GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 16, PAGES 2051-2054, AUGUST 15, 1997

High-resolution seismic reflection profiling of the Santa Monica Fault Zone, West Los Angeles, California

James F. Dolan
Department of Earth Sciences and Southern California Earthquake Center, University of Southern California, Los Angeles, CA

Thomas L. Pratt
U. S. Geological Survey, School of Oceanography, University of Washington, Seattle, WA

Abstract. High-resolution seismic reflection data obtained across the Santa Monica fault in west Los Angeles reveal the near-surface geometry of this active, oblique-reverse-left-lateral fault. Although near-surface fault dips as great as 55° cannot be ruled out, we interpret the fault to dip northward at 30° to 35° in the upper few hundred meters, steepening to ≥65° at 1 to 2 km depth. A total of ~180 m of near-field thrust separation (fault slip plus drag folding) has occurred on the fault since the development of a prominent erosional surface atop ~1.2 Ma strata. In the upper 20 to 40 m strain is partitioned between the north-dipping main thrust strand and several closely spaced, near-vertical strike-slip faults observed in paleoseismologic trenches. The main thrust strand can be traced to within 20 m of the ground surface, suggesting that it breaks through to the surface in large earthquakes. Uplift of a ~50,000-year-old alluvial fan surface indicates a short-term, dip-slip rate of ~0.5 mm/yr, similar to the ~0.6 mm/yr dip-slip rate derived from vertical separation of the oxygen isotope stage 5e marine terrace 3 km west of the study site. If the 0.6 mm/yr minimum, dip-slip-only rate characterizes the entire history of the fault, then the currently active strand of the Santa Monica fault probably began moving within the past ~300,000 years.

1. Introduction

The 1994 Mw 6.7 Northridge earthquake clearly demonstrated the hazards posed by faults within the Los Angeles metropolitan region. Because these faults are so close to major population centers, large earthquakes (Mw 7.0 to 7.5) on them could potentially cause more damage than the long-awaited 'Big One' (Mw ~8) on the more distant San Andreas fault (WGCEP, 1995; Dolan et al., 1995; Heaton et al., 1995). This study focuses on one of these urban faults, the Santa Monica fault in northwestern Los Angeles (Figure 1). Reliably assessing the seismic hazards posed by these faults requires accurate knowledge of numerous parameters, including the location, geometry, slip rate, recurrence interval, and kinematics of recent fault movements. Although geomorphologic mapping and paleoseismologic trench studies reveal much about these parameters, subsurface data are also necessary to understand the history and three-dimensional geometry of faulting.

The regional geologic structure and geometry of faults in the Los Angeles area have been interpreted from extensive seismic reflection and drill hole data obtained during petroleum exploration (e. g., Wright, 1991; Schneider et al., 1996; Tsutsumi, 1996; Tsutsumi et al., in review). Exploration data are acquired to delineate hydrocarbon reservoirs primarily at 0.5 to ~6 km depth. Consequently, a data gap commonly exists between the base of trench data (~5 m), from which the most recent earthquakes can be characterized, and the top of industry seismic reflection and drill hole data (>~200 m), which provide the overall fault geometry. In this paper, we describe high-resolution seismic reflection data, acquired from the 15-to-300 m depth range of the Santa Monica fault, that provide useful constraints on the geometry, deformation rate, and kinematics of recent fault motions.

2. The Santa Monica Fault

The Santa Monica fault is part of a system of east-trending reverse, oblique-slip, and left-lateral strike-slip faults that extends >200 km along the southern edge of the Transverse Ranges of southern California. The Santa Monica fault extends westward 40 km along the southern edge of the Santa Monica Mountains (the southernmost of the Transverse

