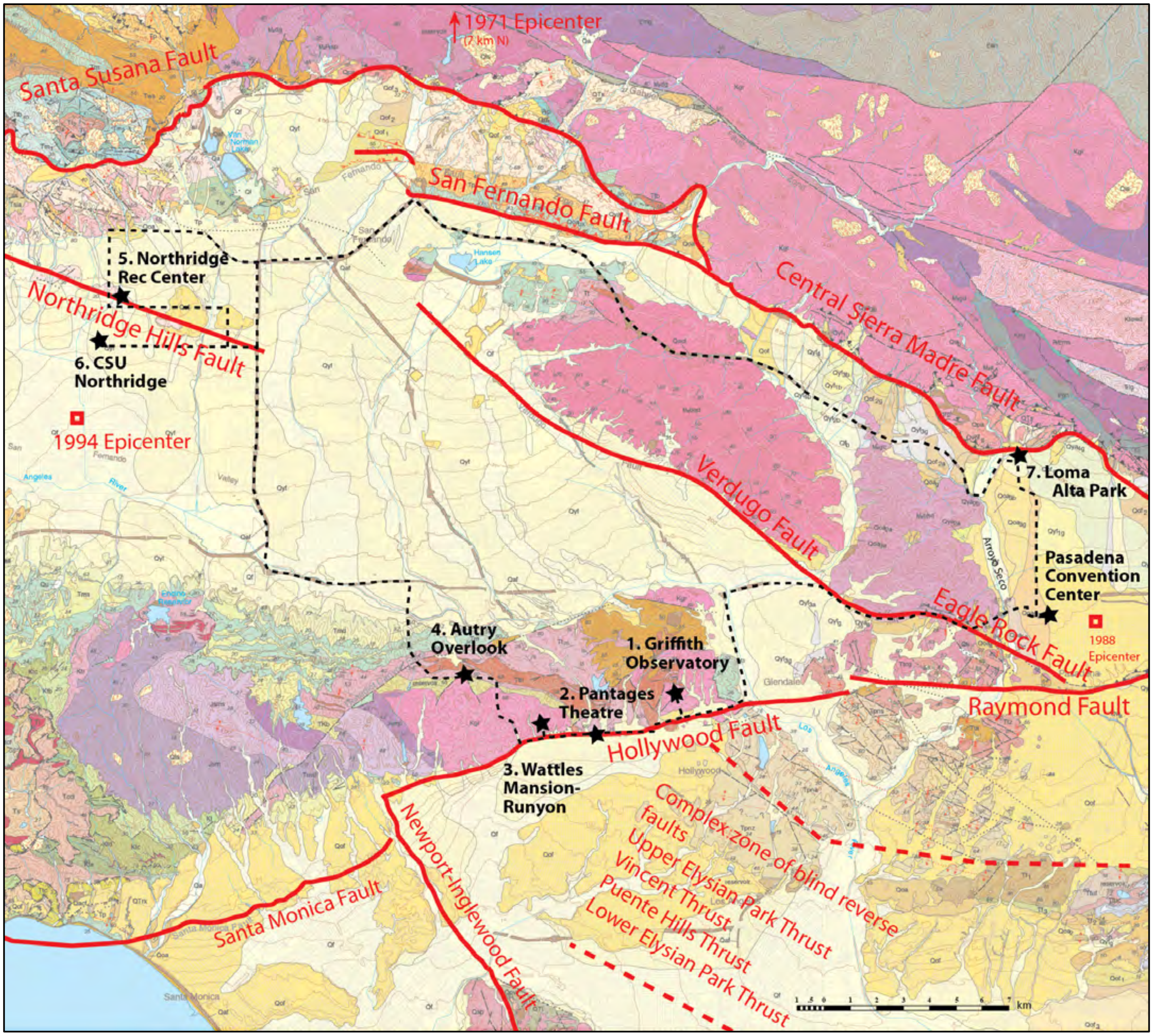
**Seismological Society of America Annual Meeting Fieldtrip 2015**

Faults, vistas, and earthquakes in the northern Los Angeles and Pasadena Region

April 24, 2015

Kate Scharer (USGS), James Dolan (USC), Jerry Treiman
and Janis Hernandez (CGS) and Doug Yule (CSUN)




Route (black line), stops (black stars), on map adapted from Geologic Map of Los Angeles Quad (Yerkes and Campbell, 2005). Main faults discussed on the trip (red lines) are generalized. Accurate information on fault location and activity can be found on the CGS and USGS websites.
CGS: http://www.consrv.ca.gov/cgs/rghm/ap/Pages/main.aspx
USGS: http://earthquake.usgs.gov/hazards/qfaults/

**THE PLAN**
8:00-8:15 Load and depart!
9:00-10:30 Griffith Observatory (Dolan)
10:30-12:00 Hollywood Blvd/Argyle St (Treiman, Hernandez)
12:00-1:15 Wattles Park for lunch (Dolan)
1:15-1:45 Autry Overlook
2:15-4:00 Northridge Recreation Center and CSU Northridge (Yule)
4:00-5:00 Loma Alta Park (Scharer, Dolan)

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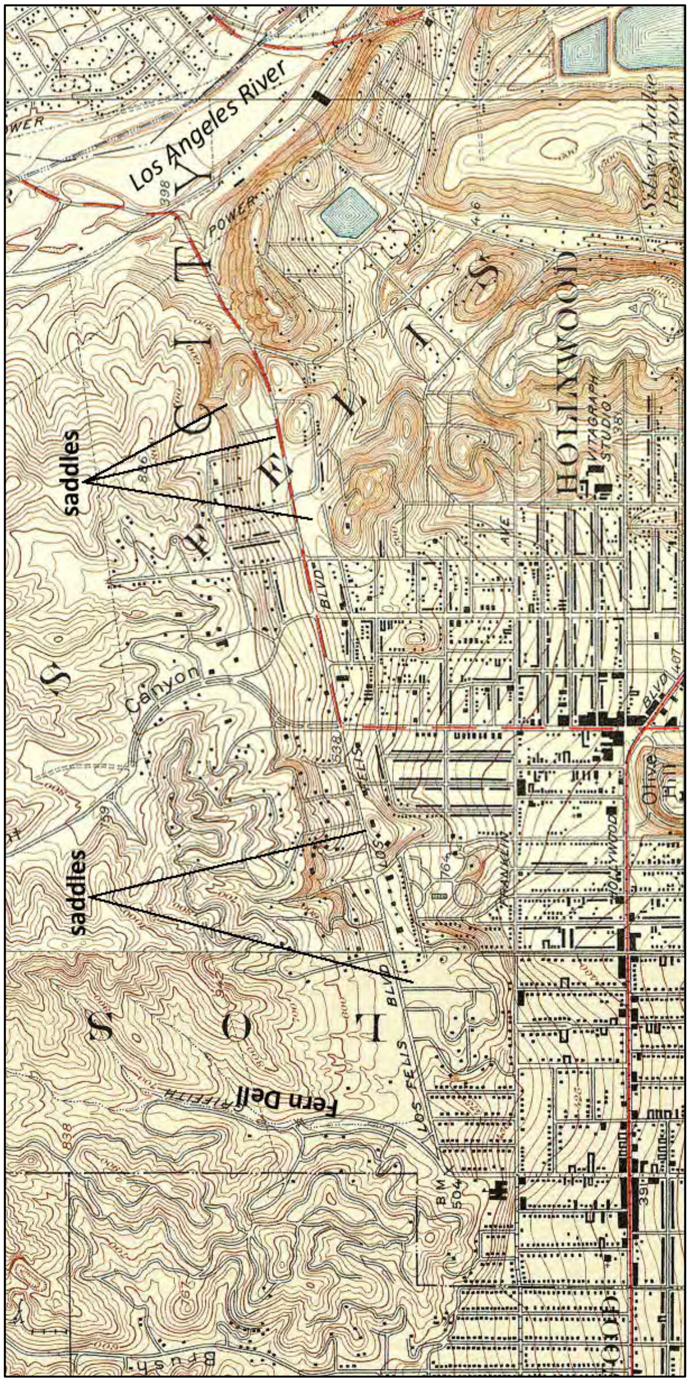
**START: Pasadena Convention Center**

*Route travels west out of Pasadena on Highway 134.* Accessing the highway, the bus will cross Arroyo Seco, a drainage that forms the western border of Pasadena (the Rose Bowl is about a mile to our north). The highway cuts the southern tip of the Verdugo Mountains, along the **Verdugo-Eagle Rock Fault system**, a northeast-dipping, northwest-trending fault with estimated < 1 mm/yr slip rate. No neotectonic studies with slip rates exist for Verdugo Fault, but Weber et al., (1980) report south facing scarps in Holocene alluvium, and deformation models by Cooke and Marshall (2006) predict it is oblique, with ~0.6 mm/yr right-lateral and 0.5 mm/yr dip slip rates. The Verdugo Mountains are largely Cretaceous gneissic quartz diorite; low terrain to the south is Miocene Topanga Group conglomerates and siltstones (Yerkes and Campbell, 2005).

*Head south on Interstate 5.* Here Interstate 5 parallels the Los Angeles River for about 4 km on the western edge of the Santa Monica Mountains; at this location they are known as the Hollywood Hills. Rocks immediately west of I-5 are Miocene Monterey Formation shale; these overlie the granodiorite basement rocks exposed to west at Griffith Observatory (Dibblee and Ehrenspeck, 1991).


🡅 This low oblique Google Earth view looks westward along Los Feliz Blvd. in our direction of travel. An aerial photo of the area from 1927 is draped over the landscape (vertical exaggeration x2). Our route follows this eroded and breached fault-line trough along which remnants of the old topography are still visible. The magenta lines indicate interpreted fault traces. (1927 photo by Fairchild Aerial Surveys).

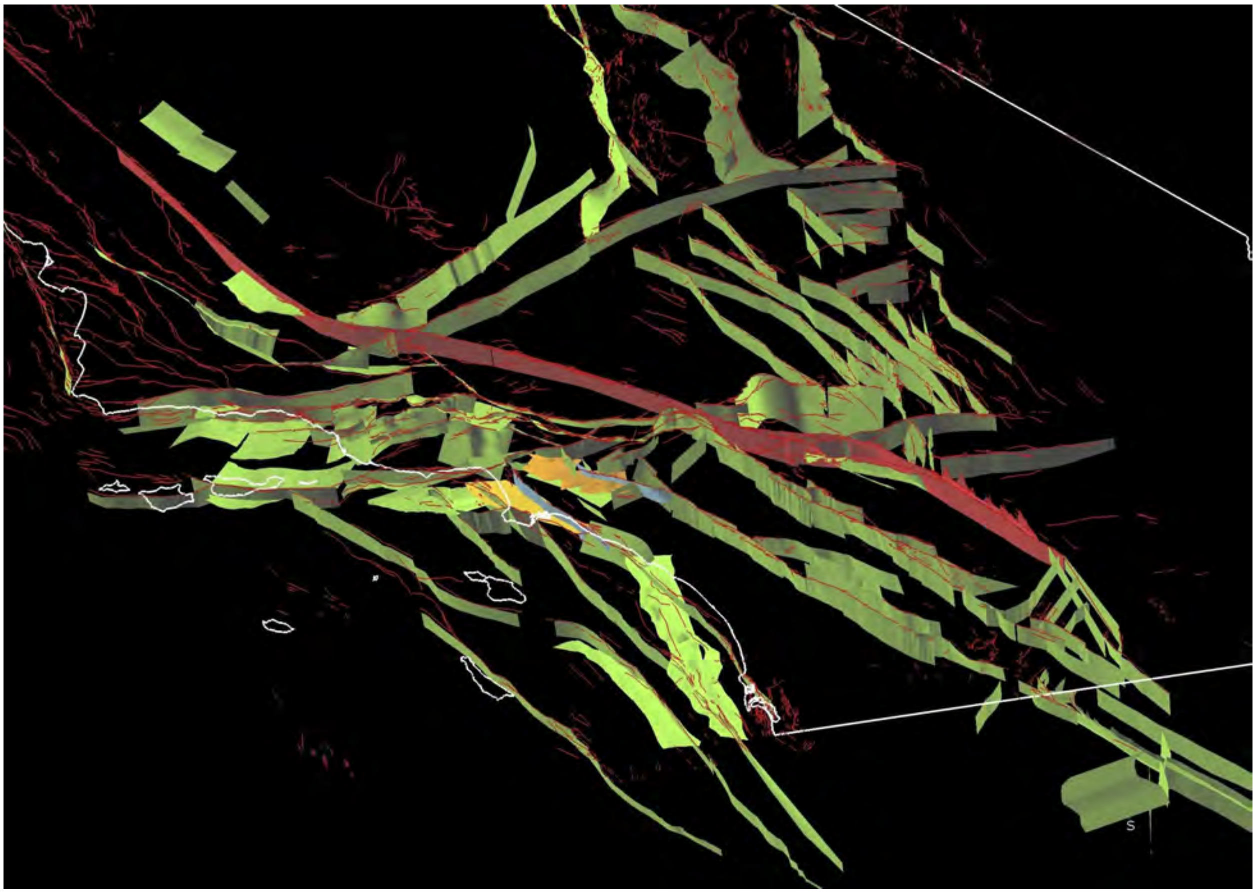



🡐 Composite map of the Burbank (1926) and Glendale (1928) 6-minute topographic maps that show the Los Feliz Blvd. portion of our route. This map series nicely depicts the topography with 5-foot contours.

**<u>STOP 1: GRIFFITH OBSERVATORY</u>**

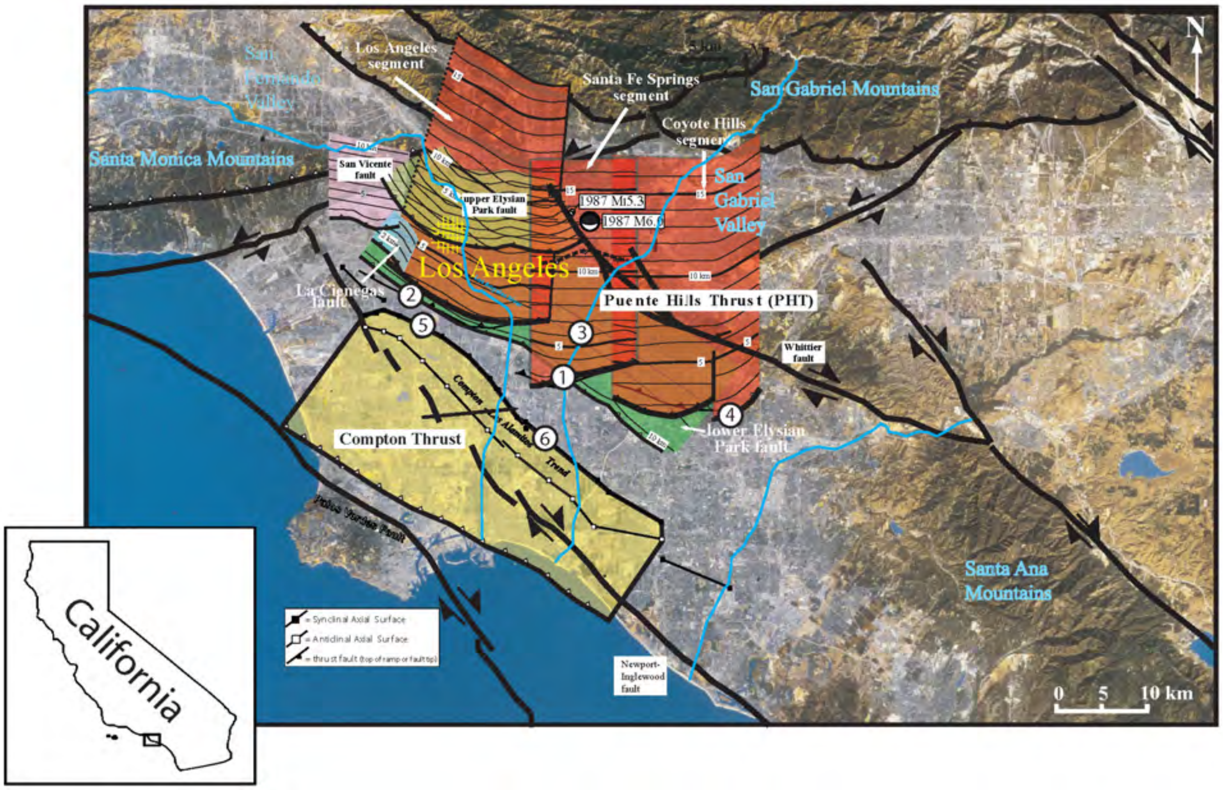
Our first stop is at the famed Griffith Park Observatory, notable for the nice view of the Hollywood sign atop the westernmost end of the Elysian Park anticlinorium (hanging wall fold above Elysian Park blind thrust fault), and for providing the backdrop for numerous movies, including perhaps most notably *Rebel Without a Cause* with James Dean (sorry, *Charlie's Angels: Full Throttle*!). The observatory is an ideal spot to introduce and discuss LA's urban fault network, as it provides expansive views of many of these structures.

At this stop we will discuss what is known about the major fault systems that underlie metropolitan Los Angeles, with a particular focus on the Sierra Madre-Cucamonga fault system, the Raymond-Hollywood-Santa Monica fault system, and the Puente Hills and Compton blind thrust faults, the two largest active blind thrust systems that underlie most of the area you can see from Griffith Park.

