Testing for slip rate changes on the Sierra Madre fault

Report for SCEC Award #16066
Submitted April 27, 2017

Investigators: Reed Burgette (NM State U), Nathaniel Lifton (Purdue U.), Katherine Scharer (USGS)

I. Technical Report

Objectives:

This project focuses on the slip rate of the central Sierra Madre fault (SMF), averaged over >≈100 ka. This longer-term Quaternary slip rate complements our previous SCEC-funded research on shorter-term slip rates for this fault based on late Quaternary (10-50 ka) fan terraces. The longer timescale of this project (1) provides context for the shorter duration slip rate estimates, and (2) yields slip rate information over a time scale when surface deformation may have progressively transferred away from the San Gabriel Mountains to active structures in the Los Angeles basin. The target of our investigation is a Middle Pleistocene (?) alluvial fan deposit which has been offset across the fault and preserved in surface and subsurface exposures. Sediment and surfaces with similar character exist along strike of the SMF (Crook et al., 1987; Morton and Matti, 1987; Yeats, 1987; DeVecchio et al., 2012), so the proposed dating will provide the first age estimate for an important marker along the entire SMF system. This improved SMF slip rate will better resolve the role of the SMF system in the broader LA Basin/Transverse Ranges area. Additionally, timing of Middle Pleistocene fan aggradation will aid in understanding Quaternary history and the ages of older deformed markers being studied in southern California, especially in the San Gorgonio Pass region (Owen et al., 2014; Heermance et al., 2014; Lifton et al., 2016).

1. Offset magnitude of the Middle Pleistocene surface

The oldest clearly preserved Quaternary surface along the SMF caps the Qal4 deposit on Gould Mesa, in the Pasadena area (Fig. 1). Previous work interpreted that correlative sediment is preserved in the subsurface footwall of the fault (Crook et al., 1987). We are reassessing previous interpretations of surface and well data, using 1) high resolution topographic data, 2) field mapping, and 3) compilation of available well log data. Targeted field mapping in the Arroyo Seco area is also important for constraining the stratigraphic and geometric relationships of the dateable horizons within the gravel deposit and the horizons used for the offset measurements. Based on our interpretations of existing work, the horizons we targeted in the Qal4 deposit will provide an age estimate for the distinctive upper soil of the deposit (Fig. 2), and will better constrain the slip rate for the frontal strands of the fault zone.

2. Cosmogenic nuclide dating

A paleosol in alluvial fan sediment exposed ~80 m below Gould Mesa was viewed as a prime target for isochron burial dating, as the now deeply buried sediment acquired significant levels of cosmogenic ^{10}Be and ^{26}Al at the surface. Our initial plan was to sample this layer to quantify the timing of the deposition of the Gould Mesa Qal4 deposit. However, once in the field, a lack of appropriate exposure of this paleosol required a rethinking of our strategy. We thus targeted coarse gravel layers with a range of lithologic source areas ca. 8 m below well-preserved portions of the upper red soil at the surface of Qal4 at two locations in hopes of capturing a spread of inherited nuclide concentrations - key to a successful isochron.

Methods:

Field work was completed between May 26-29, 2016. All PIs (Burgette, Lifton, Scharer) participated in the field work, accompanied by Dr. Devin McPhillips of the USGS Pasadena and NM State MS student Austin Hanson. We examined a reported paleosol (Crook et al., 1987) buried 80 m below the Gould Mesa surface, but appropriate exposures of the paleosol could not be located. The best exposure we found was on the upper surface of a ridge extending from the lower portions of a hillslope in upper Arroyo Seco – thus the exposure geometry was questionable, particularly for a burial dating application. The best alternative we determined was to sample fluvial or debris-flow gravels exposed ca. 8 m below the upper Qal4 surface (site 1, Fig. 1; Fig. 3A). All personnel participated in collecting the first set of samples (16SMF), while McPhillips returned the following week and collected the second set of samples (JPL) from a road-cut location agreed upon by the group (site 2,

Fig. 1; Fig. 3B). At each location, a representative range of quartz-rich cobble lithologies were collected (1-2 kg each) to maximize the chances of a spread in initial exposure histories that would enable a robust isochron.