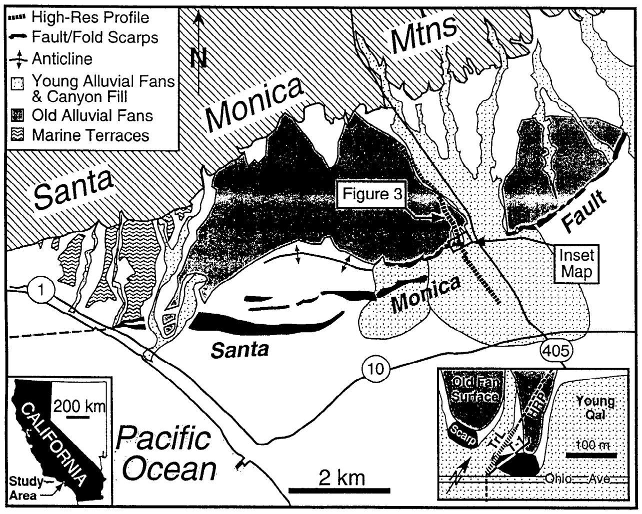

Figure 1. Map of the surficial trace of the Santa Monica fault (from Dolan et al., in review). Note location of main high-resolution seismic reflection profile. Inset map shows locations of trench and high-resolution profiles. T-1, trench; TrL, 'Trench Line' profile; HRP, Main profile.

Paper number 97GL01940.
0094-8534/97/97GL-01940$05.00

Ranges) through the northwestern Los Angeles region and offshore parallel to the Malibu coast (Figure 1; Wright, 1991; Dolan et al., in review).

Regional seismic reflection and drill hole data show that the north-dipping Santa Monica fault zone comprises two major strands, an inactive southern strand, and an active northern strand. The northern strand, which is the focus of this study, is a steeply dipping oblique reverse/left-lateral fault that projects to the surface at a prominent scarp (Tsutsumi, 1996; Tsutsumi et al., in review; Dolan et al., in review). Reverse separation of middle Miocene strata on the northern strand is ~200 m, and the fault merges with the structurally lower southern strand at a depth of ~2 km (Tsutsumi, 1996).

Our seismic reflection profiles cross the Santa Monica fault trace adjacent to a 110-m-long, 5-m-deep paleoseismologic trench, which exposed folded and faulted Pleistocene-Holocene alluvial strata (Figures 1 and 2; Dolan et al., in review). At least three major and >100 minor near-vertical faults and fractures that disrupt the pre-latest Holocene alluvial strata are interpreted as strike-slip faults on the basis of stratigraphic mismatches and contradictory vertical separations observed on individual strands. In the southern part of the trench, 15° south-dipping strata are onlapped by flat-lying, latest Holocene alluvial fan strata. Stratigraphic relationships indicate that the dipping strata were deposited near-horizontally and have subsequently been tilted.

The south-dipping package encompasses two lithologically controlled, buried soils (Figure 2). Both buried soils and the strata in which they are developed project below trench level near the south end of the trench; the top of the younger paleosol extends northwards and merges with the surface slope of the scarp along the northern 80 m of the trench. The surface soil in the northern part of the trench is much better developed than either of the buried soils or the weakly developed surficial soil at the south end of the trench. Soil analyses suggest that the northern soil probably required ~50,000 years to develop (Dolan et al., in review). In contrast, soil analyses show that the two southern buried soils each required ~15,000 to 20,000 years to develop; the flat-lying, late Holocene strata in the southernmost 20 m of the trench exhibit almost no soil development. The soil age estimates suggest that the paleo-fan surface correlative with the present ground surface in the northern part of the trench probably lies beneath the deeper buried soil below trench level in the southern part of the trench. Alternatively, the wide error bars on the soil age estimates allow the possibility that the northern fan surface could correlate with the top of the deeper buried paleosol. These proposed correlations indicate at least 10 m, and probably >13m of total vertical separation of the old fan surface across the Santa Monica fault since ~50ka.