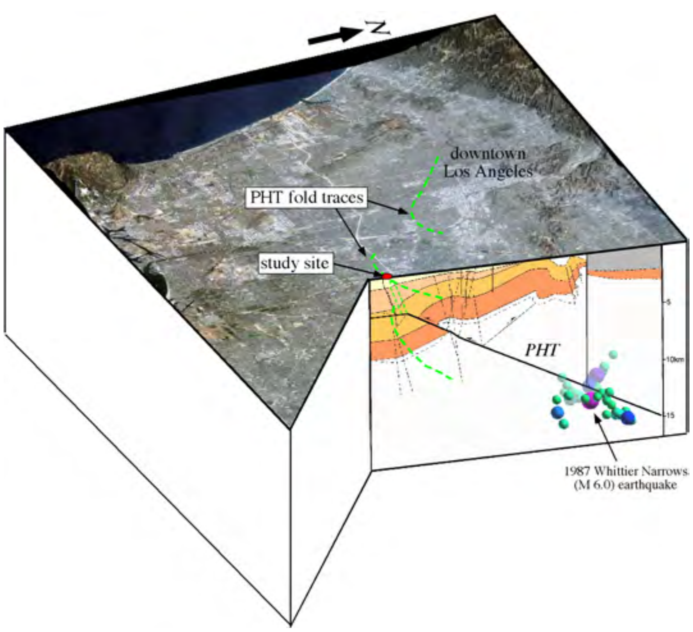


🡅 Map of major faults in southern California from the Southern California Earthquake Center's Community Fault Model (CFM). San Andreas fault (red) and Puente Hills and Compton blind thrust faults (orange) are highlighted. Thin red liens show surface traces of faults in the CFM. White lines denote coastline and California State boundaries. Image created by Andreas Plesch and John Shaw (Harvard University).

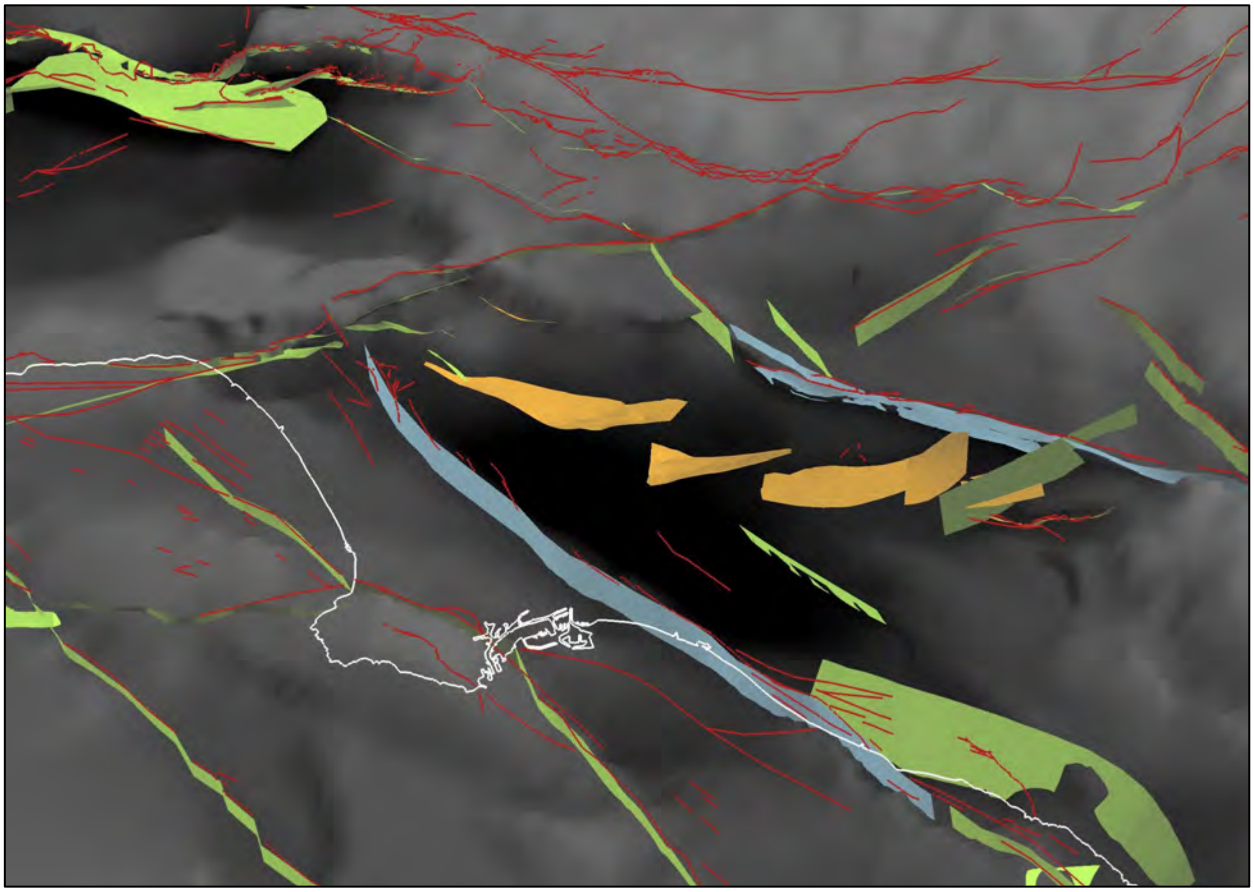
As we look southward over what is known as the LA basin, in addition to noticing the density of development, including the downtown LA high-rise district (which keeps rising higher every year), it is important to note that the "LA basin" isn't just a geographic term used by traffic reporters. Rather, the Los Angeles basin is also a deep (10 km at its deepest point), narrow, 50-km-long sedimentary trough that extends northwest-southeast beneath much of the urban core of LA. You can't see it because it has been filled with sediments eroded off the San Gabriel Mountains and deposited on the floodplains of the Los Angeles and San Gabriel Rivers. The LA basin, which has been the subject of extensive modeling efforts to understand the seismic hazard ramifications, will trap and amplify seismic waves during future earthquakes. Of particular importance in this regard is the proximity of Puente Hills and Compton blind thrust faults to the basin. Indeed, the location and geometry of the PHT render it perhaps a "worst-case-scenario" fault for metropolitan LA, as any upward rupture directivity will funnel energy directly into the downtown region and the deep sedimentary basin.




🡅 Map of major blind thrust faults in the Los Angeles basin. Note segmented nature of Puente Hills blind thrust fault (orange) and Compton blind thrust ramp (yellow) extending beneath much of much of the western LA metropolitan area. Both blind thrust ramps dip gently northward (Shaw et al., 2002; Leon et al., 2009).



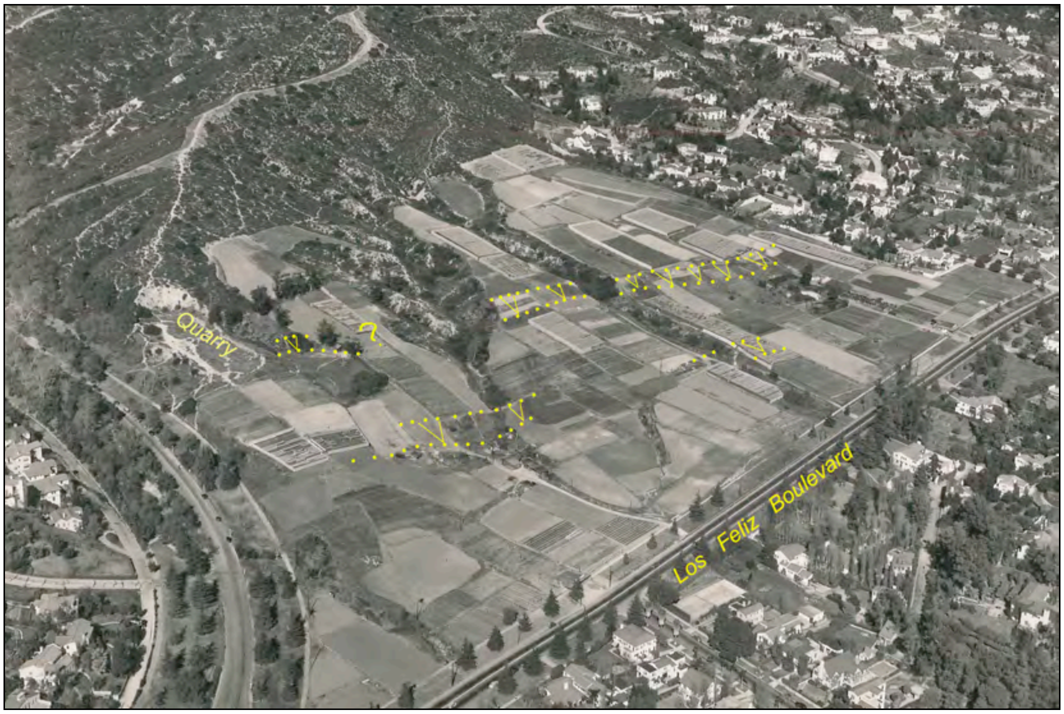

🡄 3D cutaway image showing geometry of the central, Santa Fe Springs segment of the Puente Hills blind thrust fault through the site of the 1987 Mw 6.0 Whittier Narrows focus. Geometry of the uppermost 7 km is constrained by high-quality petroleum-industry seismic reflection data, whereas the deeper fault geometry is constrained by the location of the 1987 mainshock focus and relocated aftershocks. Data from Shaw and Shearer (1999) and Shaw et al. (2002).



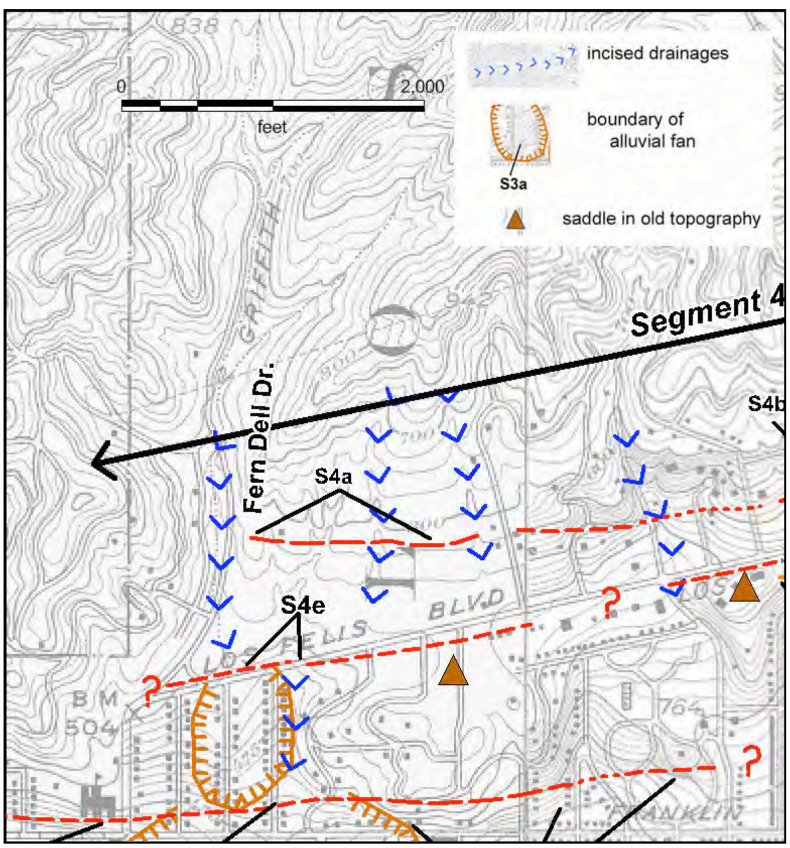
🡅 Northeastward-looking oblique view of depth to basement surface highlighting the presence of the deep Los Angeles basin (darker colors). Orange surfaces are the three main structural segments of the Puente Hills blind thrust fault. Blue surface to west of PHT is the CFM representation of the Newport-Inglewood fault, and the blue surface to the east is the CFM representation of the Whittier fault extending along the eastern end of the PHT. Red lines show surface traces of SCEC CFM faults, and the white line denotes coastline. Image created by Andreas Plesch and John Shaw (Harvard University).

**NEXT: STOP 2: HOLLYWOOD BLVD/ARGYLE STOP (PANTAGES THEATRE)**

*Exit Griffith Observatory, south onto Vermont Ave, right onto Los Feliz Boulevard, left onto Western Ave, then right at Hollywood Boulevard. From Griffith Park we will drop down the southern side of the Hollywood Hills, and drive along Hollywood Boulevard. The saddle in the hill occupied by the 101 Freeway exposes marine clastic rocks of the Miocene Upper Topanga Formation.*




↑ This vintage oblique aerial photo from 1938 is looking northeast across an elevated alluvial fan, north of Los Feliz Blvd. There are at least two fault scarps visible across this fan (yellow annotations). The area was developed by mass grading in 1962, before faulting was well understood or considered active in this area. (photo by Fairchild Aerial Surveys).




← The south-flowing drainage at Fern Dell Drive appears to have been offset at least 130 meters in a left-lateral sense (locality marked S4e in this figure) with a younger fan starting to develop where Fern Dell crosses Los Feliz. (Figure modified from Figure 14 of Hernandez & Treiman, 2014).

Seismological Society of America
Field Trip Stop – Hollywood/Argyle
April 24, 2015

# Fault Rupture Hazard
# Hollywood Fault Zone, Hollywood, California

*Jerry Treiman, Senior Engineering Geologist*
*Janis Hernandez, Engineering Geologist*
*California Geological Survey*

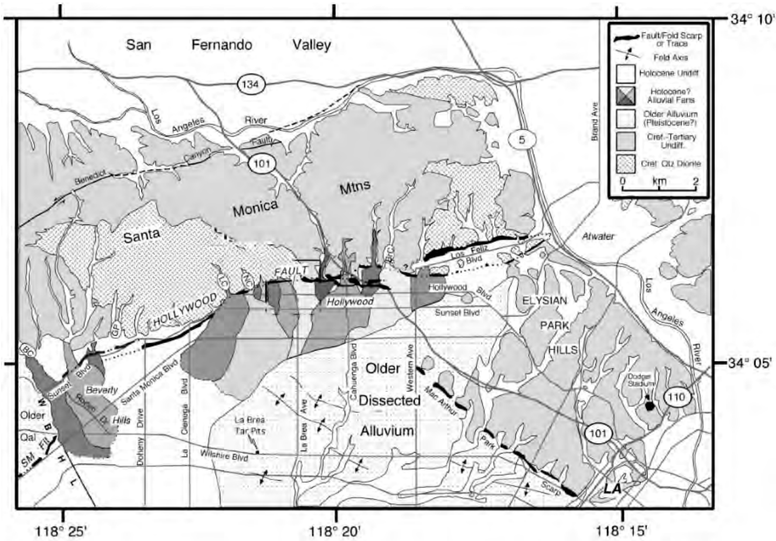
This stop will provide an overview of fault rupture hazard recognition in the Hollywood area under the Alquist-Priolo Earthquake Fault Zoning Act (the "Act"). The Act was passed in 1972 as a direct result of surface rupture damage to buildings in the 1971 M 6.6 San Fernando Earthquake, damage that led to the recognition that surface fault rupture is a readily avoidable hazard. The intent of the Act is to reduce the risk from surface fault rupture by prohibiting the location of developments and structures for human occupancy across the trace of active faults. This goal is achieved through a division of responsibilities between the State, local government and landowners/developers:

- It is the responsibility of the State Geologist to issue maps depicting zones of required investigation for the hazard of surface fault rupture. These Earthquake Fault Zones (EFZ) are typically 1000 feet wide or greater and are established to encompass identified active faults and an area around those faults where secondary fault traces might lie.
- It is the responsibility of the local permitting agency (city or county) to require and approve a geologic report defining and delineating any hazard of surface fault rupture for specified projects within the EFZ.
- It is the responsibility of the property owner or developer to cause the property to be investigated by a licensed geologist who will identify the location of any active fault traces so that they may be avoided.

For more information on the Alquist-Priolo Earthquake Fault Zoning Act refer to Bryant and Hart (2007).

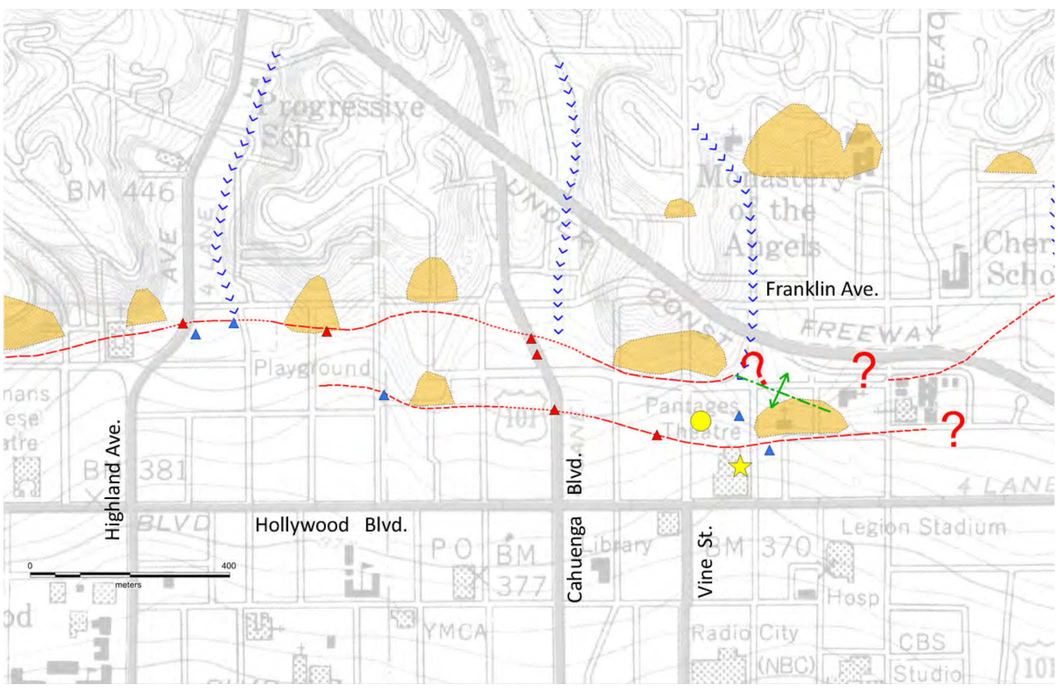
For our zoning evaluation of the Hollywood Fault within the Hollywood Quadrangle we made use of all available data. This included analysis of vintage aerial photography and topographic maps as well as the compilation and reference to all available geotechnical studies, subsurface data and mapping along the fault zone.

