borrego/Ocotillo contact are the main constraint on this. In addition, the San Jacinto fault zone is far more complex and broad than generally thought. This is especially true where the fault deforms mud-rich sedimentary rocks but dispersed faults are also developed in the crystalline damage zone adjacent to the central part of the fault zone.

We believe that this dispersed deformation partly explains the lower slip rates determined in neotectonic studies (e.g. Le et al., this volume) when compared to slip rates inverted from GPS data and calculated using offset bedrock features (Fig. 8, tables 1 and 2)(Janecke et al., in prep.).
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Day 3 - November 16th (Sunday) Paleo-erosion rates, Elsinore fault, Lake Cahuilla

Today we head south to the Fish Creek Badlands, the Coyote Mountains, and end near Interstate 8.

From camp, head west on highway **78** about **7.5 miles** to Scissors crossing and turn **left** (south) on highway **S2**. Drive south for **~26** miles to Canebrake. You will drive through Earthquake Valley (renamed Shalter Valley by developers) along the Old (Great southern) Overland Stage Road (S2). Drive past Blair Valley and the Mormon Battalion monument in Box Canyon, through Mason Valley (look to your left - the Elsinore fault is clearly visible as scarps and channel deflections), down through Vallecito Valley, past the Tierra Blanca Mountains, and cross Carrizo Wash (the Elsinore fault is just to your left at this point). We will turn off the highway and head northeast through Badlands Wash to stop 1 **(Figure 7).**

Stop 1. Fish Creek-Vallecito Basin

We will turn **left** off the highway onto a **dirt road (Figure 7)**. The road is **Old Vallecito Overland Stage Creek Route**, there may or may not be a sign. From the road, you will drive ~ **0.5** miles, until you reach the intersection with **View of the Badlands Rd (another dirt road).** Drive for approximately **~0.5** miles and park along the road. The outcrop is **1.0** miles from the intersection of the two dirt roads. We will have a short hike to STOP 1 to view the Upper Hueso Formation.

At Stop 1, we will discuss the extraction of paleo-erosion rates from the sedimentary rocks deposited in Fish Creek-Vallecito Basin. We integrate stratigraphy, paleomagnetic data, and detrital ^{10}Be concentrations to extract an archive of paleo-erosion rates from 3 Ma to present. Please see field book for details.

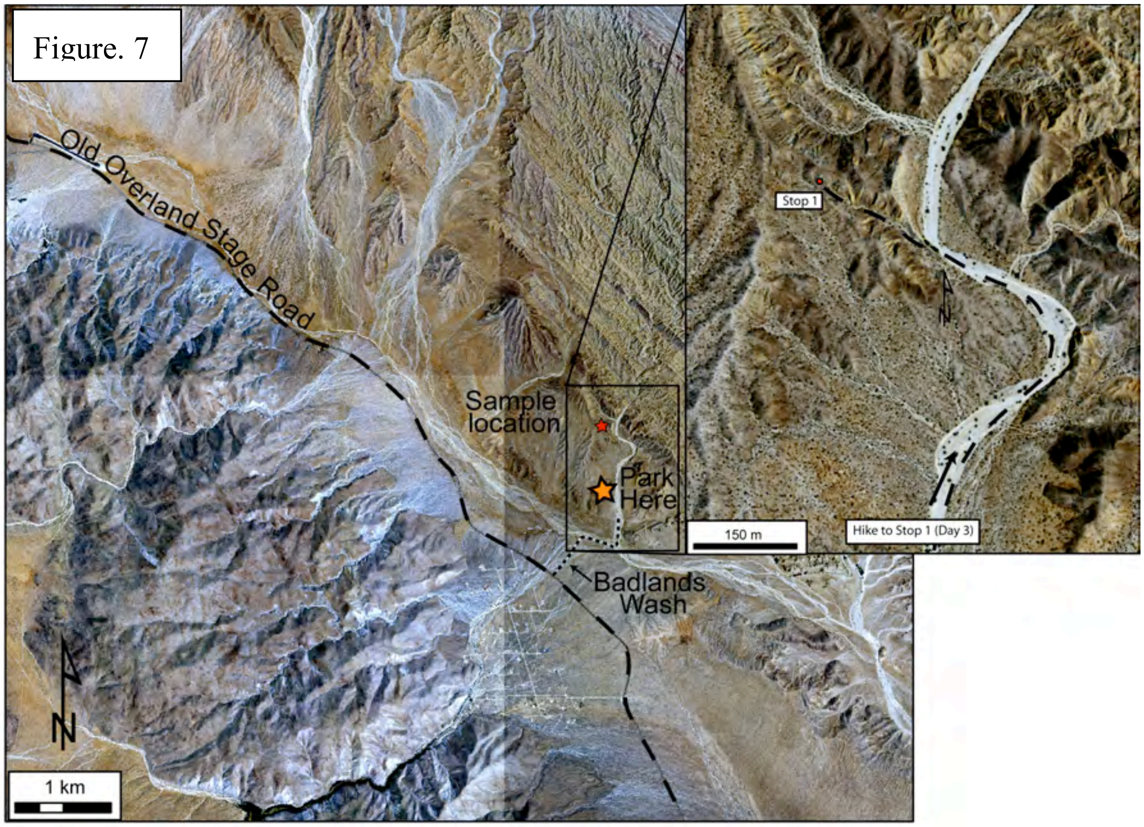
Figure. 7

From stop 1, head back up to highway S2 and continue south on S2 along the Coyote Mountains (to your left) for about **12** miles to Fossil Canyon Road at the stop sign. Turn left and head up towards the Coyote Mountains. The pave road makes several bends and crosses the fault - we will turn off the paved road to head towards Fossil Canyon just before the road heads into the quarry, about **2.2** miles from highway S2 (so we essentially go straight onto the dirt). From here, we continue on dirt for about **0.8** miles and park ALONG the road before it enters the gorge into Fossil Canyon. From here we strike out on foot to **STOP 2**.

STOP 2: Elsinore fault

We will walk about 1-1.5 miles total. The first stop is just a few hundred yards from where we park.

Here we will examine evidence for late Holocene displacement along the Elsinore fault for about 1.5 m of displacement in the most recent event. We will also see several ~5 m displacements that are interpreted as the result of three events. Then, we will look at soil pits dug into late Pleistocene deposits that are offset about 80 m, and from which we collected CRN samples and U-series samples. Here we debate the various geochronologic methods, their results, and their implications for slip rate determinations. See Fletcher et al. (this volume) for a complete discussion of the data and age comparisons. We will walk to other displaced deposits that we dated with U-series and discuss the local slip rate variations that appear to have occurred during the late Pleistocene.

After lunch, we head to our final stop of the fieldtrip. Return to pavement and back to highway S2. Turn left at the 4-way stop sign onto highway S2 and proceed 1.3 miles through the town of Ocotillo to old highway 80 (Evan Hewes Highway), immediately before the interstate 8. Turn left on old highway 80 and proceed about 11 miles through Plaster City to the late Holocene shoreline of Lake Cahuilla.

STOP 3: Lake Cahuilla Shoreline

Here we will discuss the Holocene history of the lake and OSL dating of shoreline berm deposits. See Lippincott et al. (this guidebook) for a discussion of this technique as applied to Lake Cahuilla deposits.

This ends the official part of the field trip. If there is still time, we will head back through Plaster City and examine some Pleistocene beach deposits of "Lake Cahuilla" - these are essentially the shoreline deposits for the upper Brawley Formation sediments.