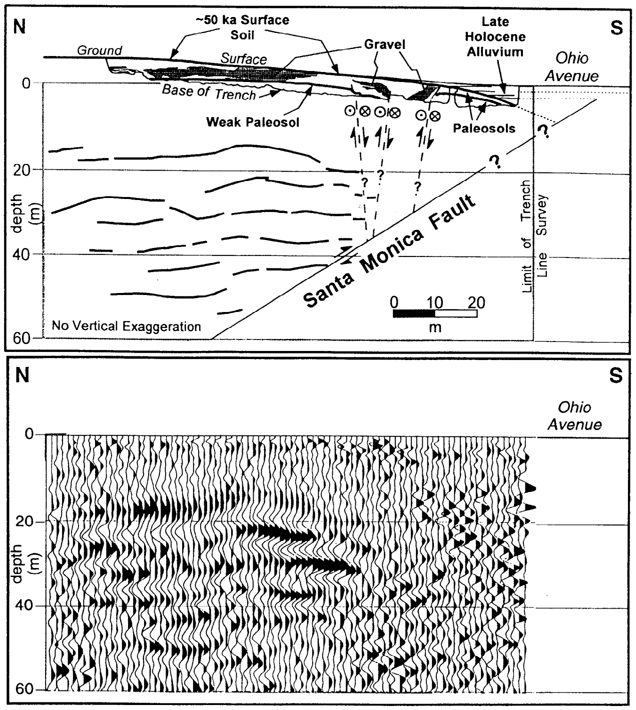

Figure 2. Data and line drawing interpretation from very high-resolution 'trench line' profile compared with simplified log of trench (from Dolan et al., in review). The N20E-trending trench data have been projected onto the N10W-trending profile. 'Zero' elevation is an arbitrary datum placed at level of ground surface at southern edge of trench.

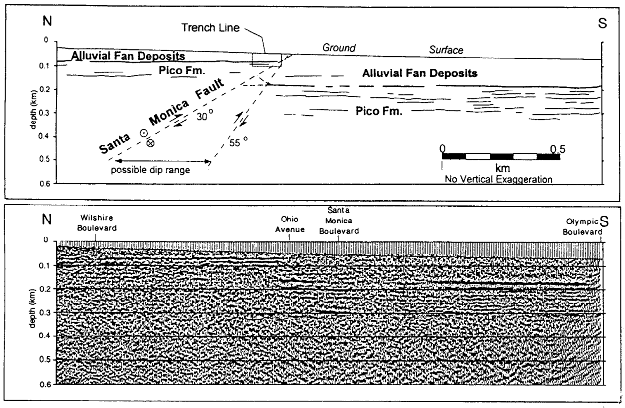

Figure 3. Data and line drawing interpretation from main high-resolution seismic reflection profile. The northernmost 1.5 km of the profile is not shown. Location shown in figure 1. Note location of very high-resolution 'trench line'. 'Zero' elevation is an arbitrary datum placed at elevation of northern end of profile.

3. High-Resolution Seismic Reflection Data

We acquired two high-resolution seismic reflection profiles at different scales near the trench. The 3.8-km-long main profile passed 5 to 20 m west of the trench on a trend nearly perpendicular to the fault (Figures 1 and 3). We also acquired a 115 m-long, higher-resolution profile ("trench line" profile) along the same trend to image detailed structural and stratigraphic relationships 10 to 60 m depth below the trench (Figure 2).

Both profiles were acquired with the Mini-Sosie system (Barbier, 1983; Stephenson et al., 1992) recorded on a 24-channel system with 28 Hz geophones. On the main profile, sources consisted of three earth tampers that struck the ground, semi-randomly, 2000 times per record; cross-correlation synthesized an impulsive source. A 7.62 m (25 ft) source and geophone spacing was used for the main profile, but adjacent common mid-points (CMPs) were summed in the processing to increase the fold and give a 7.62 m (25 ft) CMP spacing on the final section. The "trench line" profile used two earth tampers striking the ground 500 times each record; a 2.53 m (8.3 ft) source and receiver spacing produced a 1.25 m (4.15 ft) CMP spacing. Processing of both lines was routine (Yilmaz, 1987) and included residual statics analyses, post-stack time migration, and time-to-depth conversion using a smoothed velocity function.

