COLLABORATIVE RESEARCH (UNIVERSITY OF SOUTHERN CALIFORNIA, HARVARD UNIVERSITY, AND THE U. S. GEOLOGICAL SURVEY): A NEW METHODOLOGY FOR DEFINING CONCEALED EARTHQUAKE SOURCES -- APPLICATION TO THE PUENTE HILLS BLIND-THRUST SYSTEM, LOS ANGELES, CALIFORNIA

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Summary

Our NEHRP-funded research has allowed us to acquire borehole and high-resolution seismic reflection data that provide a comprehensive image of the recent deformation associated with paleo-earthquakes on the Puente Hills blind thrust fault (PHT). The location of the PHT beneath the heart of the Los Angeles, California, metropolitan region makes it one of the most potentially hazardous faults in the United States. At our primary study site in the City of Bellflower (15 km southeast of downtown Los Angeles), the seismic reflection and borehole data reveal an upward-narrowing zone of folding that extends to within 3 m of the surface. Stratigraphic relationships indicate that four discrete folding events, which we interpret as the result of large earthquakes (M_w>7) on the PHT, have occurred during the past 11,000 years. The minimum reverse-slip rate on the PHT at our study site is 1.1-1.6 mm/yr, indicating that the PHT accommodates a large percentage of the total shortening measured across the Los Angeles metropolitan region. Our research was published during 2002 and 2003 in a series of articles in Science (Dolan et al., 2003), the Bulletin of the Seismological Society of America (Shaw et al., 2002), and Geophysical Research Letters (Pratt et al., 2002).

Results

As part of this study, we have developed and tested a multi-disciplinary methodology for assessing the seismic hazards, paleoearthquake history, and recent kinematics of active blind-thrust faults. We have focused our collaborative efforts on the Puente Hills thrust fault (PHT), the active blind-thrust fault that generated the 1987 M 6.0 Whittier-Narrows earthquake beneath eastern Los Angeles (Figure 1). The location of the active PHT beneath the heart of the Los Angeles metropolitan region makes it one of the most potentially dangerous faults in the United States.

Our study site is located in the City of Bellflower, 15 km southeast of downtown Los Angeles, above the central (Santa Fe Springs) segment of the Puente Hills blind thrust fault (Figures 1 and 2). At this site, we have used petroleum industry (Shaw et al., 2002) and newly acquired high-resolution seismic reflection data (Pratt et al., 2002) to generate a continuous image of folding above the PHT from the tip of the thrust ramp at 3 km depth to ≤10 m from the Earth's surface. These data reveal an upward-narrowing zone of folding that is ≤250 wide at 15 m depth. These structural relationships are consistent with models of kink-band migration within the forelimb of a fault-bend fold (Pratt et al., 2002; Shaw et al., 2002). The discrete zone of shallow folding revealed by the seismic reflection data provided us with a target for siting a series of large-diameter (bucket-auger) and continuously cored, small-diameter boreholes designed to directly sample the folded stratigraphy.

We drilled a north-south transect of 25 boreholes along the east curb of Carfax Avenue across the locus of active folding defined by the seismic reflection data. The study site is located on the distal floodplain of the San Gabriel River, approximately 100 meters west of the active, southward-flowing river channel. The borehole transect is coincident with

the hammer-source and Mini-Sosie seismic reflection profiles that we collected during the Spring of 2000 (Pratt et al., 2002). The Carfax site is well-suited for structural analysis of deformation of young sediments, because the sedimentological conditions on an aggradational floodplain of a major river are nearly ideal and the geometry and kinematics of the causative blind thrust fault are well-documented.

The boreholes penetrated a sequence of sand- and gravel-filled channels (Units, 10, 20, 30, 40, 50, and 60) interbedded with clay and silt overbank deposits (Fig. 3). At least twelve of the sedimentary units at the Carfax site are laterally continuous, and can be traced along the entire 450 m length of the borehole transect. We also excavated a north-south transect comprising seven boreholes in an agricultural field 30 m east of the Carfax transect. Both transects penetrated the same stratigraphic section, demonstrating that all strata are laterally continuous both north to south and east to west.

