COLLABORATIVE RESEARCH WITH THE 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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Final Project Report
February 15, 2001- February 14, 2002

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Program Element II
Key Words: Quaternary Fault Behavior, Paleoseismology, Fault Segmentation

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Summary

As part of our ongoing development and testing of a multidisciplinary methodology for studying the paleoseismology, earthquake potential, and kinematics of recent deformation of blind thrust faults, we completed borehole transects at two sites above the tip of the forelimb growth triangle above the Puente Hills blind thrust fault (PHT). The location of the active PHT beneath the core the Los Angeles metropolitan region makes it one of the most potentially hazardous faults in the United States. Our borehole results reveal discrete periods of uplift along the central, Santa Fe Springs segment of the PHT. We attribute these uplift events to four large ($Mw \geq 7$) earthquakes that occurred along the PHT since ~12 ka. To the best of our knowledge, this is the first time that individual paleo-earthquakes have been identified directly from an active blind thrust fault. We have also generated Holocene slip rates at the two sites that are similar to the 1-2 mm/yr long-term rates for the PHT identified during our 2000 work on the PHT (Shaw et al., in press).

2001 Results

In this ongoing 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). During 2001, we used high-resolution seismic reflection images and kinematic information generated during our 2000 efforts to locate two study sites above the active axial surface of the anticlines that have formed above the Puente Hills thrust ramp. Specifically, the high-resolution seismic reflection images that we acquired in the first phase of our research revealed south-dipping reflectors in an upward-narrowing zone that extends to within 10-20 m of the surface at one site and to ≤50 m at the other (Pratt et al., 2002). During 2001, we excavated borehole transects across the tip of the forelimb growth triangles of the Santa Fe Springs and West Coyote Hills anticlines, as defined by the high-resolution data. The borehole data allowed us to document, in unprecedented detail, the precise geometry of near-surface folding, as well as to collect datable material from the folded strata. These data have allowed us to define fault slip rates, as well as slip per event and age data for past earthquakes on the underlying Puente Hills thrust.

Above the Santa Fe Springs segment of the PHT, we excavated a total of 21 boreholes along, and parallel to, Carfax Avenue in the City of Bellflower (Figure 2). Above the Coyote Hills segment of the PHT, we are actively excavating boreholes along Trojan Way in the City of La Mirada. Thus far, we have drilled three deep boreholes at the Trojan Way site (Figure 3).

The Carfax Site, Bellflower, California

The Carfax Avenue borehole transect is located along the east curb of Carfax Avenue. This site is on the distal floodplain of the San Gabriel River, approximately 100 meters west of the active, southward-flowing river channel (Figure 2). 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). A shorter borehole transect was also completed 25 meters east of and parallel to Carfax Avenue. We refer to this as the "SCE site" because it is located in a Southern California Edison power line right-of-way (Figure 2). The Carfax transect, which comprises fourteen boreholes, extends north-south for 311 meters and spans hammer-source shotpoint numbers (sp) 496 to sp 185 (Figure 2). The 80-m-long SCE transect consists of seven boreholes that span sp 491 to sp 411, projected 25 m due east from the high-resolution profile. All of the SCE boreholes were drilled with a large-diameter (70 cm) "bucket-auger" rig, whereas the Carfax transect comprises both bucket-auger and continuously cored, 9-cm-diameter hollow-stem holes.

The fourteen Carfax Avenue boreholes reveal a stratigraphic section that consists of laterally continuous, friable sands and gravels interbedded with cohesive intervals composed of silts and clays (Figure 4). These units range in thickness from tens of centimeters to several meters. The uppermost 20 meters of the section consists predominately of one- to several-meter-thick, fine-grained sand-filled channels that are separated from one another by centimeter- to meter-scale cohesive silt and clay units. We interpret these very fine-grained strata as overbank deposits. In contrast, the lowermost part of the section (e.g. basal 30 m of boreholes 18 and 19) is much coarser-grained, consisting primarily of friable, medium- to coarse-grained sands and pebble to cobble conglomerates, with the exception of three sub-meter to meter-scale cohesive (clay and silt) sections at the south end of the transect. These cohesive intervals do not extend north of borehole 18, and have most likely been eroded by channels. All other units, however, are traceable continuously for the entire north-south length of the borehole transect.