Vintage aerial photographs and maps are a tremendous resource for interpreting the tectonic geomorphology along a fault zone, which is often a key to identifying active fault strands. In areas such as Hollywood this can be a particular challenge because most of the area was already developed, with a grid of streets and structures obscuring the original landform, before the first stereo aerial imagery in 1927. Geologic mapping over the decades had identified some (probably inactive) faults within uplifted bedrock areas, but the more recently active fault traces are mapped as concealed near the interface between the uplifted Santa Monica Mountains and the alluvial fans to the south (Hoots, 1930; Dibblee, 1991). Dolan and others (1997) made great strides in appreciating the tectonic geomorphology of the fault zone.

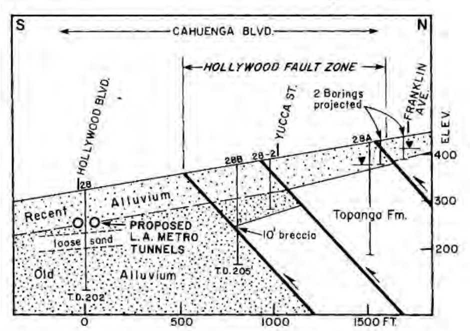



*Fault expression and bedrock geology in the Hollywood area. (Modified from Dolan and others, 2000, Fig.2)*

Within the western part of the study area we had access to a number of detailed site studies to help constrain age of faulting as well as fault location. These data tended to corroborate geomorphic assessments, but with some minor adjustments needed. In contrast, the eastern part of the study area contained relatively few site-specific studies, but perhaps a more telling geomorphic signature. We were fortunate to have a remarkable topographic survey of the area conducted in 1924 & 1925 that captured the landform with 5-foot contours (USGS, 1926 & 1928). Based on these maps, 1927 and 1928 vintage vertical aerial photography and some historic oblique images from the 1920s and 1930s, we were able to interpret a relatively continuous zone of faults across this eastern area.




*Geomorphic features in the Hollywood area with faults that are basis for APEFZ. Local anticlinal fold (green) based on geotechnical studies. Capitol Records Tower indicated by yellow dot. This field trip stop indicated by yellow star. See previous figure for explanation of symbols.*




*North-south section along Cahuenga Blvd. showing subsurface interpretation of faults based on studies for Los Angeles subway (Crook and Proctor, 1992). Northern and southern strands are indicated on previous figures.*

Fault location is only one factor of concern, the other being recency of the latest fault displacement. Several studies in the western part of the map demonstrated that the Hollywood Fault had experienced displacement during the Holocene. Fault influences on drainage and deposition patterns in the eastern part of the map appear to also be in accord with relatively young (although currently unquantified) fault activity. Holocene displacement does not need to be documented on all elements of a fault zone for those traces to be included in a zone of required investigation.

Our evaluation of regional and detailed data indicated that the Hollywood Fault is active and comprises a sometimes complex zone of faults that extends in a generally east-west direction across the Hollywood area (California Geological Survey, 2014). Our findings and conclusions were summarized in a final Fault Evaluation Report after public review of our preliminary recommendations (Hernandez and Treiman, 2014; Hernandez, 2014).

*References*

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Dolan, J.F., Sieh, K., Rockwell, T.K., Guptill, P. and Miller, G., 1997, Active tectonics, paleoseismology, and seismic hazards of the Hollywood fault, northern Los Angeles basin, California: Geological Society of America Bulletin, v.109, p.1595-1616.

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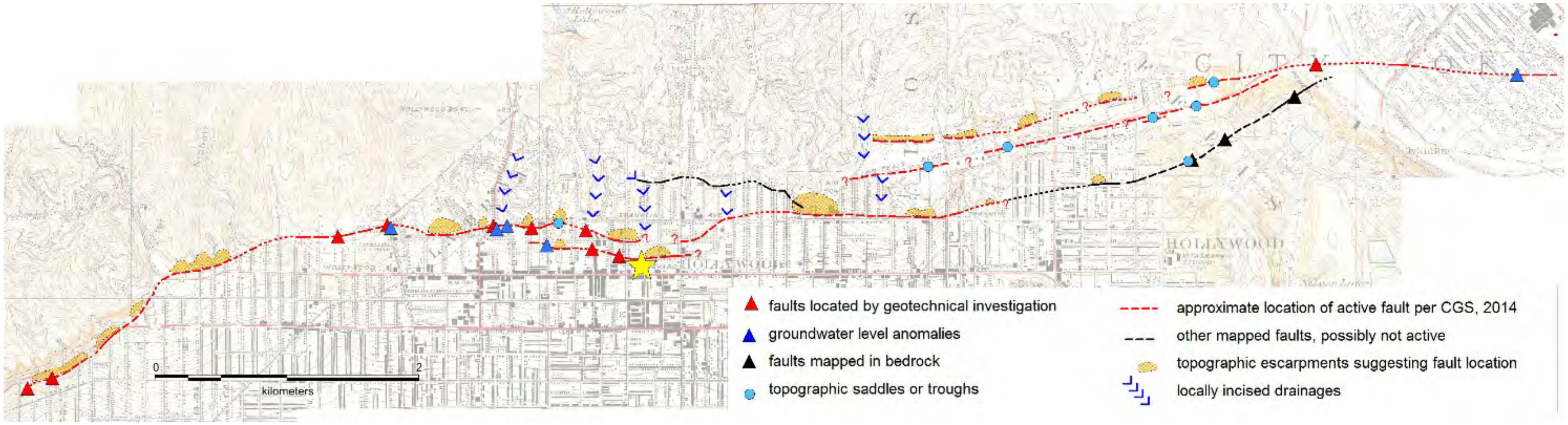
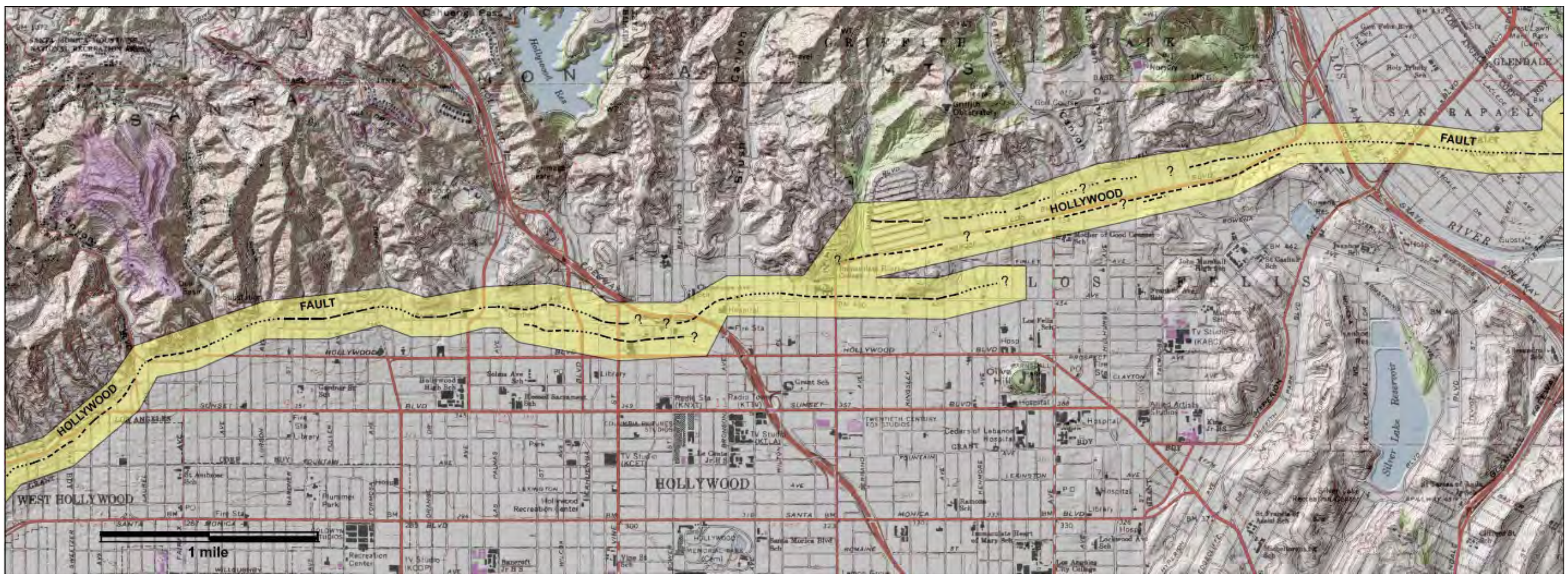
USGS, 1926, Burbank, Calif.: United States Geological Survey, 6-minute topographic map series for Los Angeles County, surveyed 1924, 1:24,000.

USGS, 1928, Glendale, Calif.: United States Geological Survey, 6-minute topographic map series for Los Angeles County, surveyed 1925, 1:24,000.




*Strip map showing features related to fault interpretation in the Hollywood, CA Quadrangle. Yellow star indicates this field trip stop location. (base map is from 1923-1925 topographic survey)*

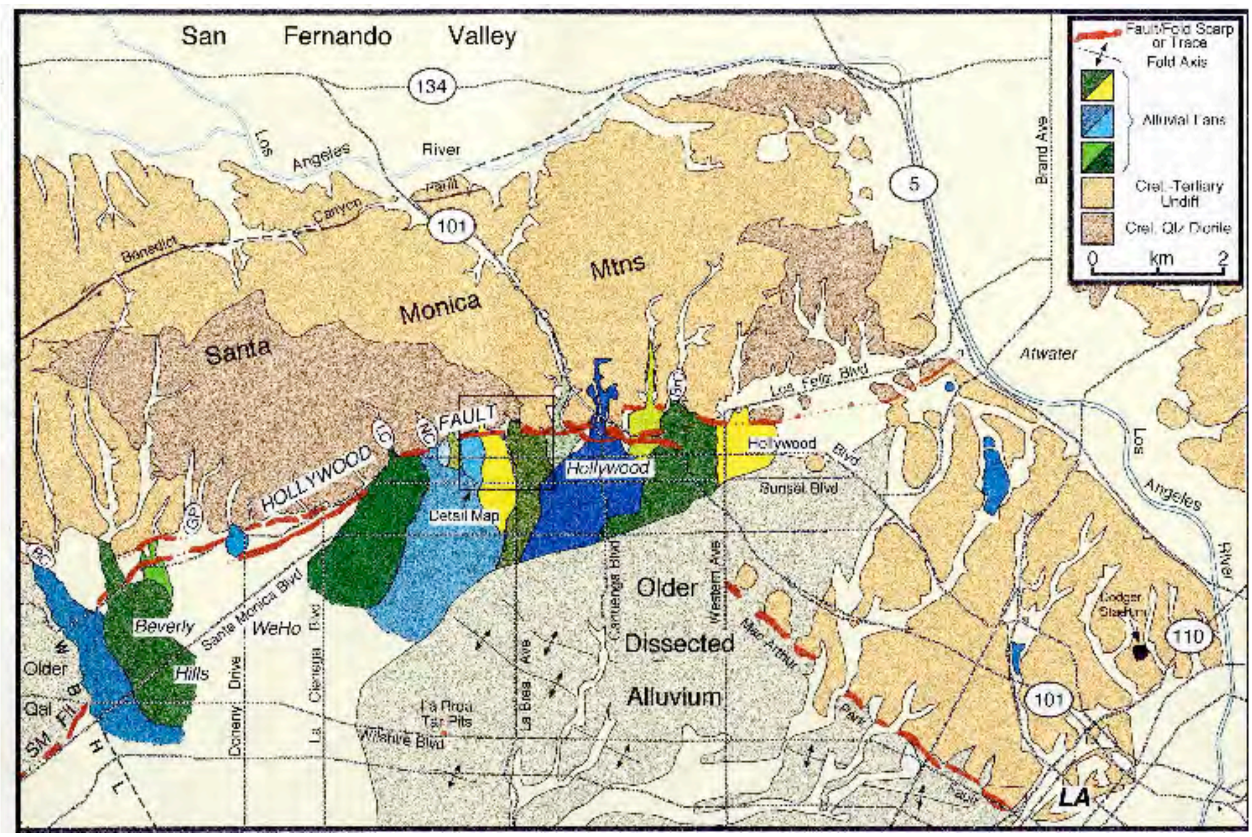



*This map shows the interpreted and locally verified active traces of the Hollywood Fault Zone across the Hollywood 7.5' quadrangle (Hernandez and Treiman, 2014; Hernandez, 2014). The yellow shaded zone surrounding the faults is the Alquist-Priolo Earthquake Fault Zone for required investigation (California Geological Survey, 2014).*

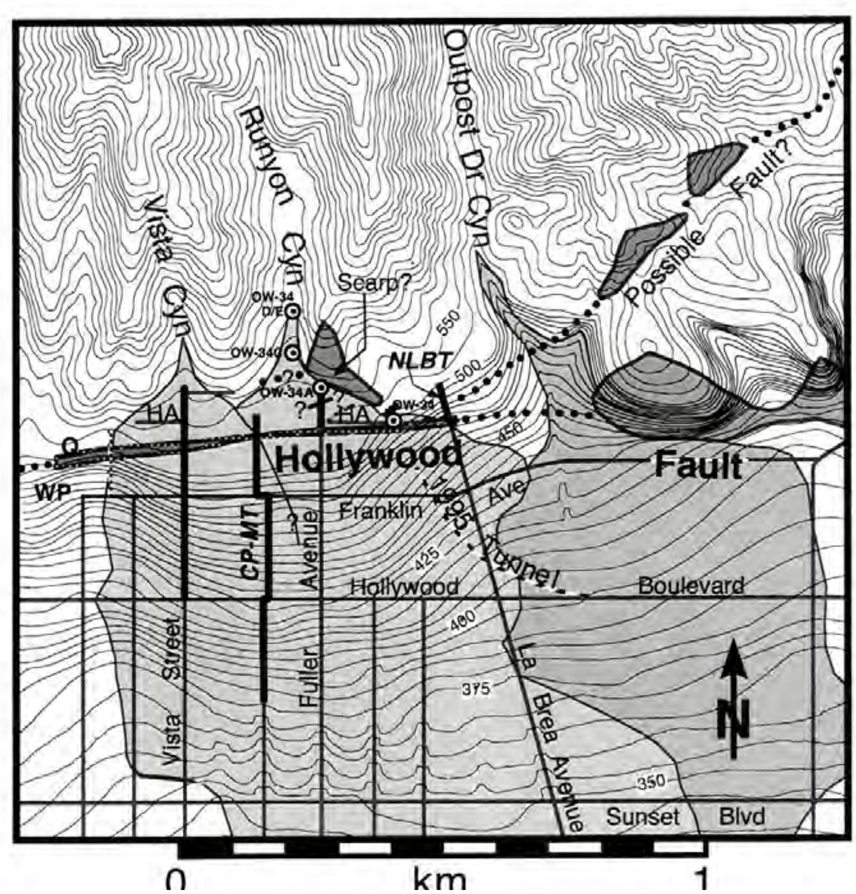
**STOP 3: LUNCH AT WATTLES MANSION / RUNYON CANYON PARK**

*From Pantages, drive west on Hollywood Boulevard, and then turn north onto Curson Ave. Our lunch stop takes us back into the Santa Monica Mountains, here a quartz diorite crystalline basement rocks that intruded the Santa Monica Slate exposed to our west.*

At this stop we will discuss what is known about the earthquake history of the Hollywood fault and its extensions to the west (Santa Monica fault) and East (Raymond fault). This section of the Hollywood fault was the subject of intensive study during the mid-1990's as part of the investigation of the subsurface conditions for the LA subway Red Line extension through the Santa Monica Mountains to the San Fernando Valley.

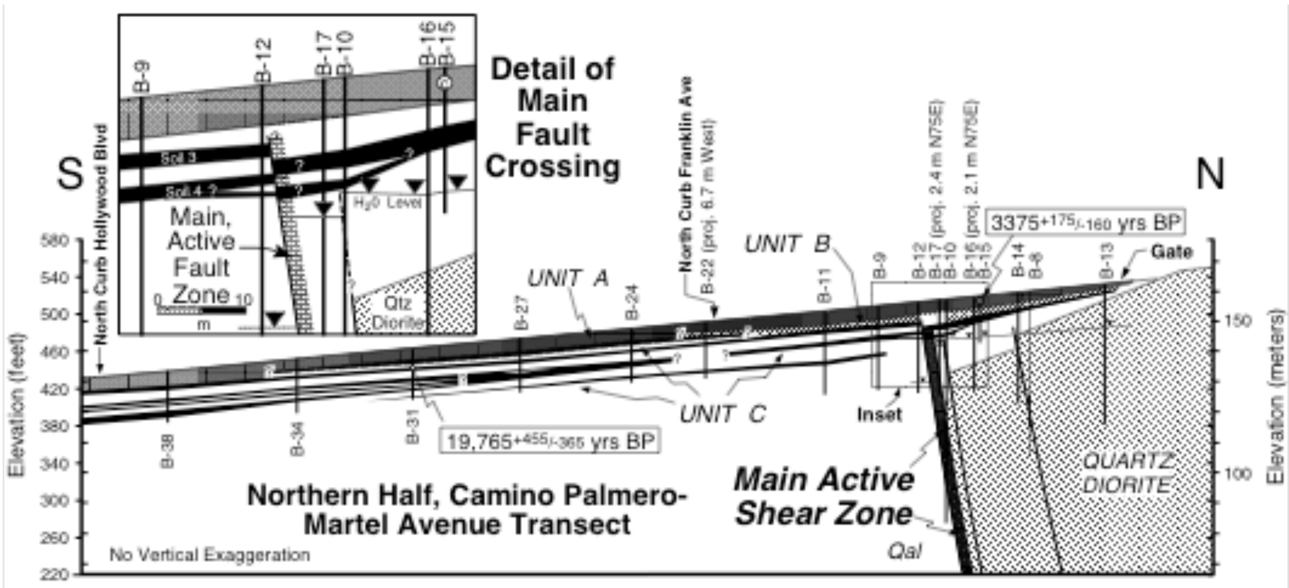



🡅 Map of Hollywood fault and environs (Dolan et al., 1997). Scarps associated with recently active traces of the Hollywood fault shown in reddish-orange. Young alluvial fans (bright colors) are actively being deposited along much of the mountain front (or at least they were being deposited before everything got paved over). Note ~1.5-km-wide left step at west end of the Hollywood fault onto its continuation farther west – the Santa Monica fault. Also note zone of uplifted older alluvium south of the active alluvial front along the Hollywood fault. This uplift is a surface manifestation of uplift above the western, Los Angeles segment of the PHT.