The main profile imaged two distinct sections, separated by the Santa Monica fault (Figure 3). To the north, a strong reflection dominates the shallow seismic section at a depth of 30 to 60 m, with weak, horizontal reflections barely visible below. We interpret the strong reflection as the erosional unconformity at the base of the Pleistocene to latest Holocene Sepulveda alluvial fan deposits, with subhorizontal strata of the Los Angeles basin beneath. These older strata comprise the fine-grained mudstone of the Pliocene-Pleistocene Pico Formation (Wright, 1991; Blake, 1991; Tsutsumi, 1996). The southern part of the profile is dominated by horizontal strata to depths of ≥250 m. We interpret a strong reflection at 110 to 130 m depth as the base of the alluvial fan strata, equivalent to the strong, shallow reflection north of the fault. Few reflectors are evident in the alluvial fan sequence above the unconformity, in contrast to the underlying well-developed, horizontal reflectors. The continuity and horizontal attitude of the reflectors on the south side of the fault indicate that they have not been deformed by recent fault motions.

Electrical logs from drill holes in the nearby Sawtelle oil field (Wright, 1991; Tsutsumi, 1996) are interpreted to show the top of the Pico Formation at a depth of ~25 m north of the Santa Monica fault, in general agreement with our seismic reflection data, and at 186 m depth to the south, ~60 m deeper than interpreted from our seismic data. The drill hole is located in the center of the major Sepulveda drainage ~500 m east of the seismic line (Figure 1), and the 60 m depth discrepancy may reflect deeper fluvial incision at the drill site than along the seismic reflection profile west of the drainage.

The Santa Monica fault is interpreted from reflector truncations at depths of ~40 to 150 m to dip northward at an angle of 30° to 35° from a surface projection at Ohio Avenue (Figure 3). Reflectors in the footwall of the fault extend northward beneath the surface projection of the fault, indicating that the fault cannot dip more steeply than ~55°. We favor a 30° to 35° dip because the near-fault footwall reflectors may be traceable northward beneath the fault (dashed lines in figure 3), whereas hanging wall reflectors all terminate where expected if truncated by a fault dipping 30° to 35°. The fault thus decreases in dip upward from the ~60° to 70° dip interpreted at 1 to 2 km depth (Tsutsumi, 1996). Furthermore, if, as we suggest, the fault dips at 30° to 35° dip to a depth of at least 150 to 200 m, then between 200 m and 1 km depth the fault cannot dip any shallower than ~65°. A steep fault dip is consistent with Dolan et al.'s (in review) inference that the Santa Monica fault accommodates a significant, and possibly predominant, component of left-lateral strike slip. Correlation of the prominent reflectors on each side of the Santa Monica fault indicates ~180 m of total near-field thrust motion (assuming a 30° to 35° dip) since development of the ≤1.2 Ma erosional surface at the top of the Pico Formation. This slip value includes both fault displacement and near-field drag folding. Total dip-slip fault displacement is between 115 and 180 m, depending on the degree of drag folding of the near-fault footwall reflectors (dashed lines beneath the fault in Figure 3).

The very-high resolution trench line delineates the Santa Monica fault in the 15 to 60 m depth range and shows features that correspond to the trench (Figure 2). Weak arrivals at the south end of the line have the appearance of reflectors that dip northward at ~30° to 40°. These could be reflections from the fault plane itself, supporting our interpretation of a shallow dip for the main thrust strand. Alternatively, they may be coherent noise within a disrupted zone. North of the fault, strong, subhorizontal reflections at 15 to 60 m depth terminate beneath the near-vertical strike-slip faults observed in the trench. We infer that disruption of the reflectors is caused by downward continuation of the strike-slip faults to their intersections with the thrust strand at 20 to 40 m depth. These data suggest that oblique slip along the San Monica fault is partitioned in the near surface into predominantly strike-slip motion along the near-vertical faults observed in the trench and predominantly thrust motion on the shallowest part of the north-dipping strand. The upper reflectors on the trench line (15 to 32 m) show a slight southward dip near the fault that may be the deeper expression of the dipping beds seen in the trench. In addition, the arched shape of the reflectors beneath the central part of the trench (most evident in the 15 to 20 m-deep reflection in Figure 2) corresponds with anticlinal warping of strata near the base of the trench (parallel to weak, buried soil in figure 2).