We have identified seven laterally continuous units of friable, fine-grained sand and coarser grain size (units 10, 20, 30, 40, 50, 60, and 70) (Figure 4). Four major sand units (10, 20, 30, and 40), are continuous in both the north-south and the east-west directions, as demonstrated by correlation with the SCE borehole transect 25 meters to the east of Carfax Avenue. Six laterally continuous units of cohesive, silty-sand to clay (units 12, 15, 25, 35, 45, and 47) have also been identified across the entire length of the borehole transect (Figure 4). In addition to the major depositional units, we have recognized several pedogenic and diagenetic sub-units (11, 46, and 61).

All units below unit 10, which extends upwards to the present-day surface, dip gently to the south within an upward-narrowing zone that is ~ 300 m wide at 25 meters depth and ~ 100-160 m wide at 2 meters depth (Figure 3). These results show conclusively that active folding above the blind PHT extends to the surface as a relatively narrow, discrete zone of deformation. Moreover, they reveal that the southward dip of strata within the growth triangle observed on seismic reflection data is acquired incrementally, with the deepest folded strata that we observed in the boreholes dipping more steeply than sediments that have been folded in fewer earthquakes. Thus, the early stages of development of the growth triangle above the Santa Fe Springs segment of the fault probably occur through a combination of kink band migration and progressive limb rotation. The overall growth of the kink band, however, as imaged on seismic reflection data (Shaw and Shearer, 1999; Shaw et al., in press) is controlled by kink band migration.

Four packages of sediment, consisting of both sand and cohesive units, thicken to the south across the borehole transect. The southward thickening of these units indicates that they were deposited across a series of now-buried, south-facing paleo-fold scarps. We have identified four of these temporally discrete paleo-fold scarps in the upper 25 meters at Carfax Avenue. The four discrete stratigraphic intervals of southward sedimentary thickening, or growth, are separated by intervals of no growth (e. g., package comprising units 46 and 47). Total southward thickening along the length of the borehole transect, as measured at the deepest continuous sand unit that we have identified (Unit 60), is 5 m (Figure 4). The four discrete buried fold scarps each exhibit 1-2 m of vertical relief.

These paleo-fold scarps indicate there have been at least four temporally discrete uplift events on the Santa Fe Springs segment of the PHT. We interpret these uplift events as having occurred in large paleoearthquakes during latest Pleistocene to Holocene time. Knowing the uplift in each of these events, we can use the well-constrained dip of the blind-thrust ramp and knowledge of the kinematics of the structure to estimate the slip that generated each fold scarp. The slip per event estimates for the four paleoearthquakes indicate that these events were on the order of M_w 7.1-7.4, using the regression of Wells and Coppersmith, 1994). Although we cannot rule out the possibility that each of these uplift “events” actually occurred during a brief cluster of moderate- to moderately large-magnitude earthquakes, we prefer the single-event interpretation, given the apparently brief duration of at least some of the uplift events and the large thrust displacements required to generate the amount of uplift observed along each paleo-fold scarp. The borehole results rule out the possibility that the anticlines above the PHT grow during steady, quasi-continuous fault creep.

The stratigraphic section exposed in the Carfax borehole transect is well dated, with 21 ^{14}C dates on detrital charcoal fragments and bulk-soil samples in hand, and 20 more ^{14}C dates pending at the University of Arizona reactor lab. These age data indicate that the four events occurred in the past ~11,000-12,000 years. On the basis of total uplift during the four scarp-forming events in the upper 25 meters of the Carfax Avenue transect, we estimate a late Pleistocene – Holocene slip rate of ~ 1 mm/yr. This rate is similar to the longer-term rates (1.6 Ma to present) determined by Shaw et al. (in press) based on petroleum industry seismic reflection data.

Our M_w 7.1-7.4 magnitude estimates suggest that the PHT commonly ruptures in its entirety, or perhaps together with adjacent faults (e. g., Montebello Hills backthrust; Shaw et al., in press). Obviously, parts of the PHT also, at least sometimes, rupture in smaller events, as shown most recently by the 1987 M 6 Whittier Narrows event. Uplift in the 1987 event was only a few centimeters, however, well below the detection limit of our methodology. Within error, all of the total uplift across the active axial surface at the Carfax site since 12 ka can be accounted for by the four uplift events that we have identified. This suggests that almost all of the total strain within the system is accommodated during relatively infrequent, large earthquakes.