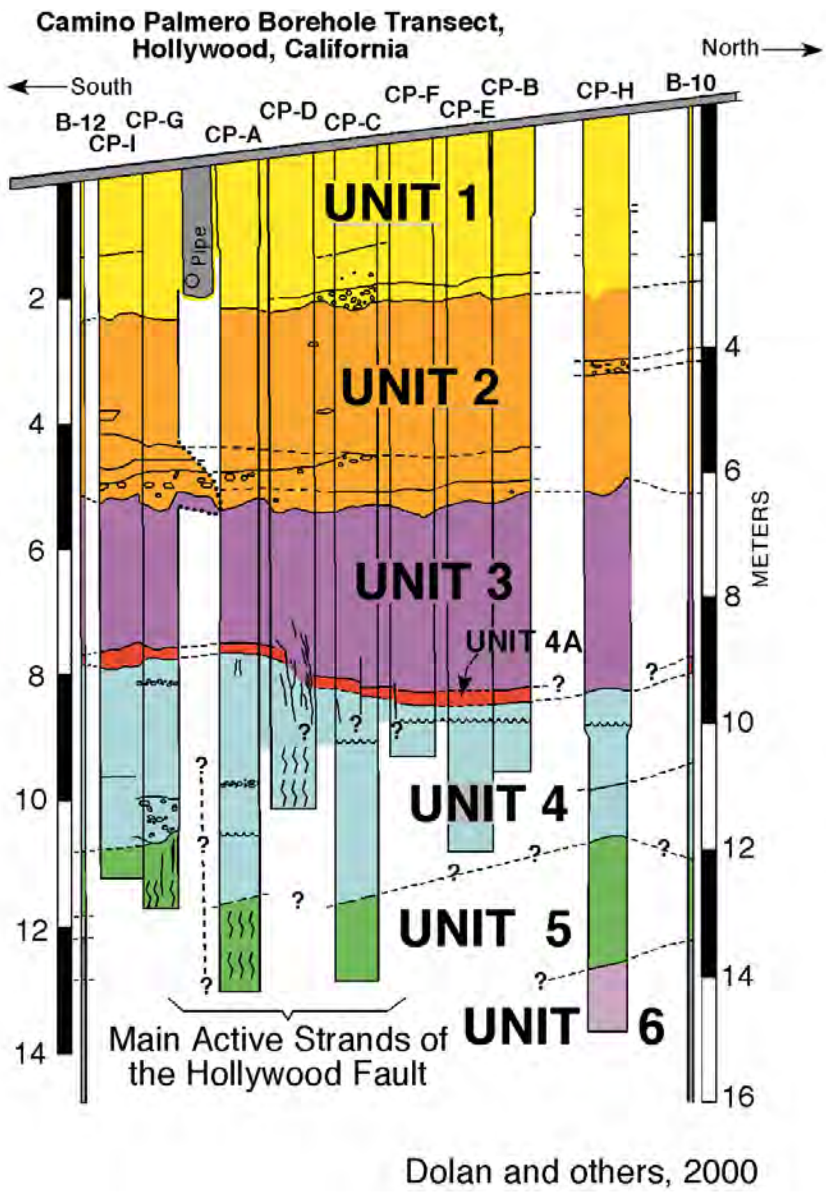

🡅 Geologic map of young features within detailed study area west of downtown Hollywood. Runyon Canyon, Vista Street, and Outpost Drive fans are shown in shades of gray. Narrow, dark gray horizontal swath shows location of Hollywood fault inferred from subsurface data. Medium gray shading shows fault scarps inferred from topography. No scarps are discernible across the recently active parts of the fans. Thick black north-south lines show locations of trenches and borehole transects discussed in text. Secondary strand of Hollywood fault encountered in Fuller Avenue trench is shown by short black line immediately south of borehole OW-34A. Location of Metropolitan Transit Authority subway tunnel excavated as of July 1995 is shown as a dashed line. Triangular facets in northeast corner of figure show possible northeast-trending fault strand. CP-MT—Camino Palmero–Martel Avenue Transect; HA—Hillside Avenue; NLBT—North La Brea transect; WP—Wattles Park; Q shows location of near-surface (<1 m depth) quartz diorite from Crook and Proctor (1992). Topography redrafted from Burbank and Hollywood 1:24 000 6¢ USGS quadrangles (~1926). Contour interval is 1.5 m (5 ft) up to the 500 ft contour, above which the interval is 7.6 m (25 ft).

Dolan et al. (1997) detailed the results of two north-south (i.e., fault-perpendicular) transects of continuously cored hollow-stem boreholes. Twenty-five boreholes comprised the longer, western transect, which extended southward from the mountain front along Camino Palmero and Martell venue for 525 m. Correlation of numerous laterally continuous soils showed that the recently active trace of the Hollywood fault is located just south of the southernmost surface exposures of the quartz diorite that makes up this part of the Santa Monica Mountains.




🡅 Cross section of the northern half of Camino Palmero–Martel Avenue borehole transect. Thick vertical lines denote continuously cored boreholes; thinner lines show sections of B-8 that were not cored. Sub-horizontal black lines denote A and Bt horizons of buried soil horizons of unit C. White zones between these buried soils denote C horizons of buried soils and unaltered sedimentary strata that do not exhibit any soil development. Small triangles and gray lines denote ground-water level in boreholes during 1992. Open circles show locations of two accelerator mass spectrometry–dated detrital charcoal samples discussed in text. Locations of boreholes B-17 and B-16 are projected due east to the line of the cross section. Because of uncertainty of the fault strike, only water-level data from these two boreholes are shown in the figure; stratigraphic data from these holes are not shown in the figure.

Subsequent investigations of the main Hollywood fault crossing by Dolan et al. (2000b) using adjacent large-diameter “bucket-auger” boreholes revealed the details of the alluvial stratigraphy and allowed direct examination of the most recent surface rupture at the site. Bulk-soil radiocarbon ages from both unfaulted and faulted strata demonstrate that the MRE occurred between ~6 ka and 11 ka, with a preferred age range of 7 ka to 9.5 ka.



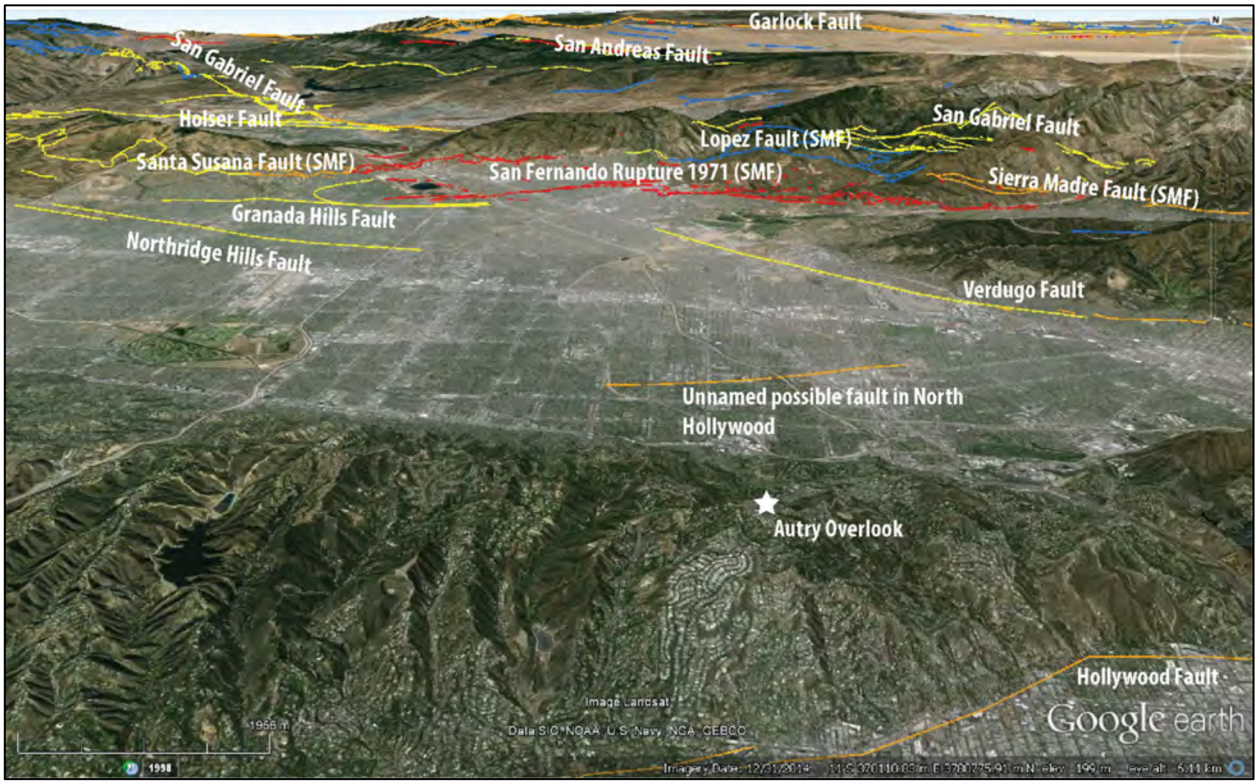

↑ Cross section of large-diameter borehole transect discussed in this article. Calibrated $^{14}C$ ages are all from bulk-soil samples except the two shallowest samples, which are from detrital charcoal fragments. Note the clear fault displacements of the Unit 3/Unit 4 contact in CP-D, CP-C, and CP-F, as well as the lack of displacement of the Unit 2/Unit 3 contact. Also note the 1.3-m-tall, north-side-down step in the Unit 4/Unit 5 contact between CP-G and CP-A. The inferred fault (dashed) shown at this step is drawn at the same dip as that of fault strands observed in CP-D (see text for discussion). The dip of the Unit 4/Unit 5 contacts in CP-C and CP-A was not mapped in detail due to very wet conditions. The average depth of these contacts, however, is accurate to within a few cm. These contacts are shown as dipping the same as the average dip of the Unit 4/Unit 5 contact between CP-H and CP-C. Zigzag lines denote numerous closely spaced fractures not logged in detail due locally unsafe hole conditions. Wavy horizontal lines denote the shallowest groundwater encountered in the boreholes; no groundwater was encountered in boreholes CP-D, CP-G, and CP-I. The irregular dotted line at 5 m depth between CP-G and CP-A shows the area that was hand-excavated from borehole CP-G in order to confirm that the Unit 2/Unit 3 contact was not faulted between the two boreholes. Small-diameter boreholes B-10 and B-12 are from Dolan and others (1997). Only the upper 15 m of these boreholes is shown. They extend to total depths of 73.2 m and 29.4 m, respectively.

**STOP 4: AUTRY OVERLOOK ON MULLHOLAND DRIVE**

*Drive west on Hollywood Boulevard to Laurel Canyon, head north. Near the top turn west onto Mulholland Drive. Bus will cross up and over the Santa Monica Mountains, stopping on Mulholland Drive to overlook the San Fernando Valley (like, totally!) and a view of the mountain ranges (and their faults) to the north.*

*https://www.flickr.com/photos/cityprojectca/4480269277/*

🡅 From this the overlook you can see the broad expanse of the San Fernando Valley. The Simi Hills and Santa Susana Mts form the western and northwestern margins of the valley, respectively, with Oat Mt forming the high point to the northwest (1142 m). The low saddle to the east of Oat Mt (Santa Susana Pass) separates the Santa Susana Mts (west) from the western San Gabriel Mts (east) capped by San Gabriel Pk as the high point (1878 m). Overpasses connecting the Golden State and Antelope Valley freeways (I-5 and Hwy 14) in Santa Susana Pass partially collapsed during both the 1971 and 1994 earthquakes. The Verdugo Mountains (where we started today) are the nearest range to the northeast, in front of the San Gabriel Mts. The north-dipping **Sierra Madre Fault System** is the longest fault seen from this vantage, including the Santa Susana Section within the Santa Susana Mountains, the San Fernando Section in the middle, and the Sierra Madre section under the San Gabriel Mountains. Splays of this fault system also include the north-dipping Mission Hills fault zone and Northridge Hills (blind) thrust, the subject of our next stop. The 1971 Sylmar earthquake ($M_w$6.7) ruptured about 15 km of the San Fernando Fault. The 1994 Northridge earthquake ($M_w$6.7) occurred on a south-dipping blind thrust that projects beneath and terminates against the overriding Northridge Hills fault in the northwest part of the valley.




🡅 Perspective view of terrain from Hollywood Hills to the Garlock Fault, from Q-fault database (http://earthquake.usgs.gov/hazards/qfaults/). Note that the unnamed blind fault responsible for the 1994 Northridge earthquake is not the Northridge Hills Fault! (The 1994 rupture plane terminates against the overriding Northridge Hills fault) SMF=Sierra Madre Fault System.

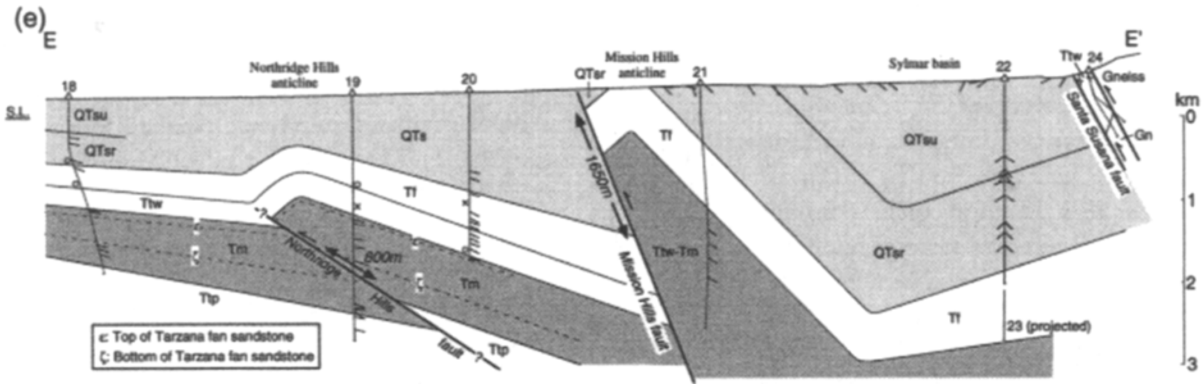
**STOP 5: NORTHRIDGE RECREATION CENTER**

*Drive west along Mulholland Drive, turn onto Coldwater Canyon Ave headed north, and get on the 101 freeway headed west. Then take I-405 N about 8 miles to Nordhoff Street exit, drive west 0.7 miles to Woodley Avenue, turn right. Drive 1.0 mile north on Woodley to Lassen Street, turn left. Drive 2.9 miles west to Reseda Boulevard, turn right. Drive north on Reseda 0.4 miles to Lemarsh Street, turn right. Drive 0.2 miles east on Lemarsh to the Northridge Recreation Center and park in the parking lot to the east of the center. Entrances to public restrooms are located at the west side of the building.*

En route to this site we crossed the Northridge Hills fault while heading north on Woodley Avenue (just east of Bull Canyon wash on Figure 1, below). Here, the structure forms an impressive south-facing topographic escarpment. This hill is part of a series of aligned, WNW-trending hills that form the *north ridge* of the San Fernando Valley, hence the name of the city, the university, and the 1994 earthquake!

It is important to note that the Northridge Hills fault does not reach the earth's surface. Rather, the Northridge hills are the expression of a fault-propagation fold above the tip of the blind Northridge Hills thrust, located ~1.5 km below this location (see cross-section E-E' below, from Figure in Tsutsumi and Yeats, 1999).

The purpose of the stop at Lemarsh Street is to visit the Northridge Park site of Baldwin et al. (2000) (Figure 1). Walk southeast from the parking area along a dirt road until you are standing in beneath LA Department of Water and Power's high-tension power lines. The power lines follow Aliso Canyon where young alluvium fills a late Pleistocene incision into Plio-Pleistocene Saugus Formation (Figure 4). Baldwin et al. (2000) chose to conduct their study at this site because it represents the only place in the Northridge Hills that has not seen significant cultural modification. Here they excavated six test pits, nine boreholes, and one trench (Figure 5). The excavations provided no evidence of surface faulting but do show Holocene growth strata with 13 ± 2 m of vertical relief across a monocline, and a dip-slip rate for the Northridge Hills fault of 1.0 ± 0.7 mm/yr (Figure 6). This study therefore provides direct evidence that the structure deforms Holocene strata, confirming previous interpretations of the faults activity (e.g., Barnhart and Slosson, 1973; Saul, 1979; Dibblee, 1992; Johnson et al., 1996; Hitchock and Kelson, 1996).




🡅 Figure 7 from Tsutsumi and Yeats, 1999. [Note: see Figure 1 of this field guide (Baldwin et al., 2000) for location of cross section line].

🡇 Figures 1, 4, 5, and 6 below are from Baldwin et al. (2000).

