JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B7, PAGES 9545–9547, JULY 10, 1989

# The 1987 Whittier Narrows, California, Earthquake: A Metropolitan Shock

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Just 3 hours after the Whittier Narrows earthquake struck, it became clear that a heretofore unseen geological structure was seismically active beneath metropolitan Los Angeles. Contrary to initial expectations of strike-slip or oblique-slip motion on the Whittier fault, whose north end abuts the aftershock zone, the focal mechanism of the mainshock showed pure thrust faulting on a deep gently inclined surface [*Hauksson et al.*, 1988]. This collection of nine research reports spans the spectrum of seismological, geodetic, and geological investigations carried out as a result of the Whittier Narrows earthquake.

Although unseen, the structure was not unforeseen. *Namson* [1987] had published a retrodeformable geologic cross section (meaning that the sedimentary strata could be restored to their original depositional position) 100 km to the west of the future earthquake epicenter in which blind, or subsurface, thrust faults were interpreted to be active beneath the folded southern Transverse Ranges. Working 25 km to the west, *Hauksson* [1987] had also found a surprising number of microearthquakes with thrust focal mechanisms south of the Santa Monica mountains, another clue to a subsurface system of thrust faults. Finally, *Davis* [1987] had presented a preliminary cross section only 18 km to the west of Whittier Narrows that identified as "fault B" the thrust that would rupture later that year. Not only was the earthquake focus and its orientation compatible with the 10-15 km depth and north dipping orientation of Davis' proposed thrust, but fault B appears to continue beneath the northern flank of the Los Angeles basin, skirting within 5 km of downtown Los Angeles, an area of dense commercial high-rise building development. These results are refined and extended by *Davis et al.* [this issue].

Six years ago, the 1983 $M$=6.5 Coalinga, California, earthquake signaled the importance of concealed thrust faulting in regions of continental compression. *Stein and King* [1984] showed that the youthful fold at the epicenter, appropriately named "Anticline Ridge" by petroleum geologists a century ago, had grown 0.75 m in amplitude during the earthquake, indisputable evidence that folds can grow suddenly by repeated earthquakes rather than by steady progressive deformation. "Coalinga's Caveat," suggested *Stein* [1984], was that earthquake hazards reduction in the United States was focused exclusively on the identification and study of surface faults, whereas active folds, and the faults they may conceal, remained largely unexplored and unassessed.

Serendipity favored us with remarkably good observations for so small an earthquake. The shock occurred where the two seismic networks, the California Institute of Technology/U.S. Geological Survey southern California network and the University of Southern California Los Angeles basin network, overlap. These networks captured high- quality recordings, whose interpretation was further refined by a calibration blast detonated near the epicentral area [*Perkins*, 1988] and by high fidelity recordings at digital broadband seismic stations located in northern California. An unusually dense and ideally configured geodetic leveling network had been fortuitously surveyed a year before the earthquake; resurvey of the bench marks following the earthquake enabled accurate portrayal of the surface deformation, even though it amounted to less than 50 mm at maximum, or just 7% of the deformation associated with the Coalinga earthquake. Borehole dilatometers (precision pressure gages) dispersed around southern California gave additional insight about the static or net deformation caused by the earthquake. Some 300 strong ground motion instruments recorded ground accelerations throughout the Los Angeles basin, enabling study of the response of the soil and structures to the shaking. Finally, the wealth of oil well logs from a history of oil exploration in the Los Angeles, Santa Maria, and Ventura basins has given geologists the tools with which to deduce the concealed geologic structures.

## THE EARTHQUAKE SOURCE

The source parameters of the Whittier Narrows mainshock have been studied using local seismic network data [*Hauksson and Jones*, this issue], local strong motion data [*Wald* et al., 1988], regional broadband data from northern California [*Bolt et al.*, this issue], and regional as well as teleseismic data [*Bent and Helmberger*, this issue]. *Hauksson and Jones* [this issue] show that the mainshock ruptured a west striking thrust fault dipping gently to the north and that the largest aftershock occurred on a west-northwest striking steeply dipping strike-slip fault. Also by using local network data, *Hauksson and Saldivar* [this issue] demonstrate that the compressional tectonics highlighted by the Whittier Narrows sequence is also present throughout Santa Monica Bay, which extends 80



Paper number 89JB00407.
0148-0227/89/89JB-00407$02.00

km to the west of Whittier. Two-thirds of the focal mechanisms in the bay indicate thrust motion, with much of the seismicity occurring beneath mapped offshore folds.