Several distinctive sedimentary contacts can also be correlated between our northernmost borehole and a water well located 175 m to the north (1589S on Fig. 3). Radiocarbon age dating of more than 25 samples from the Carfax boreholes demonstrates that sediment accumulation has been relatively continuous over at least the past 11,000 years, with no major discernible depositional hiatuses. The transition from a wetter Pleistocene climate to the drier Holocene climate at 9.5-10 ka is expressed in the sediments as an upward transition from a gravel-dominated lower section (Unit 50 and below) to a mix of sands and muds (Unit 47 and above).

The tops of all of the sedimentary units are deeper at the south end of the transect than at the north end, with the structural relief of horizons increasing with depth. This relief reflects southward thickening of sedimentary sequences that also increases with depth. The sedimentary thickening (or "growth") is localized in an upward-narrowing zone located at the updip projection of the active axial surface imaged on the seismic reflection data. The zone of south-tilted strata is ~250 m wide at 15 m depth, whereas it is only 125 m wide at 2.5 m depth. Strata to the north and south of the zone of folding are nearly flat (Shaw and Shearer, 1999; Pratt et al., 2002; Shaw et al., 2002). The southward sedimentary thickening is restricted to discrete stratigraphic intervals that are separated by intervals that do not change thickness along the length of the transect.

A key consideration for interpreting the deformation of this low-gradient fluvial system is that although cohesive silts and clays might partially drape any existing topographic slopes (e. g., fold scarps), sands and gravels will not do so. Rather, the sands and gravels will buttress, or onlap, any existing topography. Moreover, the tops of any individual sand- or gravel-filled channel will be deposited at the local stream gradient. The pre-development stream gradient and regional slope are both extremely gentle (0.15°). Outside of the zone of active folding, the stream gradient is likely to have been this gentle throughout the Holocene, given the near-flat regional topography and sub-horizontal reflectors observed to the north and south of the zone of active folding (Shaw and Shearer, 1999; Pratt et al., 2002; Shaw et al., 2002). The tops of the laterally extensive sand and gravel channels exposed at the Carfax site thus provide paleo-near-horizontal indicators. By unfolding these horizons to their depositional geometry in the direction of

shear (Novoa et al., 2000), we have reconstructed the evolution of the folded sediments, allowing incremental measurements of sediment growth and the development of structural relief across the fold.

The deposition and deformation of the section from the top of Unit 50 through the top of Unit 30 is particularly illustrative. The coarse grain size and lateral continuity of Unit 50 suggest that the top of this gravel channel was deposited at the near-horizontal paleo-stream gradient. This inference is supported by the laterally constant thickness of Unit 46-47, which indicates that these sediments were deposited near-horizontally. Units 46 and 47 record a period of structural quiescence, with no discernible uplift occurring between 8.0 and 9.5-10.0 ka. In contrast, the overlying interval comprising the Unit 40 sand and Unit 45 overbank muds thickens southward by 2 m across the zone of active folding. The absence of growth in the Unit 30-35 section supports our inference that the top of the Unit 40 channel sand was deposited at the near-horizontal paleostream gradient. Thus, the sedimentary growth within the Unit 40-45 section record onlap of a now-buried, south-facing fold scarp that developed sometime after deposition of Unit 46 at 7.8-8.0 ka, and before completion of deposition of Unit 40 prior to 6.6-6.9 ka (the age of the middle of overlying Unit 35). We refer to this stratigraphically discrete uplift episode as Event W.