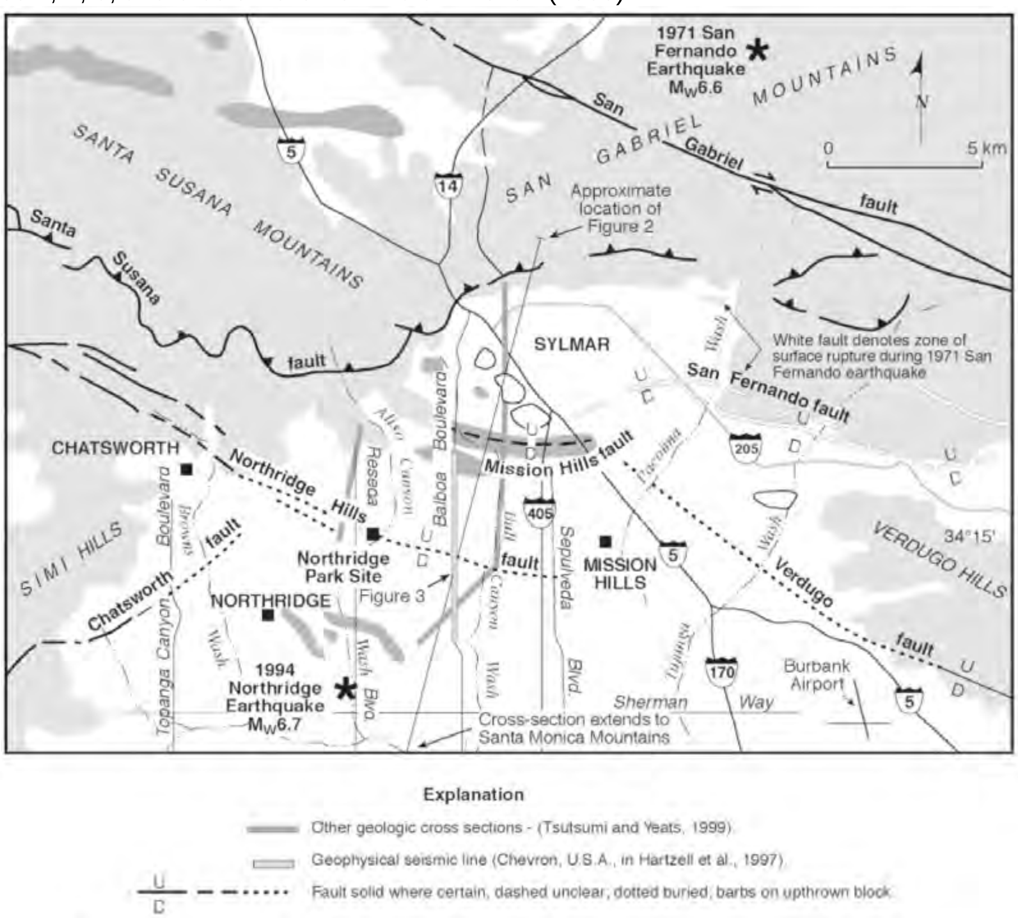



Figure 1. Regional fault map of the northern San Fernando valley (white), and Santa Susana and San Gabriel Mountains (shading), showing zones of ground deformation produced during the 1994 Northridge earthquake (stipple pattern). Modified from EERI (1994).

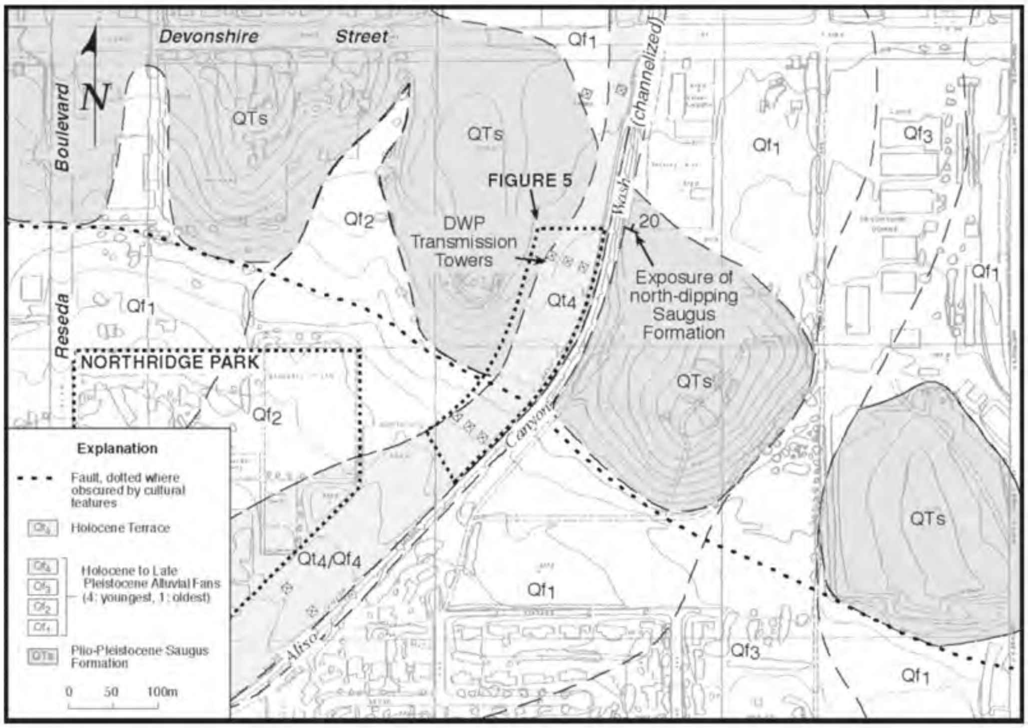



Figure 4. Map of surficial deposits and the Northridge Hills fault near Northridge Park, California. Topographic base from City of Los Angeles, dated 1970 (contour interval: 5 ft). With the exception of the 70-meter-wide undeveloped corridor directly west of the Aliso Canyon channel, all areas shown on this map are culturally modified. Geologic units modified from Wills and Hitchcock (1999).

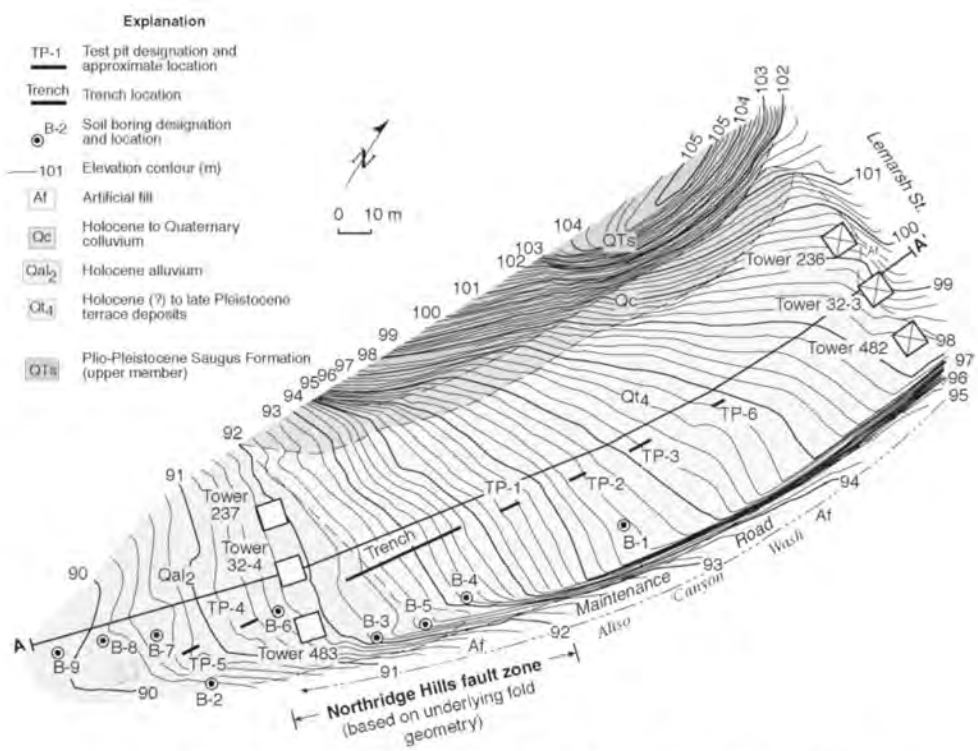



Figure 5. Topographic map of the Northridge Park site, showing locations of boreholes trenches and test pits. A-A′ shows the location of geologic cross section shown in Figure 6.

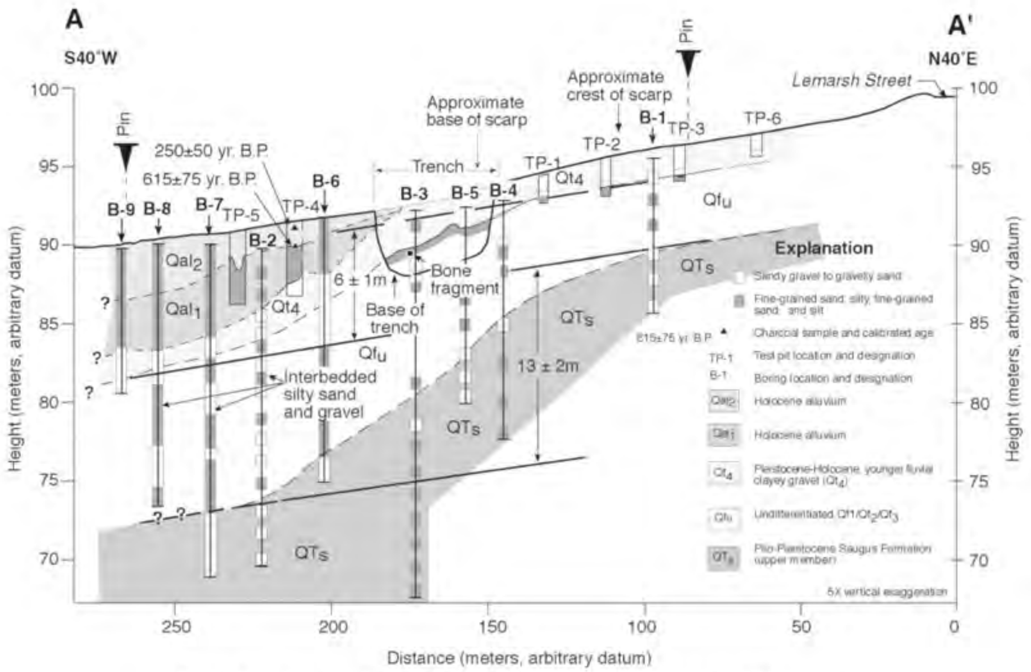



Figure 6. Cross-section A-A′ showing warping of basal contact of Pleistocene-Holocene terrace deposits (Qt4) and undifferentiated Quaternary fluvial deposits (Qfu) at Northridge Park. See Figure 5 for cross section location.

**STOP 6: CALIFORNIA STATE UNIVERSITY NORTHRIDGE, PARKING LOT F10**

*Return to the bus/vehicles. Drive 0.2 miles east on Lemarsh Street to Lindley Avenue, turn right. Drive 0.2 miles south and turn left into the northwest entrance to CSUN parking lot F10. Park at base of hill adjacent to dirt path. Walk up the path to reach the top of the hill.*

Note that the hill that you climbed has been modified extensively by grading. Resting on top of this hill are ‘relics’ of damage to CSUN’s campus during the 1994 earthquake. The relics are damaged support columns from the Oviatt Library. Rumor has it that the University has stored these ‘ruins’ with plans to use them one day to construct an earthquake memorial on campus. From this vantage point one can see the five mountain ranges that ring the San Fernando Valley (clockwise from north, the San Gabriel, Verdugo, Santa Monica (Autry overlook stop), Simi Hills/Chatsworth and Santa Susana ranges). The saddle at the eastern end of the Santa Monica Mts is Cahuenga Pass, traversed by the Hollywood Freeway (Hwy 101).

In 2005-6 California State University Northridge (CSUN) hired William Lettis and Associates, Inc. to excavate a series of trenches across this parking lot and hill. The trenches total length exceeded 300 m! At the time CSUN was planning to develop the hill with affordable housing units for faculty and staff. However, the economic downturn of 2007-2009 put a halt to these plans. If you look carefully you can still see the patched areas of the parking lot where the trenches were cut. The dirt path that you followed to the hilltop is a scar from one of these trenches. The trenches exposed minor faulting with <10 cm of offset per fault zone, suggesting the site does not experience large ground ruptures during earthquakes (John Baldwin, oral communication, 2006).

The main purpose of this stop is to discuss the tectonic setting of the 1971 Sylmar and 1994 Northridge earthquakes. The epicenters of these earthquakes are 22 km and 4 km to the north of this stop, respectively. The Northridge Hills overlie the north-dipping 1971 Sylmar and south-dipping 1994 Northridge ruptures. Aftershocks define the ruptures in cross section (Figure 7) and map view (Figure 8).

The 1971 earthquake ruptured the San Fernando section of the fault (see figure above). Southwestern splays of the San Fernando section, including the Mission Hills fault zone and the Northridge Hills fault (this stop), did not slip during this earthquake. However, small surface breaks did occur on the north-limb of the Sylmar syncline (Figure 7) interpreted to accommodate bedding-parallel flexural slip (Tsutsumi and Yeats, 1999).

The 1994 earthquake ruptured an un-named south-dipping fault that intersects the Northridge Hills thrust at 5-7 km depth beneath the Sylmar basin (~10 km to the north of this stop). Uplift at this location of ~0.25 m following the 1994 earthquake (Johnson et al., 1996) can be explained by slip on the un-named blind fault triggering slip on the overriding Northridge Hills fault. Opposite-verging thrust systems like this one are common in the region. For example, the blind Northridge/un-named thrust system here is very similar in geometry and style to the opposite-verging Oak Ridge/San Cayetano thrust system 35 km to the northwest of this location, just 7 km deeper.

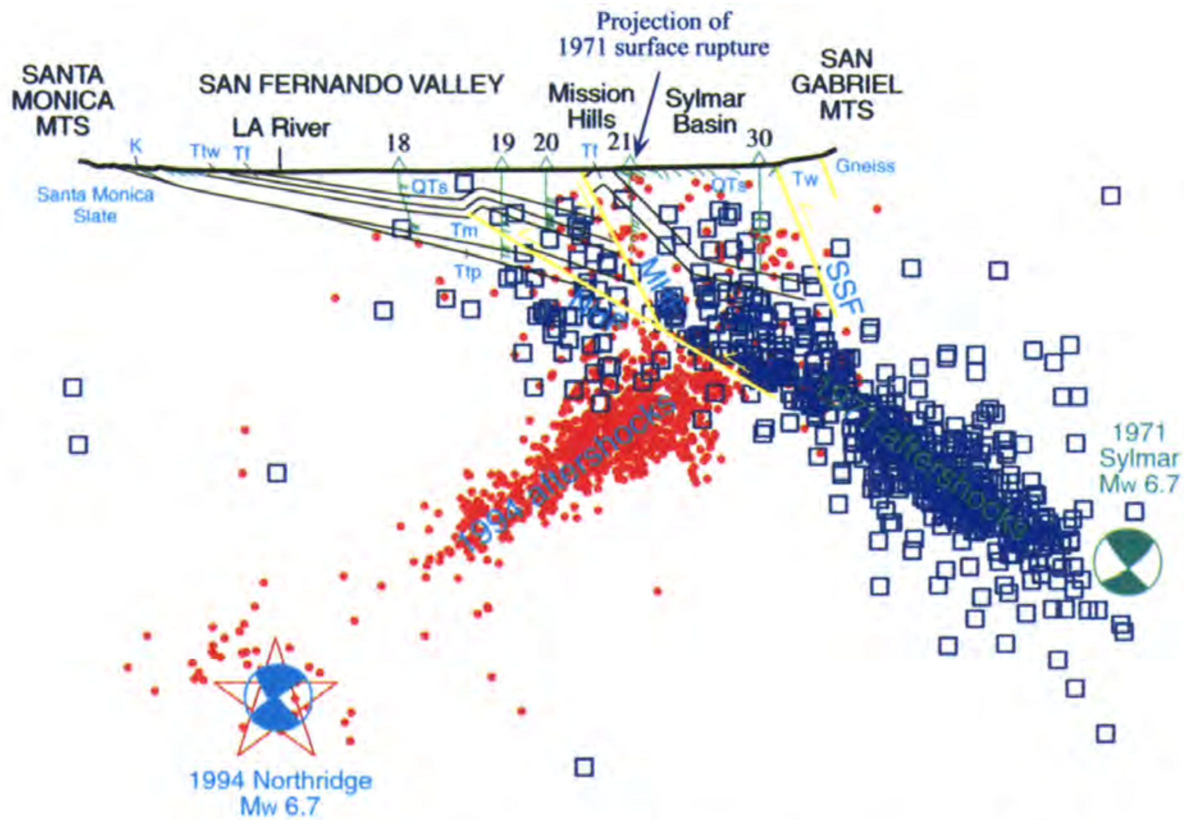



Figure 7. Cross section down to 20 km depth across the central San Fernando Valley, including the 1971 Sylmar and 1994 Northridge earthquake zones. See Figure 2 for location of the section and Figure 3 for stratigraphic abbreviations. Wells are identified in the Appendix. Aftershock data for the 1971 (blue) and 1994 (red) earthquakes within a 10-km-wide strip including the line of this section are provided by Jim Mori at Kyoto University. Abbreviation for faults: MHF, Mission Hills fault; NHF, Northridge Hills fault; SSF, Santa Susana fault.

↑ Cross section E-E' from Figure 4, Tsutsumi and Yeats, 1999.