To the best of our knowledge, this is the first time that individual paleo-earthquakes have been identified directly from an active blind thrust fault. Prior to this study, the ages and magnitudes of past earthquakes on the Puente Hills thrust were unknown. The successful determination of such data during this study thus removes a major obstacle to accurate seismic hazard assessment in metropolitan southern California. Moreover, the multidisciplinary methodology that we have established is readily exportable to other blind thrust systems around the world.

The Trojan Way Site, La Mirada, California

The Trojan Way borehole transect is located on Trojan Way between Alondra Boulevard and Desman Avenue in the City of La Mirada, ~ 1.5 km west of a petroleum industry seismic profile published by Shaw et al. (in press), and directly above our Mini-Sosie seismic reflection profile (Figure 3). The borehole transect extends north-south for 548 meters across a broad, 9-m-high, south-facing scarp. Boreholes TW-1 and TW-2 were with a hollow-stem rig, whereas TW-3 was drilled with a mud-rotary rig. All three boreholes were continuously cored. We are actively acquiring additional borehole data at the Trojan Way site, and the following results should thus be considered preliminary.

Our tentative stratigraphic correlations between the three boreholes indicate that strata dip gently southward beneath the scarp (Figure 5). This geometry is similar to that of the reflectors imaged on the Mini-Sosie high-resolution and petroleum industry seismic reflection data (Pratt et al., 2002; Shaw et al., in press). In addition to several sedimentary layers that we can correlate between TW-1 and TW-2, the prominent, well-developed surface soil observed in TW-1 and TW-2 appears to correlate with a well-developed soil with a prominent red-brown argillic horizon observed at 10 m depth in borehole TW-3 below the scarp. The color and thickness of the well-developed argillic horizon of this soil in all three boreholes suggests that it is late Pleistocene in age, and that it probably required several tens of thousands of years to develop. This inference is supported by the late Pleistocene (~33-35 ka; with approximate calendric correction based on Voelker et al., 1998) ages of radiocarbon dates of detrital charcoal fragments recovered from within the lower part of, and below, the soil. Additional ^{14}C dates (pending at the University of Arizona lab) and Optically Stimulated Luminescence (OSL) dates (pending at Professor Lewis Owen's lab at UC Riverside) will help to refine the age of strata along the Trojan Way transect.

The total relief across the top of the prominent late Pleistocene soil, including its 10 m burial depth south of the fold scarp and the 9 m height of the scarp, is 19 m. While it is possible that this soil developed at least partially across a pre-existing scarp, the similarity in geometry of deeper sedimentary units and the soil suggests that this may represent structural relief. Based on this geometry, the latest Pleistocene maximum age of the soil, and the kinematics of the structure as defined by the Mini-Sosie data (Pratt et al., 2002), we estimate a minimum latest Pleistocene - Holocene slip rate for the Coyote Hills segment of the PHT of ~ 1 – 1.5 mm/yr, similar to the longer-term (1.6 Ma-present) estimates of Shaw et al. (in press).

Future drilling will allow us to more precisely define the geometry of units deformed beneath the scarp, and should provide a more precise estimate of the latest Pleistocene-Holocene slip rate on this segment of the Puente Hills Thrust.

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Publications Resulting From This Grant

Christofferson, S. A. 2002 "Determination of Paleoearthquake Age and Slip per Event Data, and Late Pleistocene – Holocene Slip Rates on a Blind Thrust Fault: Application of a New Methodology to the Puente Hills Blind-Thrust Fault, Los Angeles County, California": unpubl. M.S. Thesis, University of Southern California, Los Angeles, California, 133 pp.

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Pratt, T. L., J. H. Shaw, J. F. Dolan, S. A. Christofferson, R. A. Williams, J. K. Odum, and A. Plesch, 2002 ."Shallow folding imaged above the Puente Hills blind-thrust fault, Los Angeles, California." Geophysical Research Letters, vol. 29, no. 9.