*Hauksson and Jones* [this issue] report a ring of aftershocks with a 5 km diameter centered on the mainshock at 12 km depth. To satisfy both long- and short-period body waveforms, *Bent and Helmberger* [this issue] find that the mainshock consisted of two subevents, in which the first event locates at 15 km depth and released 16% of the total seismic moment and was followed by a second subevent 1 s later at a depth of 12 km. Bent and Helmberger suggest a very high static stress drop of about 75 MPa (750 bars), although the geodetic data require a drop of only 18±5 MPa. The dip inferred for the north dipping nodal plane varies from the 11°±15° of *Bolt et al.* [this issue] to 40° for *Bent and Helmberger* [this issue] and *Linde and Johnston* [this issue]. The lower bound on the moment, $1.1\pm0.2 \times 10^{25}$ dyn cm (equivalent to a moment magnitude $M$=6.0), well constrained by the geodetic data of *Lin and Stein* [this issue], is compatible with all seismic estimates of the moment. The geodetic data also afford reliable estimates of the fault slip, 1.1±0.3 m, for a fault with a diameter of about 5 km, coincident with the ring of early aftershocks surrounding the mainshock.

*Linde and Johnston* [this issue] find no evidence for precursory or postseismic strain transients from the borehole dilatometer records, which serve as ultra-long-period seismographs. Two days following the Whittier earthquake it was suggested that the rate of aftershock activity was unusually small, because most of the seismic strain release following the mainshock was accommodated by a few large aftershocks. The largest aftershock of October 4, 1987, stimulated a study of the probability of occurrence of such damaging aftershocks; *Reasenberg and Jones* [1989] constructed an algorithm that allows rapid evaluation of such probabilities for mainshock-aftershock sequences in California.

## Strong Ground Motion

The Whittier Narrows earthquake was recorded by more strong motion instruments than any other earthquake [*Brady et al.*, 1988; *Shakal et al.*, 1988; *Trifunac*, 1988]. These records provide for the first time a contour map of strong ground motions in the Los Angeles basin and San Fernando Valley [*Trifunac*, 1988]. They also illustrate how modern high-rise buildings respond to ground accelerations [*Brady et al.*, 1988]. At one site, ground motion amplification was observed at a station in San Fernando Valley, with 0.63 *g* at an epicentral distance of 44 km [*Shakal et al*, 1988], reminiscent of that seen in Mexico City resulting from the ($M_S$=8.1) 1985 earthquake 300 km away [*Singh et al.*, 1987]. Despite local influences on ground motion, *Vidale* [this issue] is able to discern the seismic radiation pattern of a double couple source in the accelerations, by forming a ratio of the peak acceleration at 0.3-6.0 Hz of the mainshock to the largest aftershock at 43 stations, thereby canceling most site effects.

## Geological Structure and Convergence Rates

Perhaps the most important work to emerge from the Whittier Narrows earthquake is a new assessment and synthesis of the strongly folded structures in the Los Angeles basin and adjacent areas. These studies, begun before the earthquake hit [see, for example, *Namson and Davis*, 1988], have assumed much greater importance in its wake. The folds and surface faults in the upper 4-5 km can be used to infer the location, orientation, and cumulative slip of the blind faults they mask. The age of the youngest folded strata can be used to deduce a shortening rate across the basin; from this, slip rates on the candidate faults can be tentatively assigned. The logs of tens of thousands of oil wells in the basin make such an analysis possible. Nevertheless, this work is hampered by the lack of publicly available seismic reflection and refraction profiles across the structures and by the variegated history of the basin itself: 3-5 m. y. ago the region was pulled apart; this pattern reversed about 2 m. y. ago when the current episode of compression began. Geologists must contend with the deformation from both episodes to deduce the displacement history of the blind thrust faults.