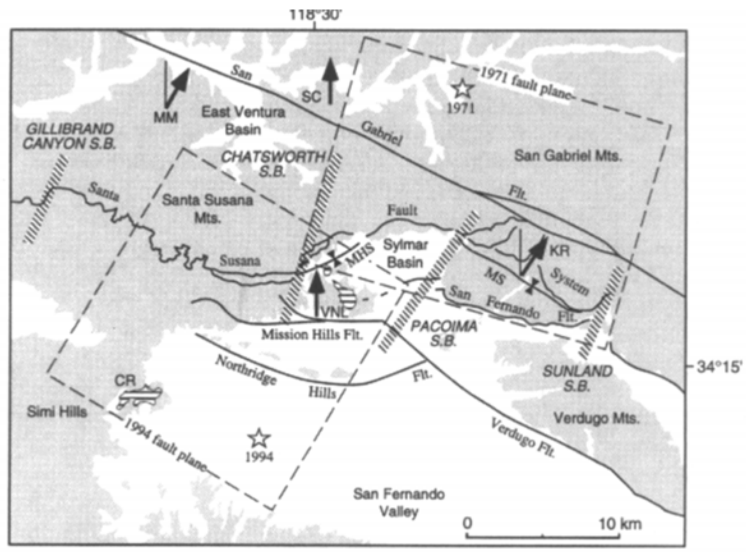


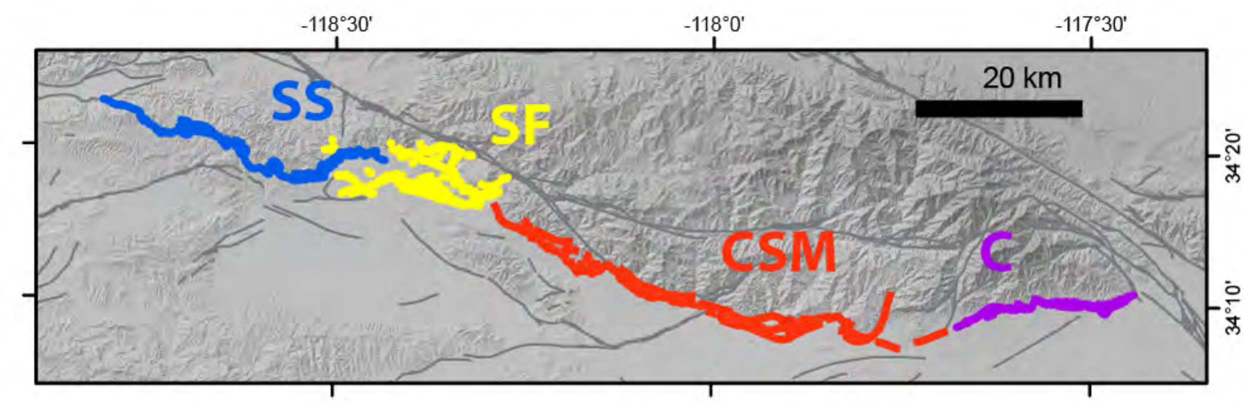

Figure 8. Segmentation of north- and south-dipping faults in the San Fernando Valley and adjacent Santa Susana Mountains. Arrows point in the direction of average declination for the Saugus Formation in Kagel Ridge area (KR), Magic Mountain area (MM), Soledad Canyon (SC), and Van Norman Lake area (VNL) from Levi and Yeats (1992; 1993). Dashed rectangles depict the surface projection of fault planes for the 1971 Sylmar and 1994 Northridge earthquakes (Mori *et al.,* 1995; Wald *et al.,* 1996). Stars locate epicenters for the earthquakes. Abbreviation: CR, Chatsworth Reservoir; MHS, Mission Hills syncline; MS, Merrick syncline; S. B., segment boundary.

🡅 Figure 8 from Baldwin et al., 2000.

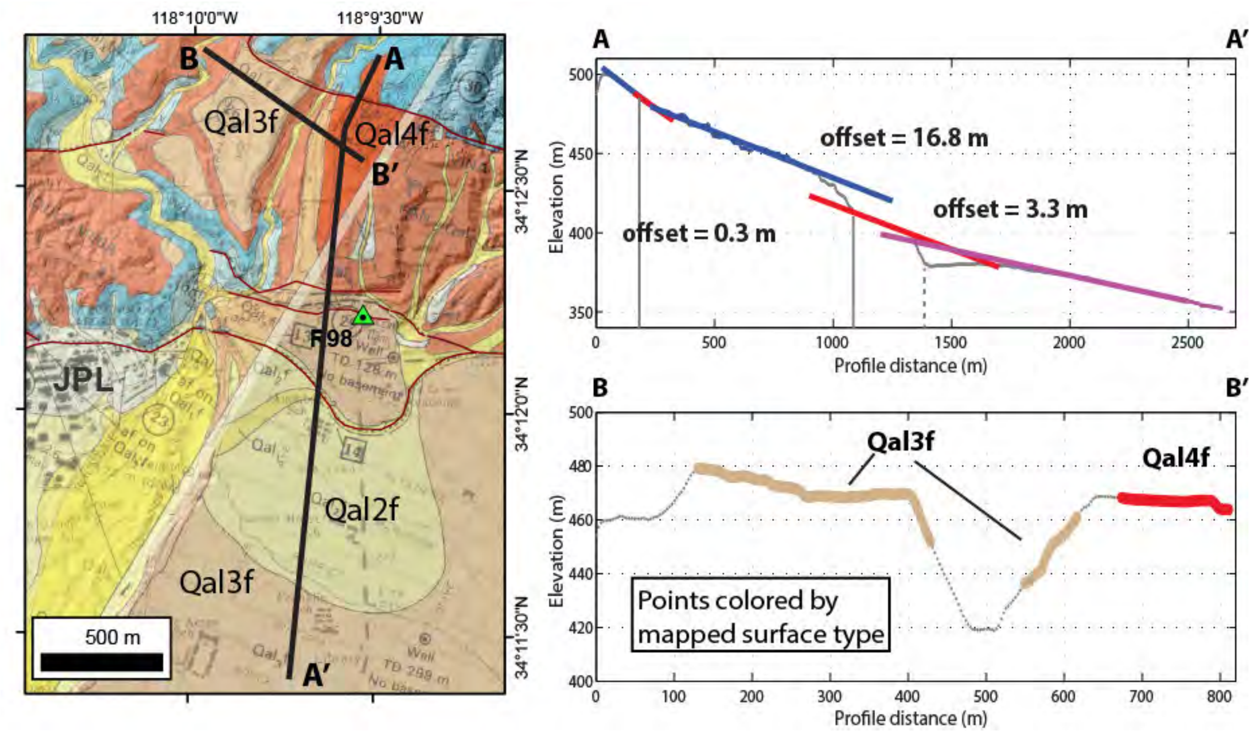
## STOP 7: LOMA ALTA PARK

*Return to Reseda Boulevard and take Hwy 118 E to I-210 E. Take Arroyo Boulevard Exit, and turn north on Windsor Ave, East on Woodbury Road, north on Lincoln Ave and East on Loma Alta Dr. The parking lot is just to north on Sunset Ridge Rd.* This part of the tour takes us between the San Gabriel Mountains (to our north) and the Verdugo Mountains (to our south).

The purpose of this stop is to provide a quick overview and description of the Sierra Madre Fault system. We are standing about half way along the Sierra Madre Fault System – recall it has several sections. From east to west, the main fault sections are the Santa Susana Fault (30 km), the San Fernando Fault (20 km), the Sierra Madre Fault (60 km), and the Cucamonga Fault (25 km). The complexity of the fault system leads to a wide range of magnitudes that could rupture on this fault; earthquakes could be moderate (like the M6.7 Sylmar earthquake) or if multiple fault sections are connected, as large as ~M8 (Field et al., 2013).




🡅 Map of Sierra Madre Fault System. BLUE: Santa Susana Fault, 6 (0.5-10) mm/yr; YELLOW: San Fernando Fault, 2 (1-3) mm/yr; RED: Central Sierra Madre Fault, 2 (1-3) mm/yr, PURPLE: Cucamonga Fault 1.5 (1-2) mm/yr. Slip rates used in UCERF3. From Burgette et al., 2014.




🡡 Quaternary geology of the JPL area (Crook et al., 1987), draped over lidar-derived shaded relief. R98 is location of Loma Alta Park. Profiles across mapped traces of the SMF show significant late Quaternary offset (e.g., A-A'). A cross-fan profile (B-B') illustrates likely miscorrelation of mapped terrace surfaces in earlier work. From Burgette et al. (2014).

Slip rates are variable across this system, and limited in number. For example, the Santa Susana Fault slip rate could be as high as 5.9±3.9 mm/yr (based on offset Plio-Pleistocene units; Huftile and Yeats, 1996) or as low as 2.5 mm/yr based on BEM modeling (Marshall et al., 2013). Lindvall and Rubin (2007) completed cosmogenic dating on the Wilson fan on the San Fernando section; summing offsets on the three strands at that location provides an upper rate of 3 mm/yr. At this location on the Sierra Madre Fault, Crook et al., (1987) estimated slip rates from soil chronosequences of 1.2-3 mm/yr. To the east, Lindvall and Rubin (2007) determined a slip rate of 1.9±0.4 mm/yr across the Cucamonga Fault zone.

There have been a few paleoseismic studies of this system. Here at Loma Alta Park, Rubin et al. (1998) trenched the ~2 m high scarp to our north and see evidence for two paleoearthquakes. They estimate that slip of ~4 m and 6.5 m occurred in the last two earthquakes, which happened since about 18,000 years ago, producing a slip rate of about 0.6 mm/yr (although this is just for one strand of system). Just west of the intersection of the Sierra Madre and Cucamonga Faults, Tucker and Dolan (2001) completed a boring and trench at Horsethief Canyon. They found evidence for one event over 8000 years ago, and determined a slip rate of 0.6-0.9 mm/yr.

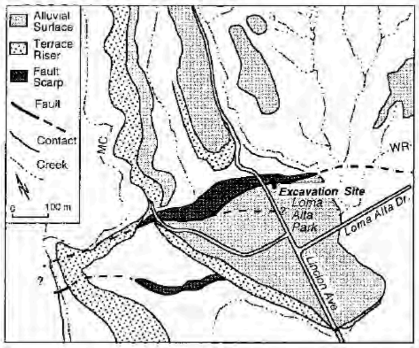



**Fig. 2.** Map of the Loma Alta Park paleoseismic site showing location of trench, fault zones, and scarp. The Sierra Madre fault shown as heavy black lines, dashed where inferred. MC, Millard Canyon; WR, West Ravine.

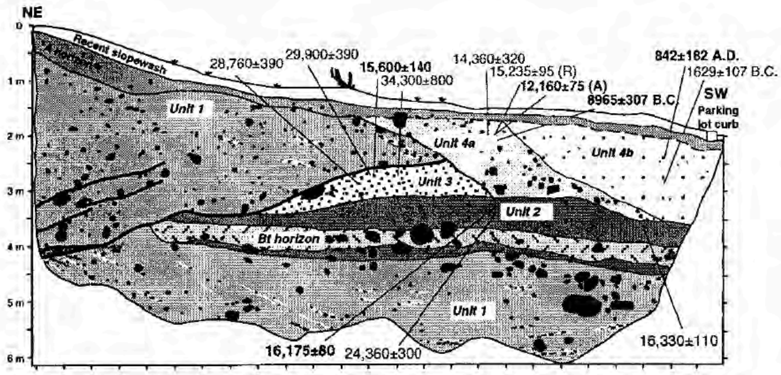



**Fig. 3.** Cross section through sediments in trench wall showing fault traces, stratigraphic units, and radiocarbon dates. A, angular detrital charcoal fragment; R, rounded detrital charcoal fragment. Faults are shown as heavy lines. Scale is shown in meters, with no vertical exaggeration. Radiocarbon ages are quoted in $^{14}C$ years before present, except calendric ages quoted as ka (years B.P.).

🡅 Figures from Rubin et al. (1998)

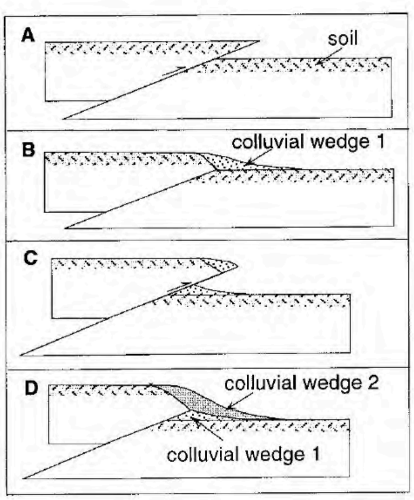



**Fig. 4.** Schematic development of colluvial wedges from two successive earthquakes. (**A**) Earthquake 1 ruptures the ground surface; scarp is known schematically as an unstable overhang. (**B**) Scarp collapses, degrades, and sheds debris, forming colluvial wedge 1. (**C**) Earthquake 2 ruptures ground surface and offsets colluvial wedge 1. (**D**) Scarp collapses, degrades, and sheds debris to form colluvial wedge 2. Surficial soil and colluvial wedge 1 are no longer preserved in the upper plate.

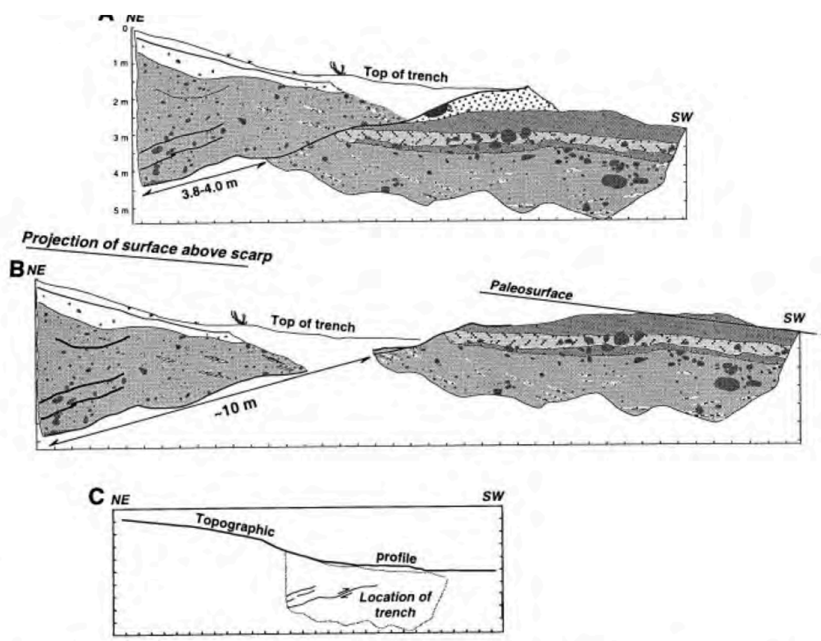



**Fig. 5.** (**A**) Restoration from the most recent earthquake yields a minimum slip of 3.8 to 4.0 m. In this restoration, the tip of the upper plate is restored to below the lower colluvial wedge; the restoration does not account for any slip on secondary faults within the hanging wall. (**B**) Restoration of slip from the last two earthquakes showing a minimum of ~10 m. Here, the upper plate is restored to below the $B_t$ horizon, and the buried paleosurface surface is matched to the topographic profile of the fault scarp. (**C**) Detailed topographic profile of fault scarp surveyed with an electronic distance meter/theodolite.

🡅 Figures from Rubin et al. (1998)


↑ 1930's photo of the San Gabriel Mountains with pre-development and relatively tree-free view of uplifted fan surfaces (arrow) above what is now Arroyo Seco.

## RETURN TO PASADENA CONVENTION CENTER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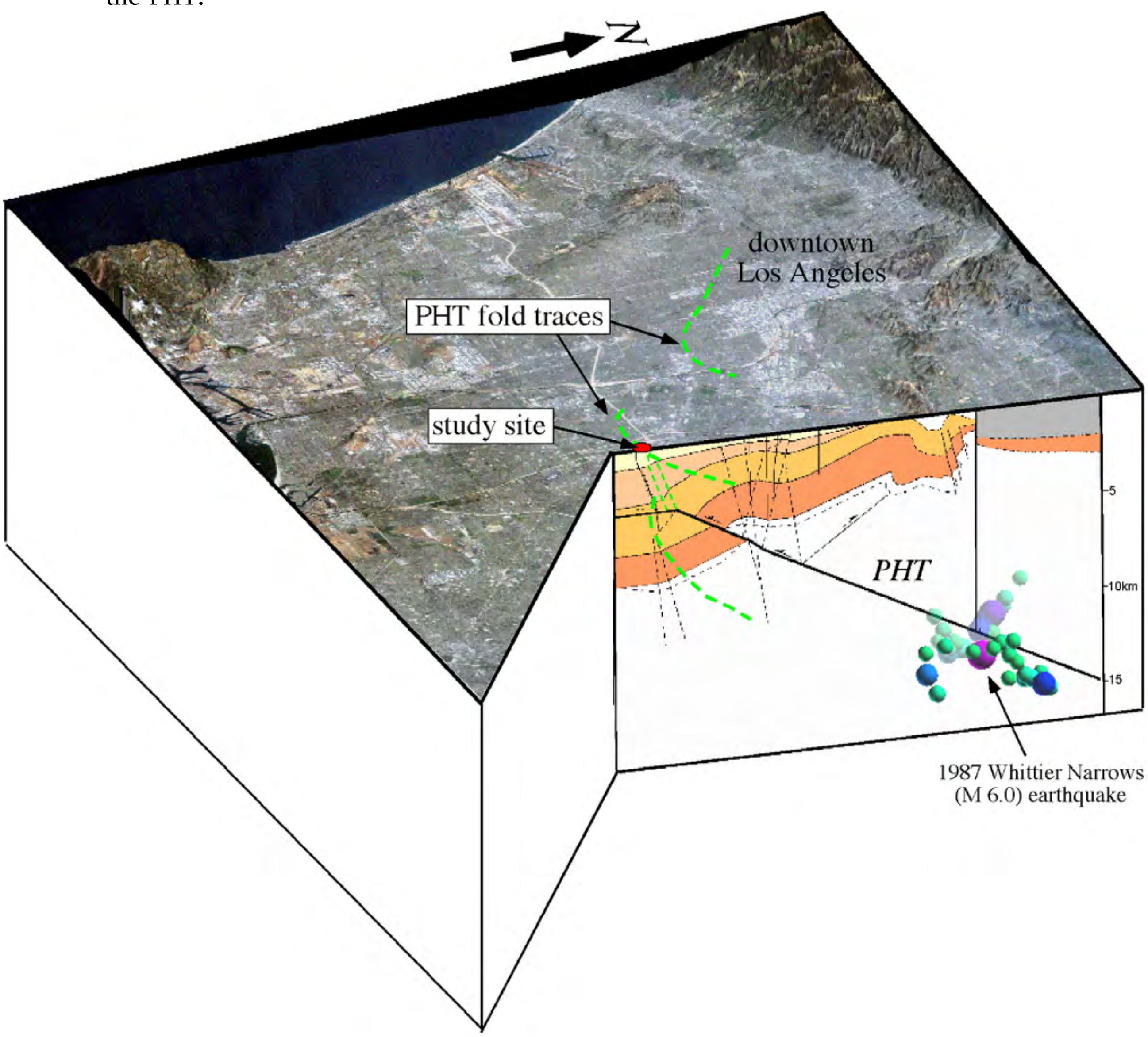
Bulletin of the Seismological Society of America, Vol. 92, No. 8, pp. 2946–2960, December 2002