Shaw, J. H., A. Plesch, P. Fiore, J. F. Dolan, S. A. Christofferson, T. L. Pratt, R. A. Williams, and J. K. Odum, "Structural Geometry, Segmentation, and Slip on the Puente Hills Blind-Thrust System: Implications for Earthquake Hazards in Metropolitan Los Angeles" EOS Transactions, AGU vol. 81, p. F850

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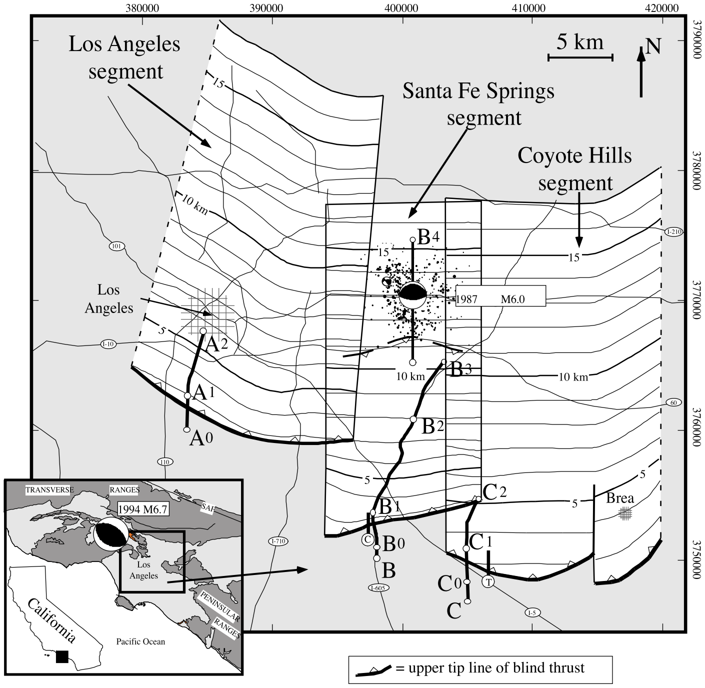

Figure 1: Structure contour map of the Puente Hills blind thrust showing the Los Angeles, Santa Fe Springs, and Coyote Hills segments and the location of the 1987 Whittier Narrows (M 6) earthquake sequence from Shaw et al. (in press). Locations of petroleum industry seismic reflection profiles A0 - A2, B - B4, and C0 - C2. Lines C and T correspond to high-resolution seismic reflection profiles on Carfax Avenue and Trojan Way.