Selected samples were individually photographed, crushed, and sieved to separate the 250-500 μm size fraction at New Mexico State University, before being sent to PRIME Lab at Purdue University for quartz purification and chemical processing. Quartz was isolated following standard procedures modified from Kohl and Nishiizumi (1992). Be and Al were isolated using standard procedures (Ochs and Ivy-Ochs, 1997) and analyzed by AMS for ^{10}Be and ^{26}Al, respectively. ^{10}Be/^{9}Be ratios were normalized to the material 07KNSTD (2.85 x 10^{-12}, using a ^{10}Be half-life of 1.39 x 10^{6} yr) (Nishiizumi et al., 2007; Chmeleff et al., 2010; Korschinek et al., 2010). ^{26}Al/^{27}Al ratios were measured relative to standard KNSTD prepared by Nishiizumi (2004) (4.694 x 10^{-12}, using a ^{26}Al half-life of 7.05 x 10^{5} yr). The total number of atoms in process blanks was subtracted from measured sample concentrations (Table 1).

Results:

1. Separation of the Qal4 surface across the SMF

The Qal4f surface that caps Gould Mesa is associated with an indurated, orange-red soil developed on fine-grained sediment overlying a thick cobble-boulder gravel deposit. The Qal4f surface is offset by two strands of the SMF in the vicinity of Arroyo Seco (Figs. 1 and 2). The southern fault trace, which bounds the southern base of Gould Mesa, is the more significant of the two traces. The total topographic relief across the southern escarpment of Gould Mesa is 155 m (Fig. 2). Additional vertical separation of the Qal4f surface across the southern fault is represented by the buried position of the top of the Qal4 surface in the footwall of the fault. Logged stratigraphy from boreholes and water well excavations south of the SMF yields information on the depth of this key horizon south of the SMF. We obtained logs for several wells in the Arroyo Seco area from the California Department of Water Resources. Additional boreholes and water wells have been interpreted in previous investigations (Crook et al., 1987; Converse Consultants, 1995). Logs from multiple wells report a distinct layer of finer grained sediment that is orange to brown in color, which is reported as being hard clay in some wells. This layer occurs at depths of ~50 to 100 m in the footwall of the SMF, and we interpret this horizon as being the paleosol that is correlative with the one capping Gould Mesa.

Our interpretation of this offset is similar to that reported by Crook et al. (1987). We benefit from additional wells that have been constructed in the JPL facility since the earlier study. The cross-section of Figure 2 shows a revised interpretation of the subsurface stratigraphy based on the additional well control. Our interpretation yields a thicker Qal4 deposit in the footwall of the frontal fault trace (in comparison to Crook et al., 1987), which is more consistent with the exposed deposit thickness in the hanging wall. Based on the revised cross-section, we estimate 230 ± 10 m of vertical separation of the Qal4f surface across the southern fault strand. The estimated uncertainty is based on the discrepancy between the top of Qal4 elevation reported in the two wells nearest to the fault trace (Fig. 2).

The northern fault strand offsets Gould Mesa by a smaller amount. The low angle Qal4f geomorphic surface is vertically separated by 31 ± 2 m across the northern fault trace (Fig. 2). We estimate the vertical separation based on two topographic profiles extracted from 0.5 m resolution lidar data in the vicinity of the Sample 1 site.

2. Age of the upper Qal4 gravel

Measured concentrations of ^{10}Be and ^{26}Al for both sets of samples are presented in Table 1. Concentrations were uniformly low and near detection limits, and did not provide a large enough spread to yield a robust isochron. As such, we averaged the lowest two ^{10}Be concentrations from each site (within 1 sigma) that also exhibited correspondingly low ^{26}Al concentrations (Table 1). By using the lowest ^{10}Be concentrations, we assume that the nuclide inventories are due solely to production at depth by the deeply penetrating muon component of the cosmic ray flux. For the Arroyo Seco site, the mean value is 8.77±1.09 x 10^{3} ^{10}Be at g^{-1}, and at the JPL site it is 9.38±0.84 x 10^{3} ^{10}Be at g^{-1}. Recent work by Balco (2017) compiled all available muon production rate data for in situ cosmogenic ^{10}Be and ^{26}Al and compared recent estimates of production parameters for each nuclide from both fast muon and slow negative muon capture reactions. MATLAB code from Balco (2017) yields a total muon production rate of ^{10}Be at the sample locations and depths (assuming parameters in Table 1) of 0.0555 at g^{-1} y^{-1}. We assume a 15% uncertainty on this rate, following Balco (2017). Combining this rate with the mean lowest ^{10}Be concentration at each site, we derive exposure ages of 164.6 ± 32.1 ka (16SMF) and 176.6 ± 30.9 ka (JPL). Since muon production is only weakly dependent on depth, we ignore erosion effects in the age calculation. Thus, although an exposure age neglecting erosion is strictly a minimum age, these ages should be reasonably robust for each deposit. We take the mean of the ages from both sites - 170.6 ± 31.5 ka - as representative of the exposure age of at least the upper 8 m of the Qal4 deposit.