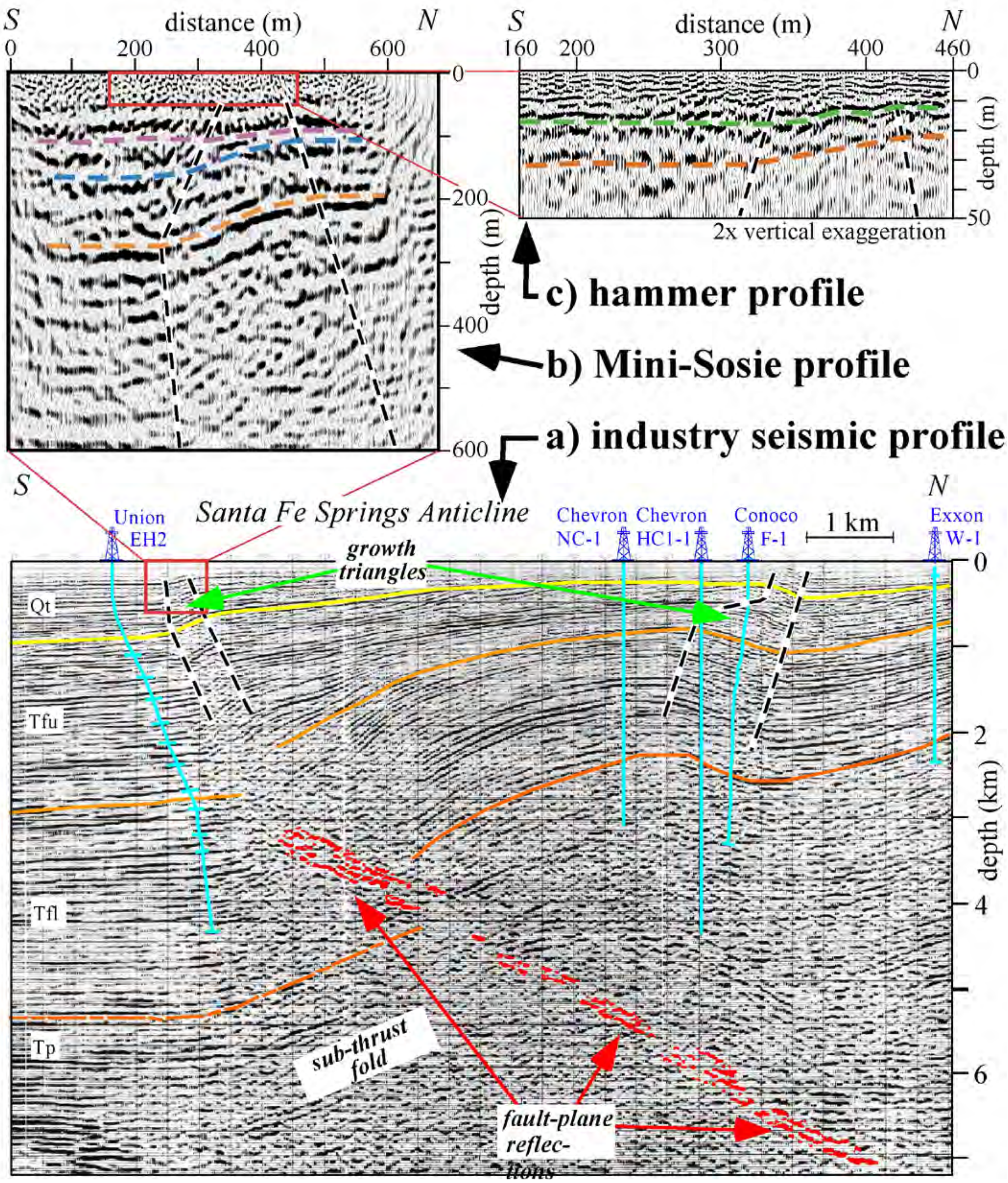
# Puente Hills Blind-Thrust System, Los Angeles, California

by John H. Shaw, Andreas Plesch, James F. Dolan, Thomas L. Pratt, and Patricia Fiore

Abstract We describe the three-dimensional geometry and Quaternary slip history of the Puente Hills blind-thrust system (PHT) using seismic reflection profiles, petroleum well data, and precisely located seismicity. The PHT generated the 1987 Whittier Narrows (moment magnitude [$M_w$] 6.0) earthquake and extends for more than 40 km along strike beneath the northern Los Angeles basin. The PHT comprises three, north-dipping ramp segments that are overlain by contractional fault-related folds. Based on an analysis of these folds, we produce Quaternary slip profiles along each ramp segment. The fault geometry and slip patterns indicate that segments of the PHT are related by soft-linkage boundaries, where the fault ramps are en echelon and displacements are gradually transferred from one segment to the next. Average Quaternary slip rates on the ramp segments range from 0.44 to 1.7 mm/yr, with preferred rates between 0.62 and 1.28 mm/yr. Using empirical relations among rupture area, magnitude, and coseismic displacement, we estimate the magnitude and frequency of single ($M_w$ 6.5–6.6) and multisegment ($M_w$ 7.1) rupture scenarios for the PHT.



Tom Pratt (USGS), James Dolan (USC) and John Shaw (Harvard) collecting high-resolution seismic reflection data above the central, Santa Fe Springs segment of the Puente Hills thrust (see Pratt et al., 2002 (BSSA); Shaw et al. 2002 (BSSA); and Dolan et al., 2004 (Science).



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, B03S03, doi:10.1029/2006JB004461, 2007



# Earthquake-by-earthquake fold growth above the Puente Hills blind thrust fault, Los Angeles, California: Implications for fold kinematics and seismic hazard

Lorraine A. Leon,[1] Shari A. Christofferson,[1] James F. Dolan,[1]
John H. Shaw,[2] and Thomas L. Pratt[3]

[1] Boreholes and high-resolution seismic reflection data collected across the forelimb growth triangle above the central segment of the Puente Hills thrust fault (PHT) beneath Los Angeles, California, provide a detailed record of incremental fold growth during large earthquakes on this major blind thrust fault. These data document fold growth within a discrete kink band that narrows upward from ~460 m at the base of the Quaternary section (200–250 m depth) to <150 m at 2.5 m depth, with most growth during the most recent folding event occurring within a zone only ~60 m wide. These observations, coupled with evidence from petroleum industry seismic reflection data, demonstrate that most (>82% at 250 m depth) folding and uplift occur within discrete kink bands, thereby enabling us to develop a paleoseismic history of the underlying blind thrust fault. The borehole data reveal that the youngest part of the growth triangle in the uppermost 20 m comprises three stratigraphically discrete growth intervals marked by southward thickening sedimentary strata that are separated by intervals in which sediments do not change thickness across the site. We interpret the intervals of growth as occurring after the formation of now-buried paleofold scarps during three large PHT earthquakes in the past 8 kyr. The intervening intervals of no growth record periods of structural quiescence and deposition at the regional, near-horizontal stream gradient at the study site. Minimum uplift in each of the scarp-forming events, which occurred at 0.2–2.2 ka (event Y), 3.0–6.3 ka (event X), and 6.6–8.1 ka (event W), ranged from ~1.1 to ~1.6 m, indicating minimum thrust displacements of ≥2.5 to 4.5 m. Such large displacements are consistent with the occurrence of large-magnitude earthquakes ($M_w > 7$). Cumulative, minimum uplift in the past three events was 3.3 to 4.7 m, suggesting cumulative thrust displacement of ≥7 to 10.5 m. These values yield a minimum Holocene slip rate for the PHT of ≥0.9 to 1.6 mm/yr. The borehole and seismic reflection data demonstrate that dip within the kink band is acquired incrementally, such that older strata that have been deformed by more earthquakes dip more steeply than younger strata. Specifically, strata dip 0.4° at 4 m depth, 0.7° at 20 m depth, 8° at 90 m, 16° at 110 m, and 17° at 200 m. Moreover, structural restorations of the borehole data show that the locus of active folding (the anticlinal active axial surface) does not extend to the surface in exactly the same location from earthquake to earthquake. Rather, that the axial surfaces migrate from earthquake to earthquake, reflecting a component of fold growth by kink band migration. The incremental acquisition of bed dip in the growth triangle may reflect some combination of fold growth by limb rotation in addition to kink band migration, possibly through a component of trishear or shear fault bend folding. Alternatively, the component of limb rotation may result from curved hinge fault bend folding, and/or the mechanical response of loosely consolidated granular sediments in the shallow subsurface to folding at depth.

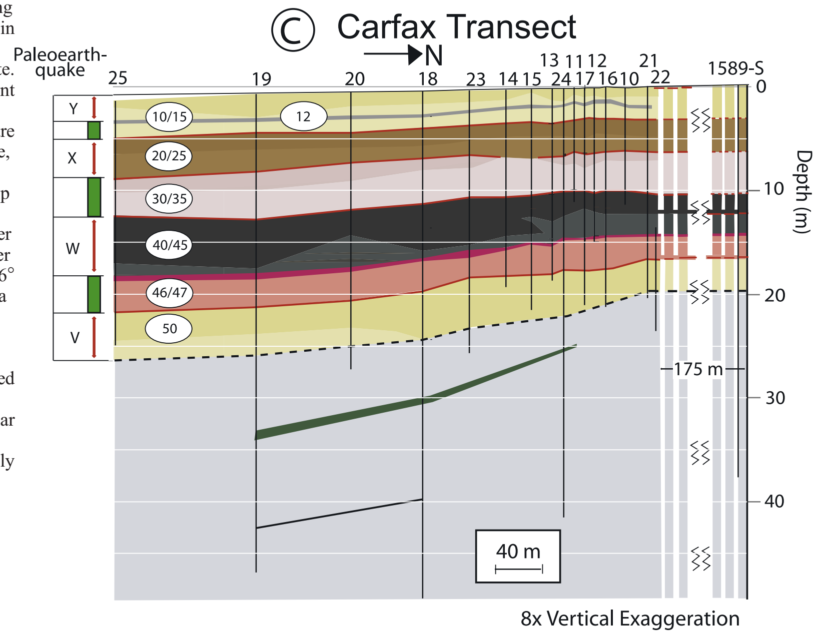
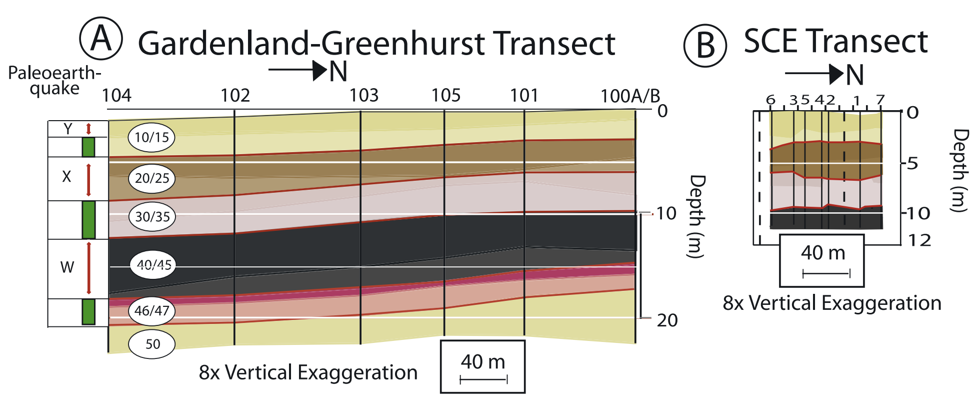



**Figure 5.** Borehole results from the Carfax Avenue transect, Gardenland-Greenhurst transect, and SCE transect showing major stratigraphic units (8X vertical exaggeration). Thin vertical lines denote boreholes. Numbers show key stratigraphic units discussed in the text. Thin red lines mark the tops of major sand- and gravel-filled units. Double-headed red vertical arrows along the left side of the figure show the stratigraphic range within which discrete uplift events occurred (see text for discussion). Solid green lines between red arrows on left side of figure show stratigraphic intervals that do not change thickness across the transect, reflecting periods of structural quiescence. Proposed correlations between Carfax boreholes and a water well (1589S) located 175 m north of the transect are shown by dashed stratigraphic contacts along the right side of the figure. Contacts at 12, 17, and 20 m depth are correlative between borehole 22 and the water well.



# Recognition of Paleoearthquakes on the Puente Hills Blind Thrust Fault, California

**James F. Dolan,[1]* Shari A. Christofferson,[1] John H. Shaw[2]**

Borehole data from young sediments folded above the Puente Hills blind thrust fault beneath Los Angeles reveal that the folding extends to the surface as a discrete zone (≤145 meters wide). Buried fold scarps within an upward-narrowing zone of deformation, which extends from the upward termination of the thrust ramp at 3 kilometers depth to the surface, document the occurrence of at least four large (moment-magnitude 7.2 to 7.5) earthquakes on this fault during the past 11,000 years. Future events of this type pose a seismic hazard to metropolitan Los Angeles. Moreover, the methods developed in this study can be used to refine seismic hazard assessments of blind thrusts in other metropolitan regions.

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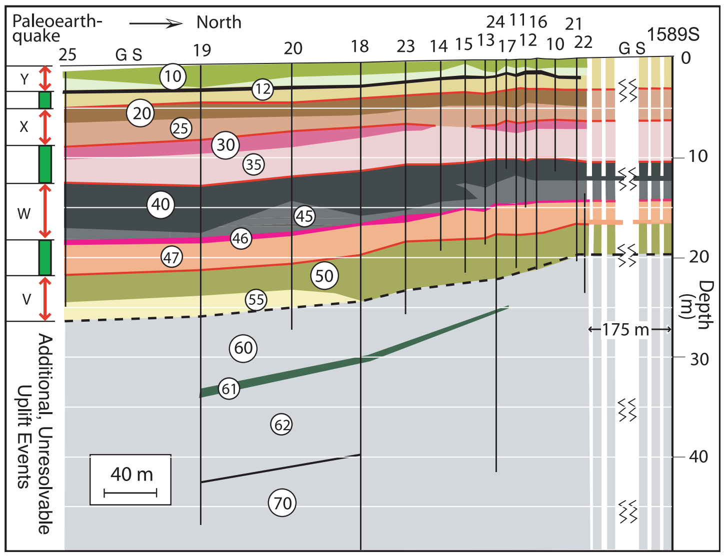



**Fig. 2.** Borehole results from the Carfax Avenue transect. Cross section of major stratigraphic units (eight times vertical exaggeration). The thin vertical lines are boreholes. Colors denote different sedimentary units. Numbers show key units discussed in the text. Thin red lines mark the tops of major sand- and gravel-filled channels. Double-headed red vertical arrows along the left side of the figure show the stratigraphic range of sedimentary growth after uplift events; green boxes show sections with constant sedimentary thickness across the transect (see text for discussion). Proposed correlations between Carfax boreholes and a water well (1589S) located 175 m north of the transect are shown by dashed stratigraphic contacts along the right side of the figure. Contacts at 12, 17, and 20 m are correlative between borehole 22 and the water well. G, ground; S, surface.