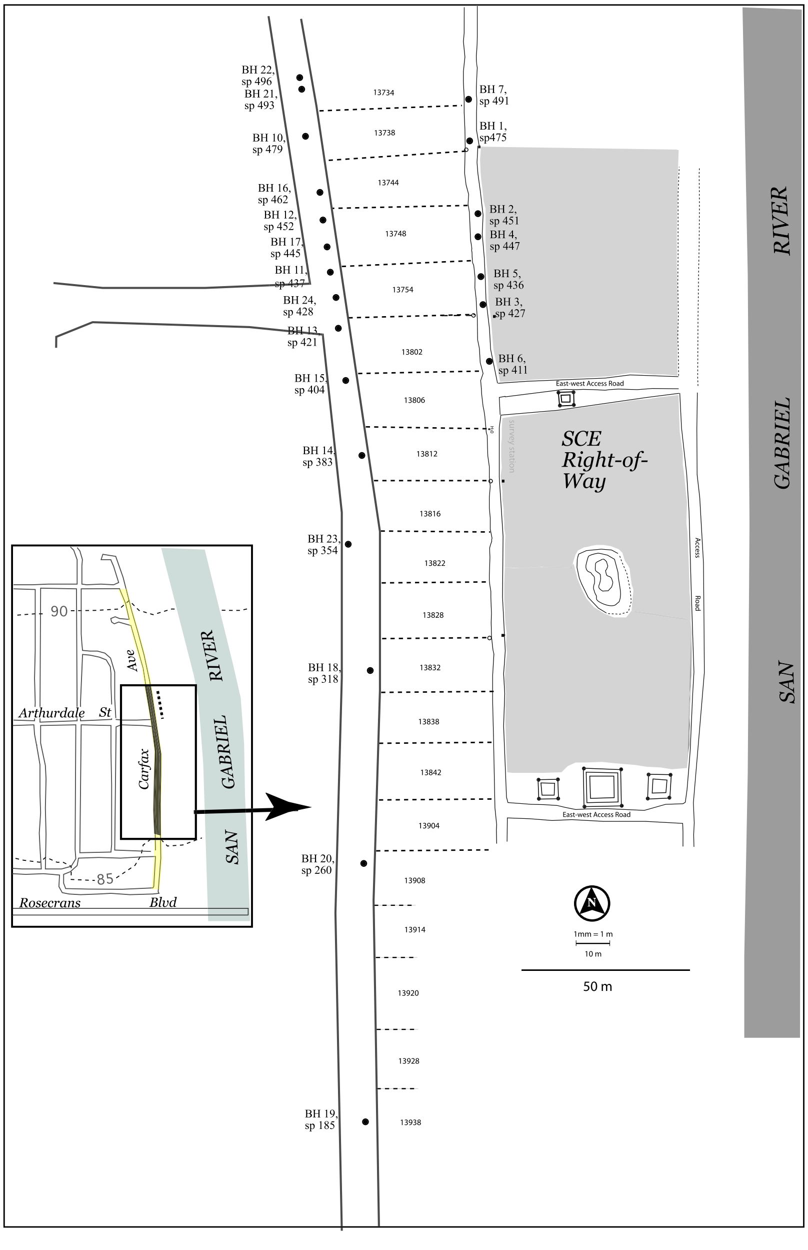

Figure 2: Detailed map of Carfax Avenue and the Southern California Edison right-of-way land west of the San Gabriel River showing the locations of boreholes and residential property lines. Inset map shows the location of both the Mini-Sosie (yellow) and hammer-source (dark gray) high resolution reflection lines.

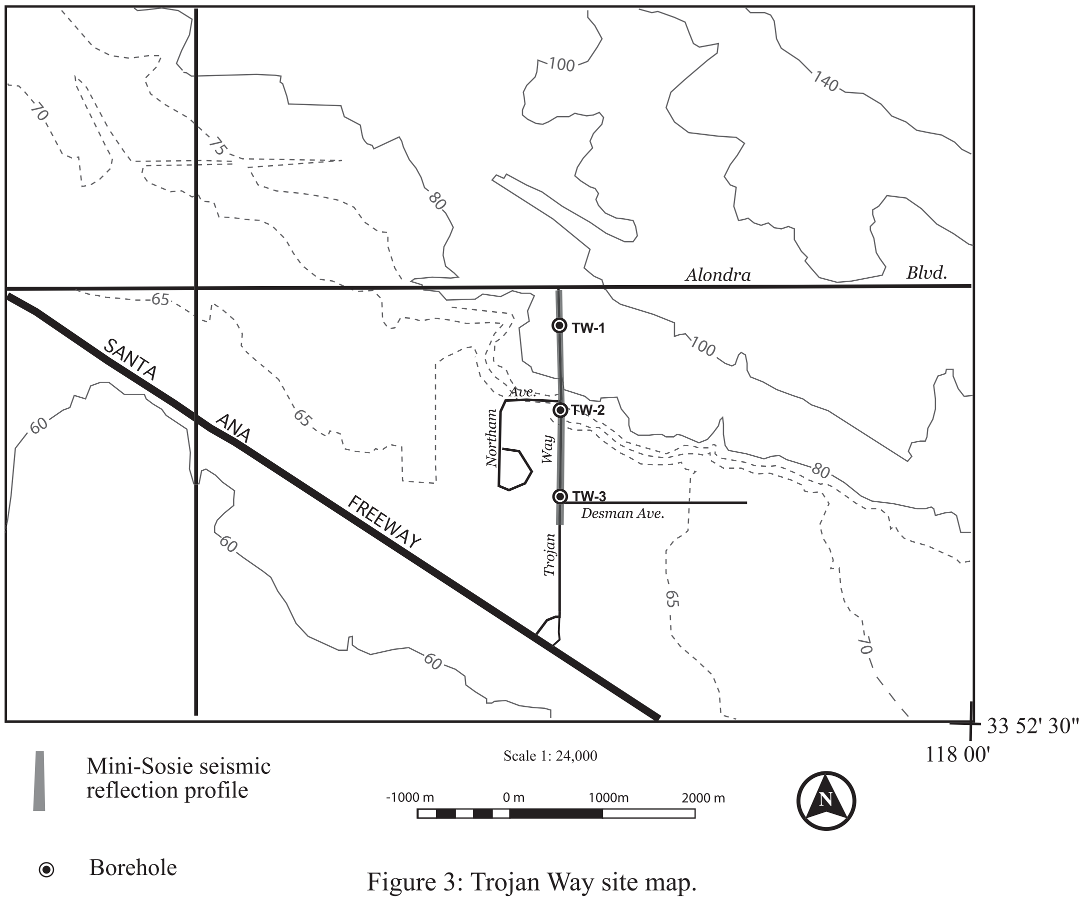

Figure 3: Trojan Way site map.