Using similar observations, we have identified three other temporally discrete periods of uplift during the past 8,000 years (Events Y, X, and V), as well as evidence for additional older uplift and sedimentary thickening. Event Y, the most recent earthquake, is recorded by a 1.0±0.1 m-high scarp capped by the buried Unit 11 paleosol. The age of this earthquake is poorly constrained, as the precise age of the Unit 11 paleosol, which post-dates the event, is unknown. A detrital charcoal age of 3.0-3.4 ka from the middle of Unit 20 provides an absolute maximum age for this earthquake. The large magnitude of this earthquake suggests that it predates the historic period, which began about 200 years ago. Penultimate Event X is recorded by 1.0±0.2 m of southward thickening of the unit 20-25 section, which reflects uplift and subsequent burial of a 1-m-high fold-scarp that developed after the end of Unit 30 deposition ≤6 ka, and before the end of Unit 20 deposition ~2-3 ka. Event X followed a period of structural quiescence during deposition of Units 30 and 35 from ~5 to 7 ka. Event V, the oldest episode of discrete fold growth that we can identify, is recorded by 2.2 m of southward thickening of the Unit 50-55 section. Event V occurred after deposition of Unit 60, and probably after deposition of Unit 55 at ~10.2-10.7 ka, and before the end of deposition of the Unit 50 gravel channel at ~9.5-10.0 ka. Progressive downward thickening of units below Unit 55 in the southern part of the transect records additional latest Pleistocene uplift (e. g., Unit 61 paleosol exhibits an additional 2 m of structural relief), but we cannot distinguish discrete structural events in this gravel-dominated section.

We attribute these four uplift events to co-seismic fold growth during large earthquakes on the PHT. On the basis of the episodic nature of the uplift and the spatial association of the zone of uplift with the active axial surface (locus of active folding) of the fold forming above the deep PHT ramp (Shaw and Shearer, 1999; Pratt et al., 2002; Shaw et al., 2002), we attribute these four uplift events to co-seismic fold growth during large

earthquakes on the PHT. Alternatively, if each of the stratigraphically discrete uplift events records multiple moderate-sized earthquakes, rather than a single large event, these smaller earthquakes must have occurred during brief clusters, on the order of no more than approximately a thousand years in the cases of Events W and V, for example. For comparison, at least six to ten Northridge-sized (M_w 6.7) earthquakes would have had to occur to account for the displacement observed during Event W (Wells and Coppersmith, 1994). We consider this possibility unlikely, and favor the single-event interpretation for each of these temporally discrete uplift events. Moreover, the episodic development of the fold scarps rules out the possibility that the folds grow quasi-continuously in response to fault creep on the PHT. In either case, these discoveries obviate concerns that near-surface deformation above blind thrust faults may be too diffuse to record useful paleoseismological information, and demonstrate that earthquake ages and displacements can be extracted from blind thrust faults with precision comparable to that of traditional paleoseismologic studies.

The well-constrained geometry and kinematics of the PHT and its associated folds (Shaw and Shearer, 1999; Pratt et al., 2002; Shaw et al., 2002), allow us to convert uplift in Events V-Y to estimates of co-seismic displacement on the PHT. We have conservatively assumed simple rigid-block motion of the hanging wall up the PHT ramp (i. e., that no strain is consumed by deformation of the hanging wall block), yielding minimum measurements of reverse slip on the PHT ramp in past earthquakes (Table 1). The minimum 13.7±1.7 m of slip in these earthquakes indicates a minimum slip rate of 1.1-1.6 mm/yr since the 9.5-10.7 ka age of Event V. The 1.1-1.6 mm/yr minimum slip rate averaged over the past 9.5-10.7 ka indicates that the PHT accommodates at least ~15-30% of the geodetically measured north-south horizontal shortening rate across the Los Angeles region (Walls et al., 1998; Argus et al., 1999; Bawden et al., 2001). Shaw et al. (Shaw et al., 2002), however, showed that the Carfax site records only ~65% of the long-term maximum displacement on the Santa Fe Springs segment of the PHT, implying that the slip rate of the central part of the SFS segment may be as high as ~1.5-2.3 mm/yr. Thus, over the long term, the PHT may accommodate ~20-45% of the seismic energy release on thrust faults in this part of metropolitan Los Angeles.