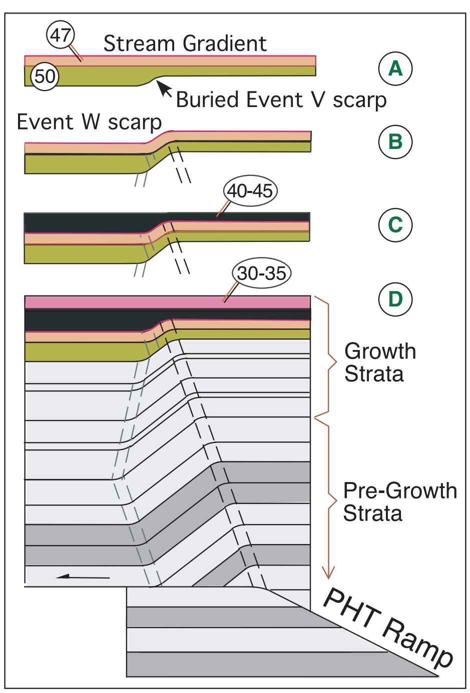
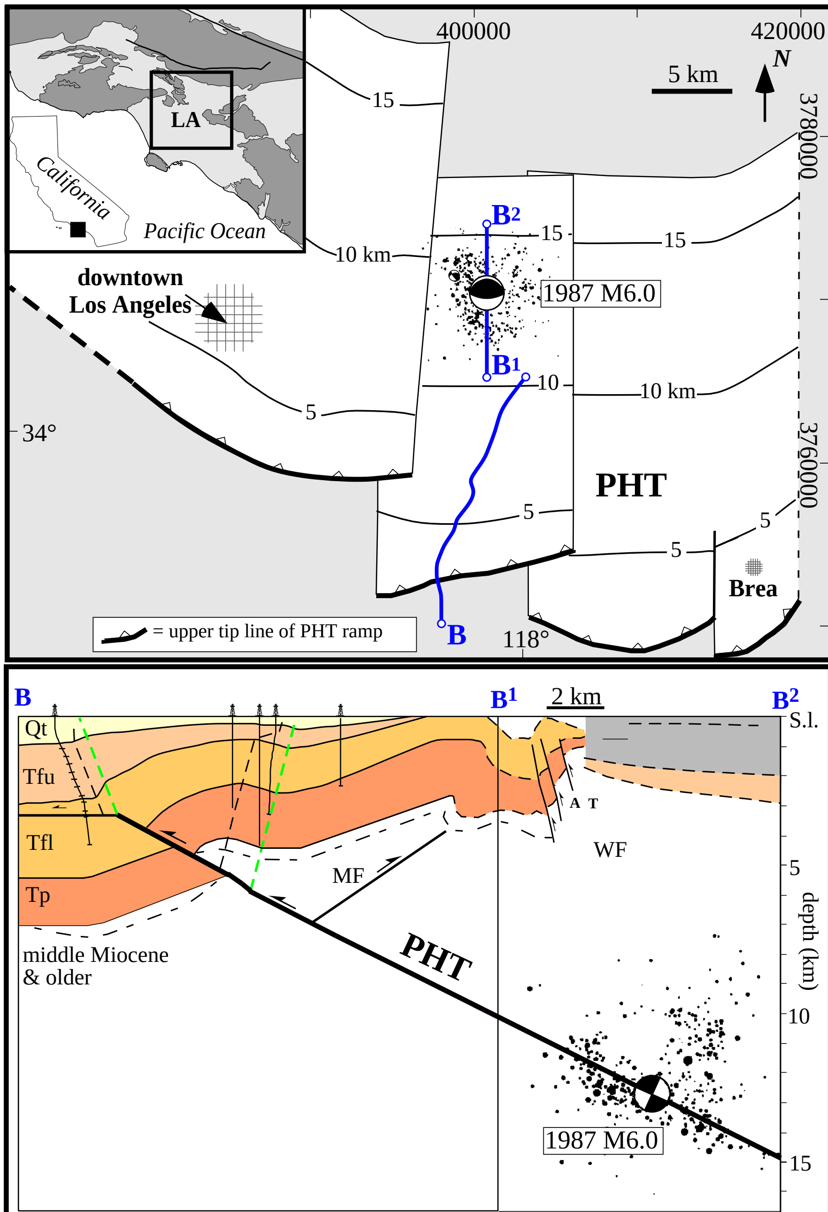



**Fig. 3.** Schematic reconstructions of growth strata showing the kinematic relation between development of fold scarps and slip on the PHT. Colors of young growth strata are the same as for Carfax Units 30 through 50 shown in Fig. 2. (**A**) Deposition of Units 47 and 46 (and probably the lower part of 45) at a near-horizontal stream gradient after burial of the Event V fold scarp by Unit 50 sand. (**B**) Coseismic development of a 2-m–high fold scarp in earthquake W. (**C**) Onlap of the Event W fold scarp by Unit 40 sand. (**D**) Deposition of Units 30 to 35 at a near-horizontal stream gradient after Event W. The steeply dipping black dashed line shows the active anticlinal axial surface; the gray dashed line shows the inactive synclinal axial surface (*7*, *9*, *10*).




# Shaw et al. (2002)

(A) Map of three main structural segments of the Puente Hills Thrust (PHT). From west to east these are the Los Angeles segment, the Santa Fe Springs segment, and the Coyote Hills segment, which itself comprises two distinct sub-segments. (B) Cross section based on petroleum-industry seismic relfection data (to 7 km depth) and mainshock and relocated aftershocks of the 1987 Mw 6.0 Whittier Narrows earthquake (Shaw & Shearer, 1999 Science) from 11–15 km depth).

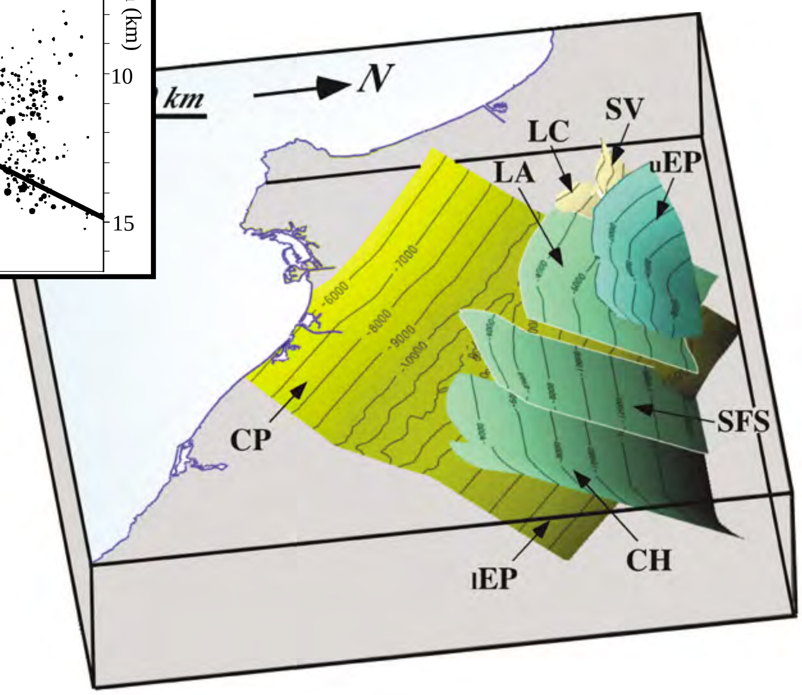



Figure 14. Perspective view of a three-dimensional model describing the PHT in relation to other major blind-thrust systems in the northern Los Angeles basin. PHT segments: CH, Coyote Hills; SFS, Santa Fe Springs; LA, Los Angeles segment; SV, San Vicente fault; LC, Las Cienegas fault (Schneider *et al.*, 1996); uEP, upper Elysian Park thrust (Oskin *et al.*, 2000); lEP, lower Elysian Park (Davis *et al.*, 1989; Shaw and Suppe, 1996); CP, Compton ramp (Shaw and Suppe, 1996).

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# Evidence for large Holocene earthquakes on the Compton thrust fault, Los Angeles, California

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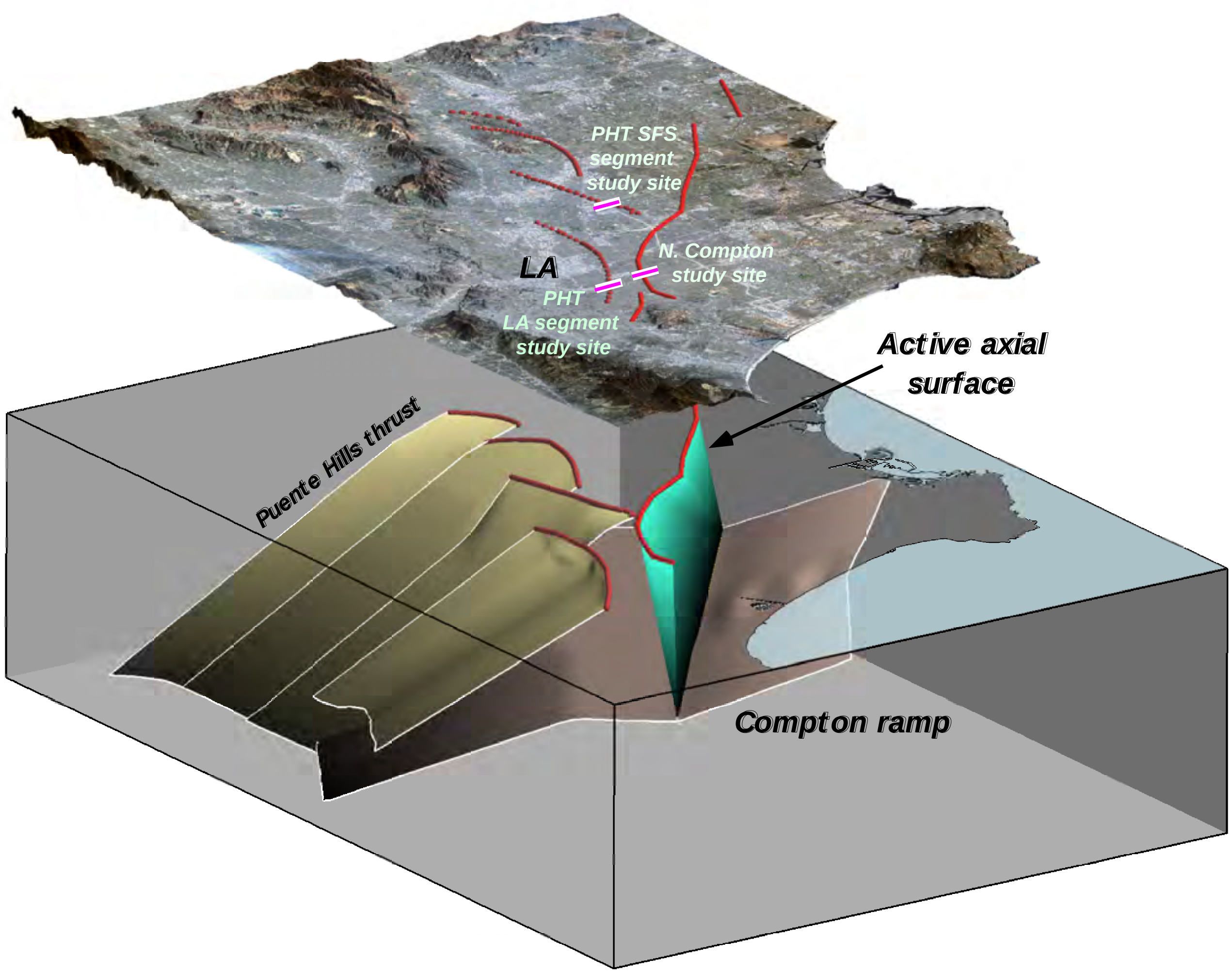
[1] We demonstrate that the Compton blind thrust fault is active and has generated at least six large-magnitude earthquakes ($M_w$ 7.0–7.4) during the past 14,000 years. This large, concealed fault underlies the Los Angeles metropolitan area and thus poses one of the largest deterministic seismic risk in the United States. We employ a methodology that uses a combination of high-resolution seismic reflection profiles and borehole excavations to link blind faulting at seismogenic depths directly to near-surface fault-related folding. Deformed Holocene strata record recent activity on the Compton thrust and are marked by discrete sequences that thicken repeatedly across a series of buried fold scarps. We interpret the intervals of growth as occurring after the formation of now-buried paleofold scarps that formed during uplift events on the underlying Compton thrust ramp. Minimum uplift in each of the scarp-forming events, which occurred at 0.7–1.75 ka (event 1), 0.7–3.4 ka or 1.9–3.4 (event 2), 5.6–7.2 ka (event 3), 5.4–8.4 ka (event 4), 10.3–12.5 ka (event 5), and 10.3–13.7 ka (event 6), ranged from ~0.6 to ~1.9 m, indicating minimum thrust displacements of ≥1.3 to 4.2 m. Such large displacements are consistent with the occurrence of large-magnitude earthquakes ($M_w \geq 7$). This multidisciplinary methodology provides a means of defining the recent seismic behavior, and therefore the hazard, for blind thrust faults that underlie other major metropolitan regions around the world.



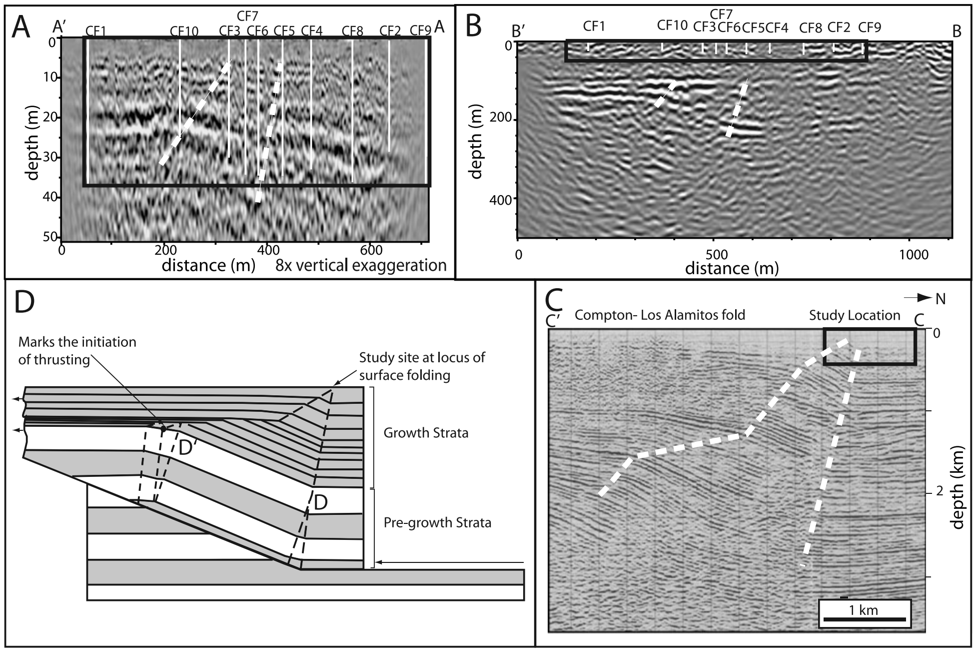



**Figure 3.** Compton fault seismic reflection data illustrating the multidisciplinary methodology utilized in this study [*Pratt et al.*, 2002; *Shaw et al.*, 2002; *Dolan et al.*, 2003] (see also similar studies by *Sugiyama et al.* [2003] and *Ishiyama et al.* [2004, 2007]). (a) Hammer source seismic reflection profile (migrated; 8× vertical exaggeration). The prominent reflector at 10–17 m depth shows the kink band clearly. Thin, vertical, white lines show borehole locations. Dashed white lines represent active, synclinal and inactive, anticlinal axial surfaces. Black box indicates location of borehole transect cross section in Figure 4. A–A′ marks the trace of the seismic reflection profile in Figure 2. (b) Weight drop source seismic reflection profile (migrated). The prominent reflector at 120–200 m depth shows the kink band well. The subhorizontal reflector at about 100 m depth is likely the water table, as velocities above the reflector are consistent with unsaturated strata. The reflector also cuts across the geologic structure consistently defined by the underlying reflectors and overlying drill hole data, as would be expected for the water table. Thin, vertical, white lines show borehole locations. Dashed white lines represent active, synclinal and inactive, anticlinal axial surfaces. Black box indicates location of hammer source profile shown in part A. B–B′ marks the trace of the seismic reflection profile in Figure 2. (c) Seismic reflection image of the back-limb fold structure showing upward narrowing zone of active folding (growth triangle) delimited by sharply defined axial surfaces [*Shaw and Suppe*, 1996]. Dashed white lines represent active, synclinal and inactive, anticlinal axial surfaces. Black box indicates location of weight drop source profile shown in part B. C–C′ marks the trace of the seismic reflection profile in Figures 1 and 2. (d) Fault bend fold model of back-limb fold structure of the Compton fault with discrete axial surface yielding an upward narrowing fold limb in growth strata (modified after *Shaw and Suppe* [1996]).

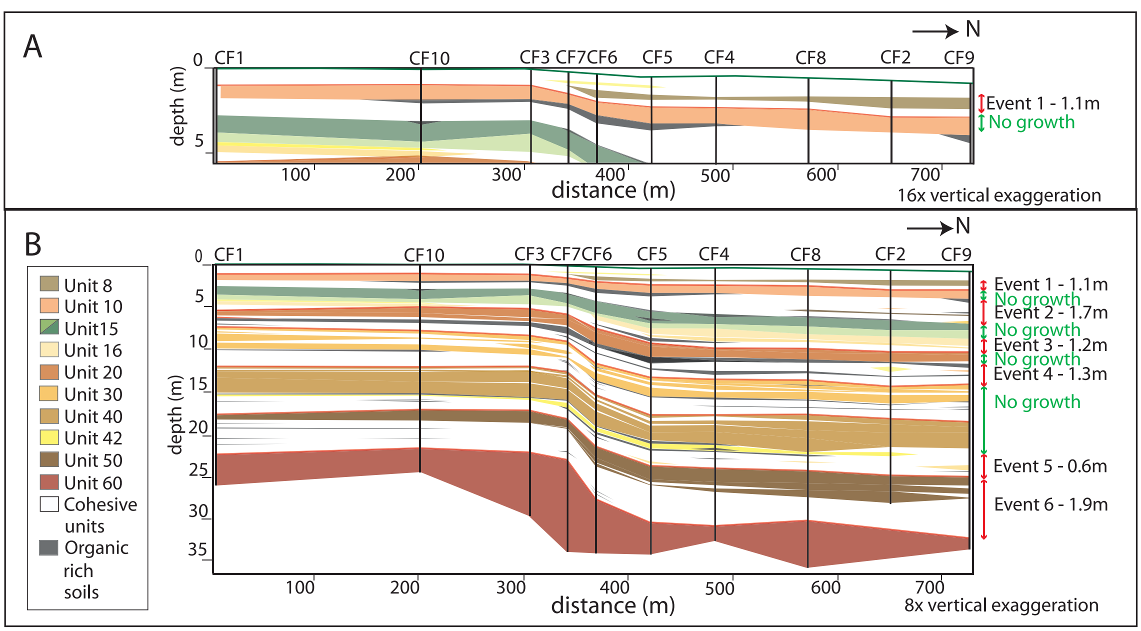



**Figure 4.** (a) Borehole results from the Stanford Avenue transect. Cross section of major stratigraphic units (16× vertical exaggeration) showing the details of the most recent uplift event (event 1). Thin vertical lines are boreholes. Green horizontal line is the present ground surface. (b) Cross section of major stratigraphic units (8× vertical exaggeration). Colors denote different sedimentary units. Thin red lines mark the tops of major sand and gravel units. Double-headed red vertical arrows along the right side show the stratigraphic ranges of intervals of sedimentary thickening across the transect, with the uplift in each event shown to the right of each arrow. Double-headed green vertical arrows show intervals of no sedimentary growth.