4. Discussion

The ~180 m of thrust separation across the Santa Monica fault is nearly equal to the ~200 m separation of upper Miocene strata on the active northern strand of the Santa Monica fault observed ~500 m east of the profile (Tsutsumi, 1996). This indicates that most, and probably all, of the thrust separation across the fault has occurred since development of the unconformity atop ~1.2 Ma strata of the uppermost Pico Formation. These data yield a minimum average Pleistocene-Holocene dip-slip rate of ~0.15 mm/year. This is a minimum rate because the erosional unconformity may be much younger than the age of the Pico Formation.

Uplift of ≥10 m of the ~50,000-year-old fan surface in the hanging wall of the fault yields a dip-slip-only rate of ~0.5 mm/yr. A similar late Pleistocene-Holocene minimum reverse-slip-only rate of ~0.6 mm/yr on the northern strand of the Santa Monica fault is interpreted at Potrero Canyon, 3 km west of the trench site, from the ~55 m vertical separation of the ~120,000-year-old oxygen isotope stage 5e marine terrace (McGill, 1989; Johnson et al., 1996; Dolan et al., in review). Furthermore, the trench data indicate that the Santa Monica fault has generated at least six surface ruptures during the past ~50,000 years, showing that this average dip-slip rate holds over several earthquake cycles. The maximum dip-slip rate cannot be determined at the trench site because the ~50,000-year-old surface has not been identified below trench depth in the southern part of the profile.

The stratigraphic separation measured from the seismic reflection data represents only the dip-slip component of the total oblique slip, and the oblique-slip rate on the fault may be significantly faster than the dip-slip rate. Significant, but unmeasured, amounts of left-lateral motion are indicated by the strike-slip faults in the trench and the left-stepping, *en echelon* pattern of the scarps.

If the dip-slip rate on the Santa Monica fault has been constant at ~0.6 mm/yr since the fault's inception, the ~180 m of total reverse displacement that we interpret indicates that fault slip on the active, northern strand initiated ≤~300,000 years ago. This age estimate is consistent with Hoots (1931), who used biostratigraphic data to show that the fault began moving during 'middle San Pedro' time (mid-Pleistocene time; McGill, 1989).

In addition to the near-vertical strike-slip faults exposed in the trenches, the high-resolution data suggest that the north-dipping thrust strand also ruptures through to the surface in large earthquakes. The thrust strand can be traced to within ~20 m of the surface beneath the trench. Unfortunately, the details of the upward termination of the fault could not be determined because the trench ended ~10 m north of the surface projection of the fault, which lies beneath Ohio Avenue (Figure 2). The south-tilted strata in the southern part of the trench have been buried by at least 5 m of late Holocene alluvial-fan strata since the most recent earthquake (Dolan et al., in review). This implies that the main fault may extend upward all the way to the position of the now-buried paleo-fan surface at the time of the most recent surface rupture. This inference has important implications for land-use zonation, suggesting a ~50 m-wide zone of active surface faulting that encompasses the secondary strike-slip faults as well as the main thrust strand. If scarps along the entire length of the Santa Moncia fault are similar to that exposed in the trench, with tilted strata dipping parallel to the scarp slope, then the gentler, wider scarps that occur farther west along the Santa Monica fault may indicate an even wider zone of active potential surface faulting there (Dolan et al., in review).