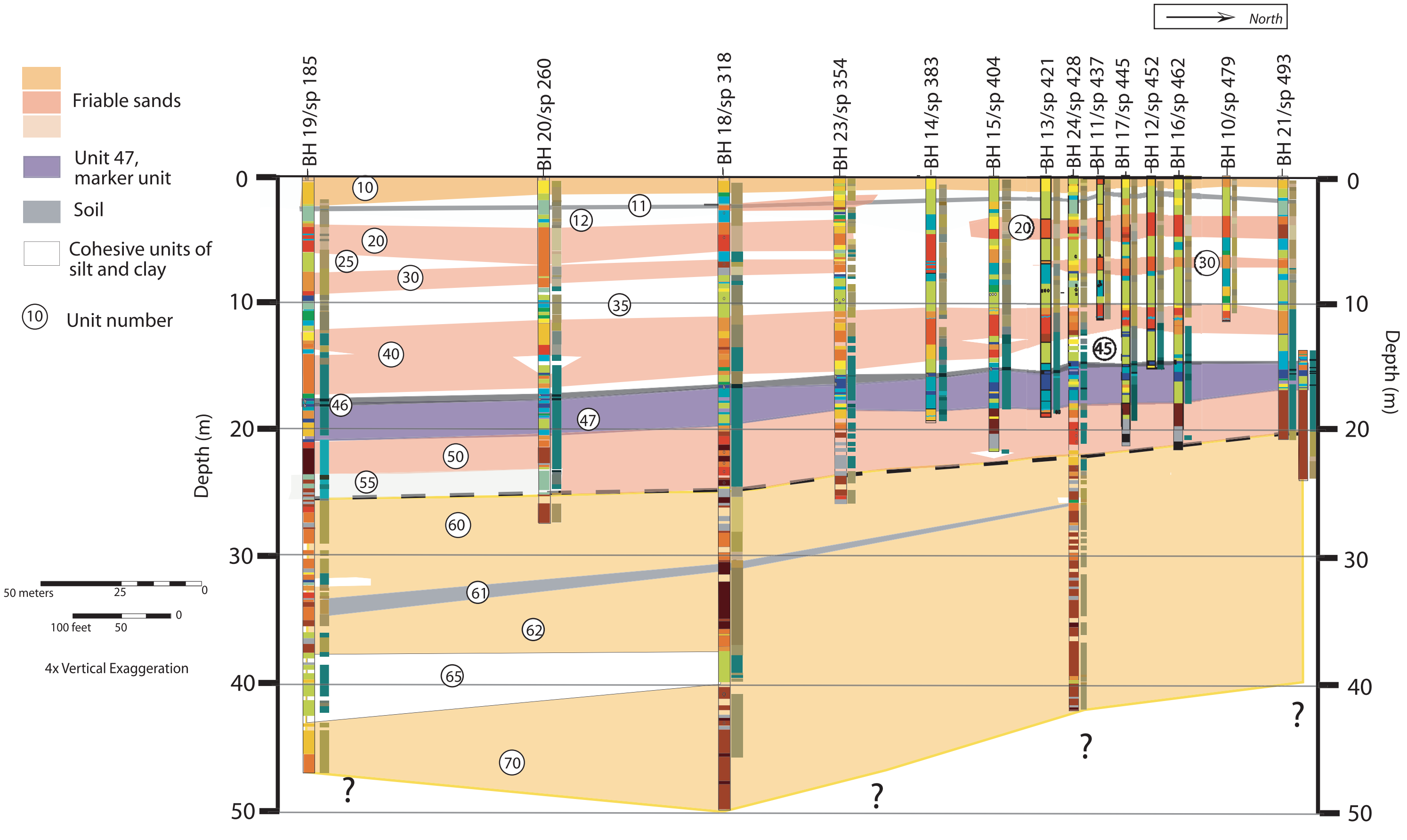

Figure 4: Stratigraphic correlation across the Carfax Avenue borehole transect.