We estimate a conservative range of paleomagnitudes for these earthquakes by assuming that our minimum slip estimates represent either average slip or maximum slip during past PHT ruptures. In a long-term sense, however, the minimum displacements that we measured cannot all represent maximum slip values in all four earthquakes because the Carfax site records only ~ 65% of maximum slip along the Santa Fe Springs segment (Shaw et al., 2002). Moreover, we have assumed that there was no erosion of upstream, uplifted portions of the paleo-fold scarps. Any undetected erosion would increase our estimates of uplift for each folding event, and therefore our estimates of displacement per event. Comparison of our minimum blind thrust displacements with regressions of maximum and average slip versus moment-magnitude (Wells and Coppersmith, 1994) indicates that Events X, Y, and U were on the order of M_w 7.2+0.1/-0.3, whereas Events W and V were much larger, on the order of M_w 7.4+0.15/-0.3.

Shaw et al. (2002) estimated the maximum magnitude for PHT earthquakes of M_w ~7.1, somewhat smaller than our suggested magnitudes, especially for Events W and V. Their analysis, however, extended only to the northwestern limit of then-available, high-quality petroleum-industry seismic reflection data, at a point ~4 km northwest of downtown Los Angeles. Dolan (1998) suggested that geomorphic evidence for young folding (uplifted older alluvium and drainages diverted around the western nose of a young, west-northwest-trending anticline) indicates that the PHT has propagated westward into the Beverly Hills area, ~10-15 km west of downtown Los Angeles. This would almost double the area of the PHT Los Angeles segment ramp, and would increase the total fault-plane area of the PHT system by as much as ~25%, adding significantly to size of a system-wide rupture. Alternatively, the PHT may rupture together with adjacent faults.

The large displacements associated with Events V-Y suggest that the PHT typically ruptures in large earthquakes (M_w >7). These PHT earthquakes would have been much larger than any earthquakes that have occurred on Los Angeles-region faults (excluding the San Andreas fault) during the 200-year-long historic period. Specifically, excluding the San Andreas fault, the largest earthquakes to occur on Los Angeles-region faults during the historic period (~1775 to present) are the 1971 San Fernando and 1994 Northridge earthquakes, both of which were M_w 6.7. Our observations add to a growing body of evidence that shows that the historic period in the Los Angeles area has been part of a seismic "lull" that is not representative of the long-term patterns of seismic strain release in the region, in terms of both earthquake sizes and moment-release rates (e. g., Dolan et al., 1995)

A large-magnitude PHT event would have devastating societal and economic impact on California. Not only does the PHT lie directly beneath Los Angeles, but this north-dipping fault also defines the northeastern edge of the Los Angeles basin, a 10-km-deep, sediment-filled trough. Computer simulations indicate that these thick basinal sediments will significantly amplify both the duration and amplitude of strong ground motions (Olsen and Archuleta, 1996; Wald and Graves, 1998; Field et al., 2000). If a major PHT rupture similar to those we have documented were to exhibit updip directly, a common occurrence in many thrust earthquakes, seismic energy would be focused directly into the thick sedimentary fill of the Los Angeles basin. In addition to strong ground motions associated with $M_w \geq 7$ earthquakes on the PHT, the coseismic development of 1- to 2-m-high, ≤125 m-wide fold scarps, such as those observed at the Carfax site, will greatly disrupt any infrastructure built across the zone of active folding. Recognition of these narrow zones of co-seismic folding indicates that blind thrust faults represent as significant a surface-deformation hazard as faults that breach the surface.

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Figure Captions

Figure 1. Perspective view of the PHT and associated fold depicted in a cross section through the Santa Fe Springs segment (image generated by Andreas Plesch and John H. Shaw of Harvard University). The forelimb extends upwards from the tip of the thrust ramp and deforms sediments excavated by our borehole transect at the Carfax site. LandsatTM image is draped over topography, illustrating the proximity of the thrust to downtown Los Angeles. Relocated mainshock and aftershocks of the 1987 M_w 6.0 Whittier Narrows earthquake are from Shaw and Shearer (1999).