3. Preliminary slip rate

We estimate the slip rate for the two strands of the SMF at Gould Mesa using a method that accounts for fault and marker geometry, and propagates relevant uncertainties (Thompson et al., 2002). Measured fault dips in the vicinity of the cross-section are consistently ~45° (Crook et al., 1987). The 45° subsurface dip of the southern trace is defined by boreholes in the hanging wall of this trace (Crook et al., 1987). We use fault dips of 45° ± 5° for both faults. Slip magnitudes for the two fault traces are estimated from the vertical separations described above. Dip-slip rates are then calculated with the age estimate for the Qal4f surface. The summed dip-slip rate across the two fault strands is $2.16\ ^{+1.06}/_{-0.55}$ mm/yr (2σ uncertainty).

This slip rate is greater than the ≤ 1 mm/yr slip rate we have estimated for this portion of the SMF based on offset late Pleistocene alluvial fan surfaces (Hanson et al., 2016). However, the rate averaged over the period since the late middle Pleistocene overlaps with a recent geodetic slip rate estimate of 2.7 ± 0.9 mm/yr for the SMF (Daout et al., 2016). The discrepancy in slip rates estimated over ~40 ka and ~170 ka time spans may be a result of irregular earthquake recurrence behavior, with the most recent SMF surface rupture having occurred ~8-9 ka (Rubin et al., 1998; Tucker and Dolan, 2001). Alternatively, the apparently slower rate observed in the late Quaternary could reflect strain progressively being transferred away from the San Gabriel Mountains over a time scale when fault systems to the south appear to be accelerating in rate (Bergen et al., 2017).

References:

Balco, G., 2017. Production rate calculations for cosmic-ray-muon-produced ^{10}Be and ^{26}Al benchmarked against geological calibration data. Quaternary Geochronology 39, 150–173. doi:10.1016/j.quageo.2017.02.001.

Bergen, K. J., Shaw, J. H., Leon, L. A., Dolan, J. F., et al., 2017. Accelerating slip rates on the Puente Hills blind thrust fault system beneath metropolitan Los Angeles, California, USA. Geology, doi:10.1130/G38520.1.

Burgette, R. J., Lifton, N., Scharer, K. M., McPhillips, D., & Hanson, A., 2016. Testing for slip rate changes on the Sierra Madre fault: Progress on dating an offset terrace surface of possible middle Pleistocene age. Poster Presentation at 2016 SCEC Annual Meeting, Abstract 6946.

Chmeleff, J., Blanckenburg, von, F., Kossert, K., Jakob, D., 2010. Determination of the ^{10}Be half-life by multicollector ICP-MS and liquid scintillation counting. Nuclear Instruments and Methods in Physics Research Section B 268, 192–199. doi:10.1016/j.nimb.2009.09.012

Converse Consultants West, 1995. Hydrogeologic investigation, Devil's Gate water collection tunnel, Pasadena, California, Report for City of Pasadena, 31 p.

Crook, R. Jr., Allen, C.R., Kamb, B., Payne, C.M., & Proctor, R.J., 1987. Quaternary geology and seismic hazard of the Sierra Madre and associated faults, western San Gabriel Mountains, Recent reverse faulting in the Transverse Ranges, California: US Geological Survey Professional Paper 1339: 27-64.

Daout, S., Barbot, S., Peltzer, G., Doin, M. P., Liu, Z., & Jolivet, R., 2016. Constraining the Kinematics of Metropolitan Los Angeles Faults with a Slip-Partitioning Model. *Geophysical Research Letters*.

DeVecchio, D. E., Heermance, R. V., Fuchs, M., & Owen, L. A., 2012. Climate-controlled landscape evolution in the Western Transverse Ranges, California: Insights from Quaternary geochronology of the Saugus Formation and strath terrace flights. *Lithosphere*, *4*(2), 110-130.