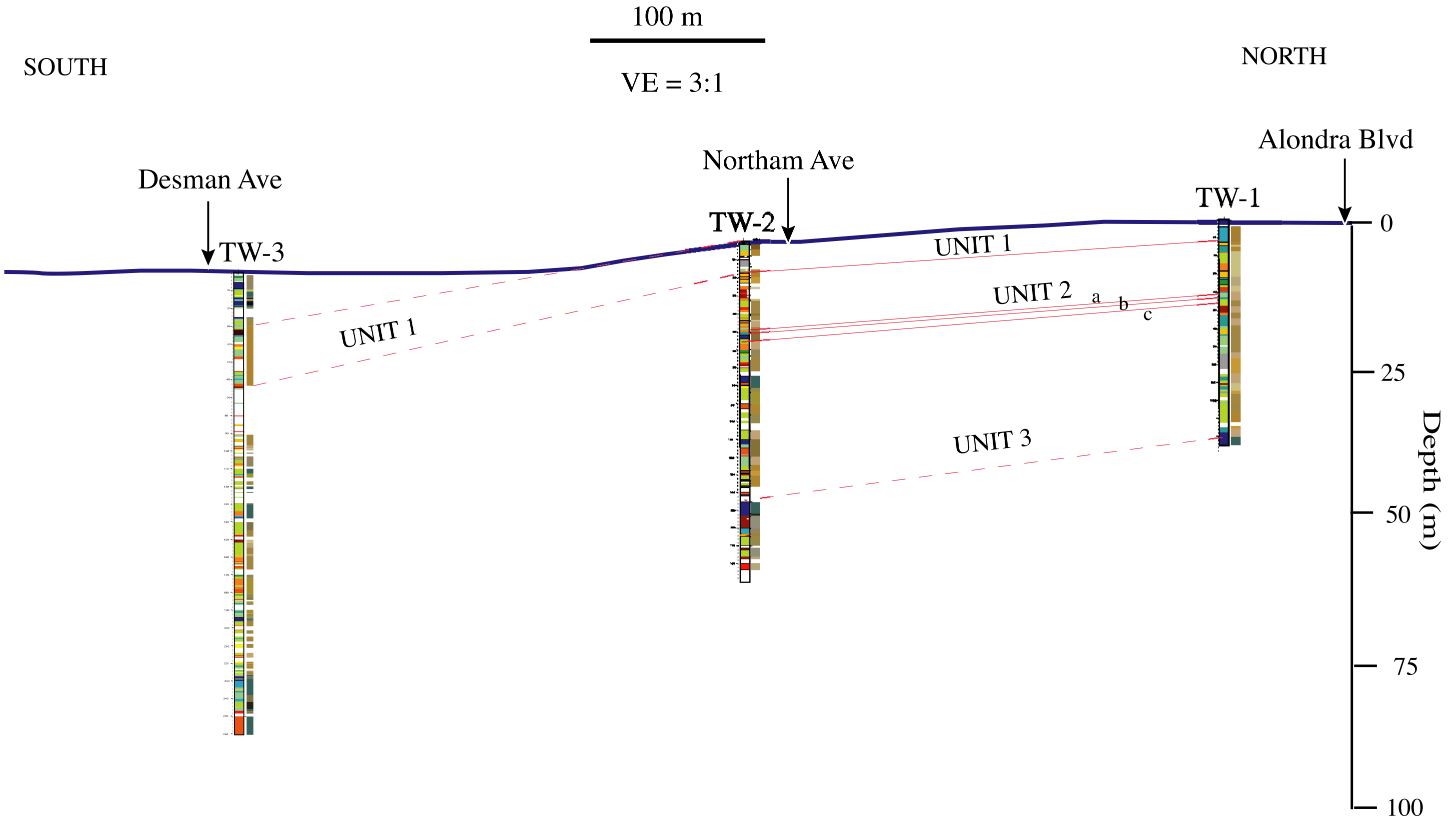

Figure 5 : Borehole transect across Trojan Way showing stratigraphic correlations.