Figure 2. (A) Map of the three major segments of the Puente Hills blind thrust fault (modified from Shaw et al., 2002). B1-B2 shows location of seismic reflection profile shown in (B). Our primary study site is located above the center of the central Santa Fe Springs segment of the fault

Figure 3. Borehole results from the Carfax Avenue transect (modified from Dolan et al., 2003). (**A**) Cross section of major stratigraphic units (8X vertical exaggeration). Thin vertical lines are boreholes. Colors denote different sedimentary units. Numbers show key units discussed in text. Thin red lines mark the tops of major sand- and gravel-filled channels. Double-headed red vertical arrows along left side of figure show stratigraphic range of sedimentary growth following 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 transect shown by dashed stratigraphic contacts along right side of figure. Contacts at 12 m, 17 m, and 20 m are correlative between borehole 22 and the water well. (**B**) Calibrated, calendric ages of detrital charcoal and bulk-soil samples from Carfax boreholes, plotted versus sample depth as projected along stratigraphic contacts to borehole 19. Note that the two deepest radiocarbon samples are wood, and may be reworked, yielding an anomalously old apparent age for Unit 62; we suspect that sediment accumulation was actually quite rapid in this gravel-dominated stratigraphic interval.

Publications Resulting From This Grant

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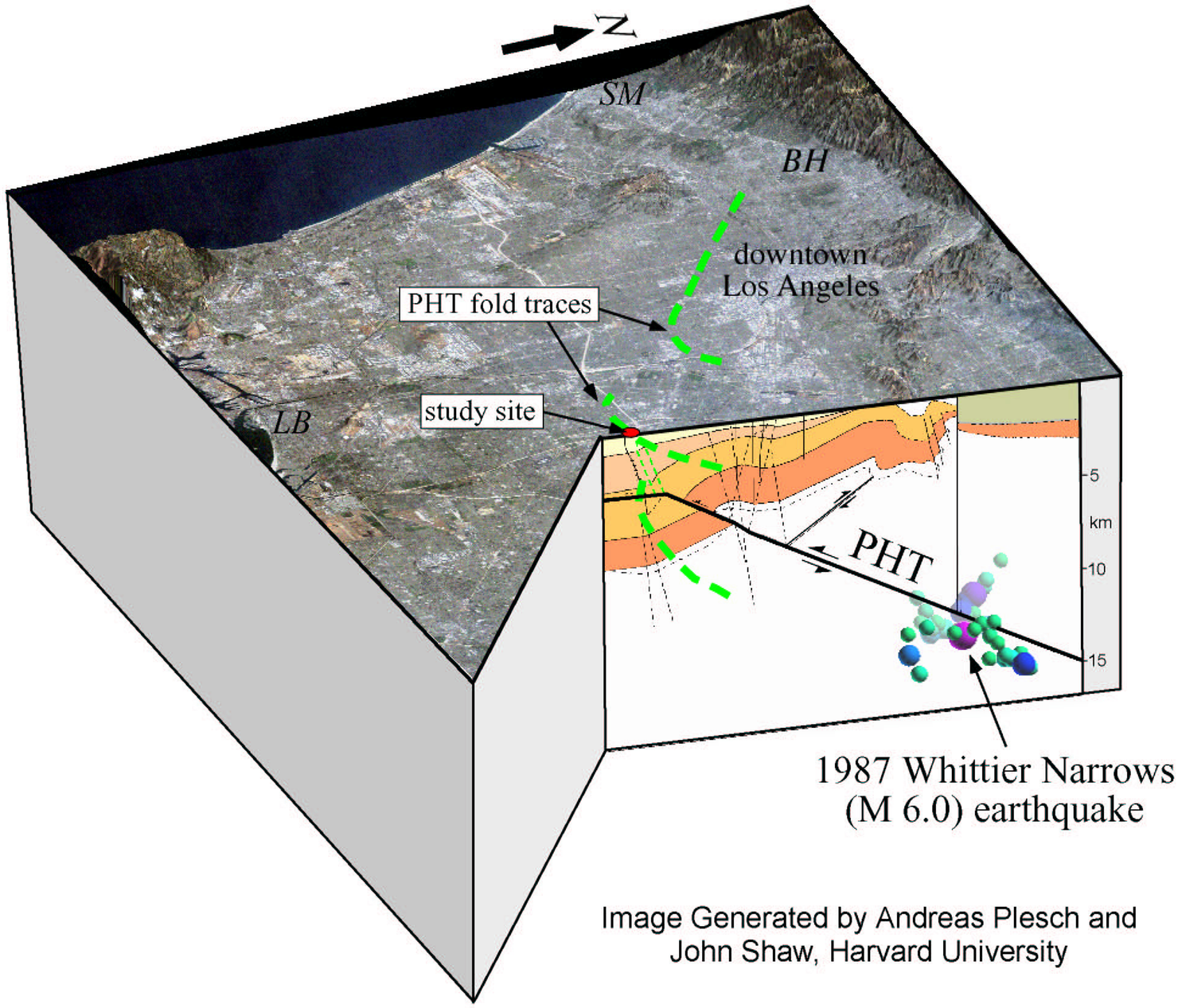
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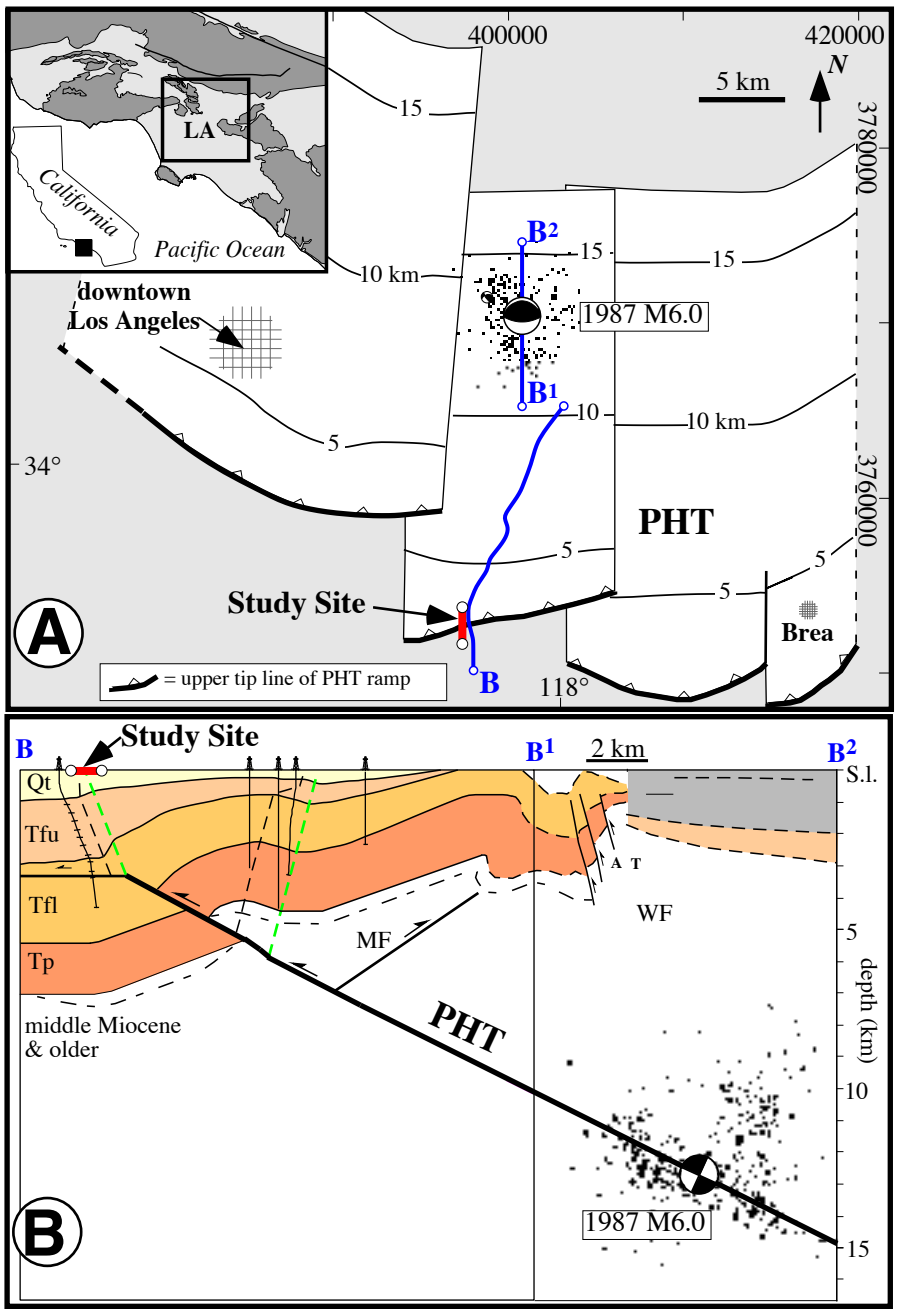
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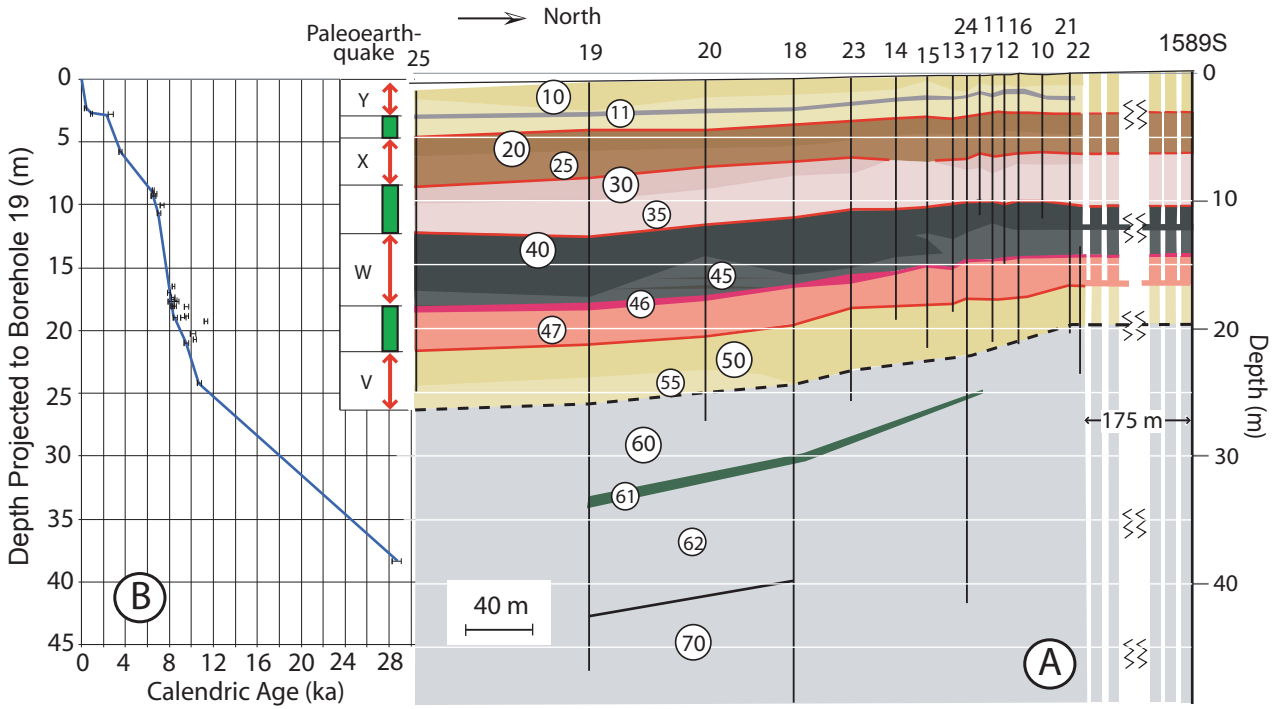
Paleoearth-quake
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