Granger, D.E., 2014. Cosmogenic Nuclide Burial Dating in Archaeology and Paleoanthropology, in: Treatise on Geochemistry. Elsevier, pp. 81–97. doi:10.1016/B978-0-08-095975-7.01208-0

Hanson, A., Burgette, R. J., Scharer, K. M., & Midttun, N., 2016. Late Quaternary slip rates from offset alluvial fan surfaces along the Central Sierra Madre fault, southern California. Poster Presentation at 2016 SCEC Annual Meeting, Abstract 6909.

Heermance, R.V., K.J. Kendrick, I. Dijarlais, D. Yule, P. McBurnett, and S. Ramzan, 2014. Geochronology of surfaces within the San Gorgonio Pass from radiocarbon, in–situ cosmogenic nuclides, and pedogenesis: implications for climate and tectonics since the mid–late Pleistocene. Southern California Earthquake Center Annual Meeting, September 6-10, 2014, Palm Springs, CA, poster 279.

Kohl, C., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of in-situ-produced cosmogenic nuclides. Geochimica Et Cosmochimica Acta 56, 3583-3587.

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., Gostomski, C.L.V., Kossert, K., Maiti, M., Poutivtsev, M., Remmert, A., 2010. A new value for the half-life of ^{10}Be by Heavy-Ion Elastic Recoil Detection and liquid scintillation counting. Nuclear Inst. and Methods in Physics Research, B 268, 187–191. doi:10.1016/j.nimb.2009.09.020

Lifton, N., Heermance, R. V., Yule, D., & Huerta, B., 2016. Isochron burial dating of paleosols within the Whitewater Fan, northern Coachella Valley, California. Poster Presentation at 2016 SCEC Annual Meeting, Abstract 6755.

Lifton, N., Sato, T., Dunai, T.J., 2014. Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes. Earth and Planetary Science Letters 386, 149–160. doi:10.1016/j.epsl.2013.10.052

Morton, D., Matti, J., 1987. The Cucamonga fault zone: Geological setting and Quaternary history. Recent reverse faulting in the Transverse Ranges, California: US Geological Survey Professional Paper 1339: 179–203.

Nishiizumi, K., 2004. Preparation of ^{26}Al AMS standards. Nuclear Instruments and Methods in Physics Research Section B 223, 388-392.

Nishiizumi, K., Imamura, M., Caffee, M., Southon, J., Finkel, R.C., Mcaninch, J., 2007. Absolute calibration of ^{10}Be AMS standards. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 258, 403-413.

Ochs, M., Ivy-Ochs, S., 1997. The chemical behavior of Be, Al, Fe, Ca and Mg during AMS target preparation from terrestrial silicates modeled with chemical speciation calculations. Nuclear Instruments and Methods in Physics Research Section B 123, 235–240. doi:10.1016/S0168-583X(96)00680-5

Owen, L. A., Clemmens, S. J., Finkel, R. C., & Gray, H., 2014. Late Quaternary alluvial fans at the eastern end of the San Bernardino Mountains, Southern California. *Quaternary Science Reviews*, *87*, 114-134.

Phillips, F.M., Argento, D.C., Balco, G., Caffee, M.W., Clem, J., Dunai, T.J., Finkel, R., Goehring, B., Gosse, J.C., Hudson, A.M., Jull, A.J.T., Kelly, M.A., Kurz, M., Lal, D., Lifton, N., Marrero, S.M., Nishiizumi, K., Reedy, R.C., Schaefer, J., Stone, J., Swanson, T., Zreda, M.G., 2016. The CRONUS-Earth project: a synthesis. Quat. Geochron. 31, 119–154. doi:10.1016/j.quageo.2015.09.006

Rubin, C. M., Lindvall, S. C., & Rockwell, T. K., 1998. Evidence for large earthquakes in metropolitan Los Angeles. *Science*, *281*(5375), 398-402.

Tucker, A. Z., & Dolan, J. F., 2001. Paleoseismologic evidence for a> 8 ka age of the most recent surface rupture on the eastern Sierra Madre fault, northern Los Angeles metropolitan region, California. *Bulletin of the Seismological Society of America*, *91*(2), 232-249.