These data illustrate how a combination of trench, high-resolution seismic reflection, and petroleum-industry data can reveal critical details of the geometries, kinematics, and slip histories of active faults. High-resolution seismic reflection data collected in logistically difficult urban settings will be crucial to understanding the faults that represent potential sources of 'other Big Ones'--large earthquakes on faults directly beneath the Los Angeles metropolitan area that could be potentially even more damaging than a great earthquake on the more distant San Andreas fault.

Acknowledgments. We thank the U. S. Veteran's Administration and the American Red Cross for allowing us to conduct this study on their property. Thanks also to J. Odum, B. Stephenson, R. Williams, D. Worley, J. Michael, A. Blythe, C. Contopulous, K. Mueller, D. Stevens, and M. Templeton for help with field work. Ann Blythe, Tom Brocher, Uri ten Brink, and Bob Yeats provided thoughtful reviews of the manuscript. Southern California Earthquake Center publication 380.

References

Barbier, M. G., The Mini-Sosie Method, *International Human Resources Development Corporation*, Boston, MA, 186 p., 1983.

Blake, G. H., Review of the Neogene biostratigraphy and stratigraphy of the Los Angeles basin and implications for basin evolution, in *Active Margin Basins* (ed. Biddle, K. T.) Amer. Assoc. Petrol. Geol. Memoir, 52, 135-184, 1991.

Dolan, J. F., Sieh, K., Rockwell, T. K., Yeats, R. S., Shaw, J., Suppe, J., Huftile, G., and Gath, E., Prospects for larger or more frequent earthquakes in greater metropolitan Los Angeles, California, *Science, 267*, 199-205, 1995.

Heaton, T. H., Hall, J. F., Wald, D. J., and Halling, M. W., Response of high-rise and base-isolated buildings to a hypothetical Mw 7.0 blind thrust earthquake, *Science, 267*, 206-211, 1995.

Hoots, H. W., Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, *U. S. Geol. Surv. Prof. Paper 165-C*, 83-134, 1931.

Johnson, M. L., Dolan, J. F., and Meigs, A., Geomorphologic and structural analysis of Stage 5e marine terrace, Malibu coast, California, suggests that the Santa Monica Mountains blind thrust fault is no longer a major seismic hazard, *EOS, 77*, F461, 1996.

McGill, J. T., Geologic maps of the Pacific Palisades area, Los Angeles, California, *U. S. Geol. Surv., Misc. Investigations Series Map I-1828*, 1989.

Schneider, C. L., Hummon, C., Yeats, R. S., and Huftile, G. L., 1996, Structural evolution of the northern Los Angeles basin, California, based on growth strata, *Tectonics, 15*, 341-355, 1996.

Stephenson, W. J., Odum, J., Shedlock, K. M., Pratt, T. L., and Williams, R. A., Mini-Sosie high-resolution seismic method aids hazards studies, *EOS, 73*, 473-476, 1992.

Tsutsumi, H., Evaluation of seismic hazards from the Median Tectonic Line, Japan, and blind thrust faults in the Los Angeles metropolitan area, California, *Ph. D. thesis*, Oregon State University, Corvallis, Oregon, 129 p., 1996.

WGCEQ (Working Group on California Earthquake Probabilities), Seismic hazards in southern California: probable earthquakes, 1994 to 2024, *Bull. Seismol. Soc. Amer., 85*, 379-439, 1995.

Wright, T. L., Structural geology and tectonic evolution of the Los Angeles Basin, in *Active-Margin Basins* (ed. Biddle, K. T.) Amer. Assoc. Petrlm. Geol., Memoir 52, 35-106, 1991.

Yilmaz, O, Seismic Data Processing, *Soc. Exploration Geophys.*, Tulsa, Oklahoma, 526 p., 1987.

J. F. Dolan, Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089 (e-mail: dolan@earth.usc.edu)

T. L. Pratt, U. S. Geological Survey, School of Oceanography, University of Washington, Seattle, WA, 98195 (e-mail: tpratt@ocean.washington.edu)

(Received April 15, 1997; Accepted June 16, 1997)