Thompson, S. C., Weldon, R. J., Rubin, C. M., Abdrakhmatov, K., Molnar, P., & Berger, G. W., 2002. Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, central Asia. *Journal of Geophysical Research: Solid Earth*, 107(B9), 2203.

Yeats, R., Lee, W., Morton, D., Yerkes, R., 1987. Geology and seismicity of the eastern Red Mountain fault, Ventura County. Recent reverse faulting in the Transverse Ranges, California: US Geological Survey Professional Paper 1339: 161–167.

Table 1:

Sample Number	PRIME Lab ID	Mass Quartz *g*	$^{10}Be/^{9}Be$ *10^{-15}*	$[^{10}Be]$ *10^{3} at/g*	Native Al *mg*	^{27}Al carrier *mg*	$^{26}Al/^{27}Al$ *10^{-15}*	$[^{26}Al]$ *10^{3} at/g*
Site 1 - Arroyo Seco								
16SMF-03	201602272	16.403	9.57 ± 1.09	**9.01 ± 1.13**	2.036	–	23.94 ± 3.58	66.32 ± 9.92
16SMF-04	201602273	18.817	10.29 ± 1.14	**8.52 ± 1.03**	0.3088	1.2321	37.92 ± 5.95	66.81 ± 11.06
16SMF-07	201602276	26.200	27.30 ± 1.71	16.90 ± 1.10	2.282	0.5483	59.68 ± 5.63	143.11 ± 13.59
16SMF-08	201602277	19.231	14.50 ± 1.51	11.95 ± 1.32	3.945	–	17.72 ± 2.98	81.14 ± 13.63
16SMF-13	201602282	14.312	8.87 ± 1.39	9.53 ± 1.64	5.064	–	6.23 ± 1.75	49.18 ± 13.78
16SMF-14	201602283	10.407	6.45 ± 0.75	9.12 ± 1.24	5.805	–	7.73 ± 1.85	96.19 ± 23.01
Site 2 - JPL								
JPL-03	201602392	17.447	12.60 ± 1.82	11.71 ± 1.78	0.3894	1.0178	42.97 ± 4.81	77.37 ± 8.76
JPL-04	201602393	4.244	3.35 ± 0.62	11.51 ± 2.82	0.3617	1.0947	11.49 ± 3.48	88.02 ± 27.24
JPL-06	201602395	17.272	13.49 ± 1.15	12.52 ± 1.15	0.4951	1.1542	49.21 ± 5.66	104.90 ± 12.16
JPL-07	201602396	39.910	22.25 ± 1.62	**9.15 ± 0.70**	2.164	–	71.35 ± 6.70	86.36 ± 8.10
JPL-09	201602398	38.307	22.61 ± 2.18	**9.60 ± 0.96**	0.7722	0.7844	90.23 ± 6.93	81.84 ± 6.30
JPL-12	201602401	24.975	19.50 ± 1.55	12.65 ± 1.06	0.5066	0.7559	82.58 ± 8.31	93.19 ± 9.41

Notes: 0.25 mg Be carrier added to each sample. Blank of (4.61 ± 1.46) x 10^4 at ^{10}Be/mg ^{9}Be carrier and (3.82 ± 3.00) x 10^4 at ^{26}Al/mg ^{27}Al carrier (when used) subtracted from SMF samples, and (2.90± 2.35) x 10^4 at ^{10}Be/mg ^{9}Be carrier and (0.00 ± 2.18) x 10^4 at ^{26}Al/mg ^{27}Al carrier (when used) subtracted from JPL samples. Site 16SMF (Arroyo Seco) coordinates: 34.210432°N, 118.175375°W, 469 m. Site JPL coordinates: 34.205611°N, 118.173516°W, 467 m. Assumed sample depth – 775 ± 25 cm, deposit density: 2.2 ± 0.2 g cm^{-3}, yielding a mass depth of ca. 1700 g cm^{-2}. Assumed long-term atmospheric pressure at site 960.79 hPa. **Bold** values of ^{10}Be concentrations were averaged for each site and taken as the most likely to reflect an exposure age from pure muon production at depth.

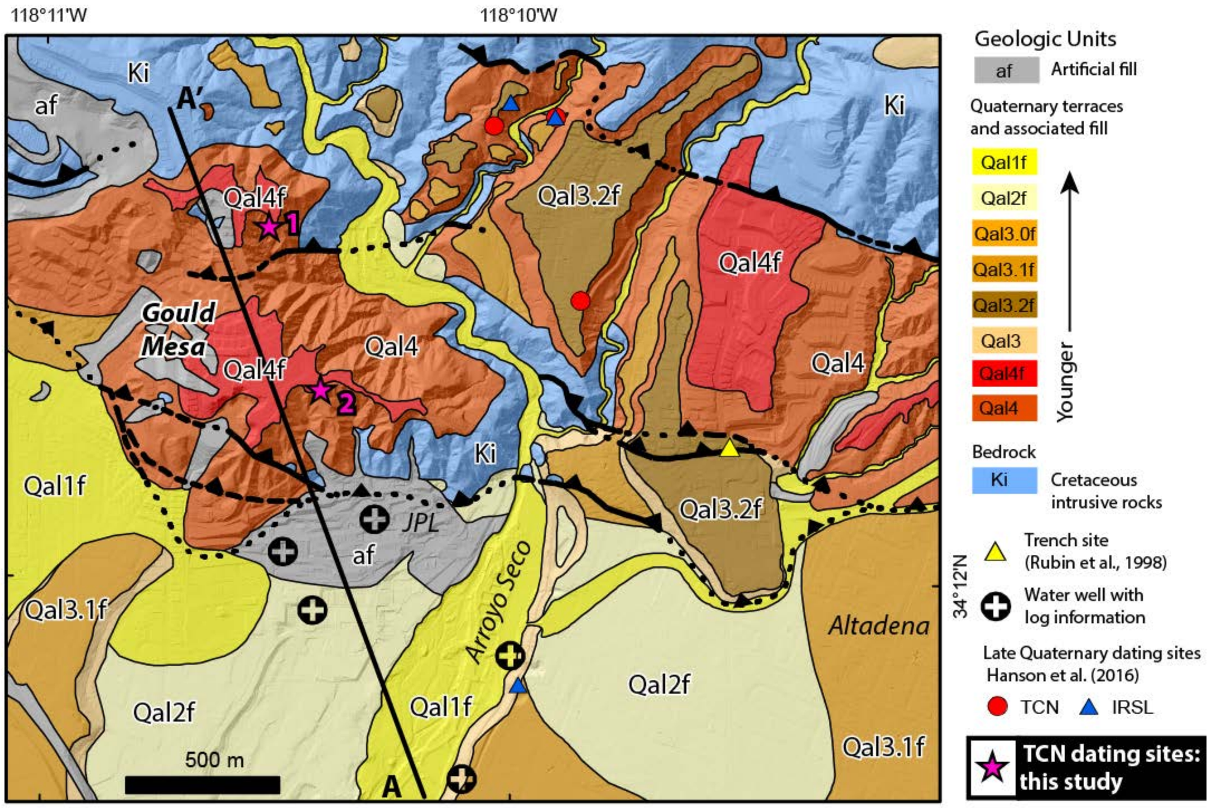


Figure 1. Geologic map of the Arroyo Seco area showing sampling locations. Geology modified from Crook et al. (1987) with our observations, draped over shaded relief derived from 0.5 m bare-earth USGS lidar data (Hanson et al., 2016). Well data in the footwall of the SMF constrain the subsurface positions of the upper and bottom contacts of the Middle Pleistocene Gould Mesa Qal4 deposit (Crook et al., 1987).

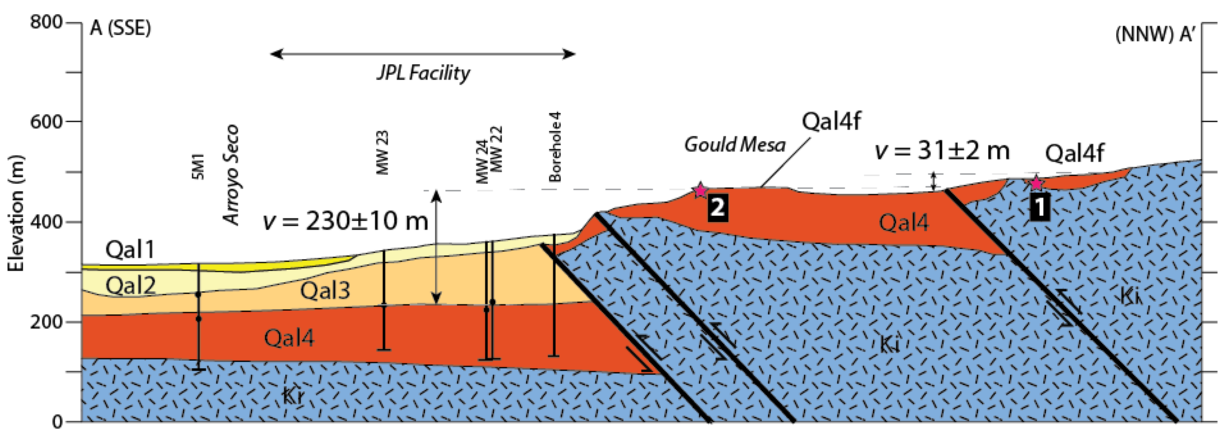
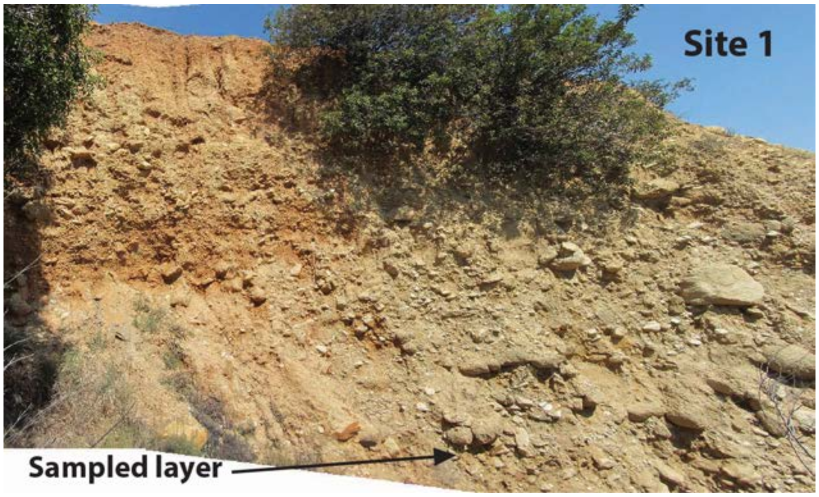
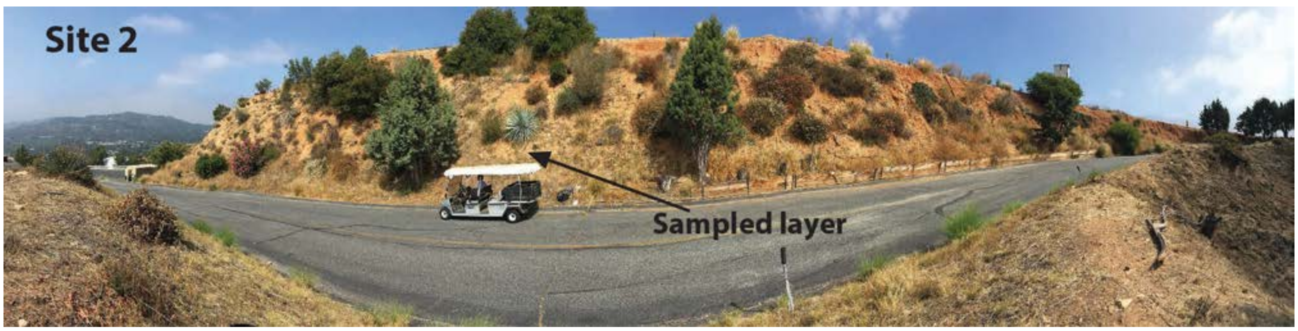


Figure 2. Cross-section modified from Crook et al. (1987) showing interpreted subsurface correlations of deformed markers across the frontal strands of the CSMF zone in the Arroyo Seco area, Pasadena. Approximate horizons sampled for cosmogenic isochron burial dating shown as magenta stars (1 and 2). The age of the upper deposit provides a maximum age for the capping surface and a minimum age for the basal unconformity of the deposit.

A – 16SMF



B – JPL



Figures 3A and 3B. Photos of sampled outcrops. Sampled clasts are quartz-rich cobbles taken from a depth range of <50 cm, ~ 8 m below the uppermost surface of the Gould Mesa deposit. See Fig. 1 for locations.