*Davis et al.* [this issue] infer 22 km of north-south convergence on top of the crystalline basement rocks and argue for a 30 km displacement on an hypothesized basal detachment between the San Andreas fault to the north and the California continental borderland in the Pacific Ocean. This results in a minimum estimated Quaternary convergence rate of 6-14 mm/yr, with perhaps 2-5 mm/yr of slip on the fault which ruptured during the Whittier Narrows earthquake and similar slip rates on one other blind and one other surface fault system that span the region between the San Andreas and the Pacific Ocean to the south. The contraction rate proposed by *Davis et al.* [this issue] is much higher than previous estimates [see *Ziony and Yerkes*, 1985] and thus occupies a central role in the problem of assessing earthquake risk. It is now essential that space geodetic networks be established across the basin to measure the contemporary rate of motion.

## Earthquake Potential

Several authors [*Davis et al.*, this issue; *Lin and Stein, this issue*; *Hauksson and Saldivar*, this issue] evaluate the earthquake potential of the blind thrust faults. This can be accomplished by comparing the long-term rate of uplift of the Quaternary fold to its coseismic uplift in 1987, by comparing the deduced earthquake fault slip to the long-term slip rate, or by relating the cumulative seismic convergence to the long-term geological convergence rate. All of these approaches yield a similar result, that the historical record of earthquakes in the basin and adjacent Santa Monica Bay, which has been capped by earthquakes of $M$=6, is deficient. Earthquakes with $M \approx 6$ should recur every 5-15 years; instead their rate of occurrence is about once every 25 years since 1860. If the convergence rate of *Davis et al.*[this issue] is correct, then either most of the slip occurs aseismically or it occurs during larger and hence less frequent earthquakes.

After discovery of a broad system of active thrust faults beneath a region populated by 11 million people, we are thus left with a conundrum: Is the message writ by the Whittier earthquake that much of the fault slip is accommodated quietly by aseismic creep, in which nothing more damaging than a Whittier Narrows earthquake can occur, or are we now overdue for a larger event with much more vigorous shaking? Seeking the answer to this question will undoubtedly drive further study. To answer it, we must confirm the geological contraction rate, estimate the total length and individual segment lengths of the thrust faults, and read the record of past events in the geomorphology of the urban landscape. All of these are challenging tasks.

*Acknowledgments.* We would like to thank Charlie Sammis and Andy Michaels for reviewing this introduction and the authors of the Whittier Narrows Earthquake special section for making preprints of their papers available to us. E. Hauksson was supported by USGS grant 14-08-0001-G1328.

## REFERENCES

Bent, A. L., and D. V. Helmberger, Source complexity of the October 1, 1987, Whittier Narrows earthquake, *J. Geophys. Res.*, this issue.

Bolt, B. A., A Lomax, and R. A. Uhrhammer, Analysis of regional broadband recordings of the 1987 Whittier Narrows, California, earthquake, *J. Geophys. Res.*, this issue.

Brady, A. G., E. C. Etheredge, and R. L. Porcella, Preliminary assessment of strong ground motion records, *Earthquake Spectra, 4*, 55-74, 1988.

Davis, T. L., National Earthquake Hazard Reduction Program Summary of Technical Reports XXIV, *U.S. Geol. Surv. Open-File Rep., 87-374*, 143-147, 1987.

Davis, T. L., J. S. Namson, and R. F. Yerkes, A cross section of the Los Angeles area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard, *J. Geophys. Res.*, this issue.

Hauksson, E., Seismotectonics of the Newport-Inglewood fault zone in the Los Angeles basin, southern California, *Bull. Seismol. Soc. Am., 77*, 539-561, 1987.

Hauksson, E., et al., The 1987 Whittier Narrows earthquake in the Los Angeles metropolitan area, California, *Science, 239*, 1409-1412, 1988.

Hauksson, E., and L. M. Jones, The 1987 Whittier Narrows earthquake sequence in Los Angeles, southern California: Seismological and tectonic analysis , *J. Geophys. Res.*, this issue.

Hauksson, E., and G. V. Saldivar, Seismicity and active compressional tectonics in Santa Monica bay, southern California, *J. Geophys. Res.*, this issue.

Lin, J., and R. S. Stein, Coseismic folding, earthquake recurrence, and the 1987 source mechanism at Whittier Narrows, Los Angeles basin, California, *J. Geophys. Res.*, this issue.

Linde, A. T., and M. J. S. Johnston, Source parameters of the October 1, 1987, Whittier Narrows earthquake from crustal deformation data, *J. Geophys. Res.*, this issue.

Namson, J. S., Structural transect through the Ventura basin and western Transverse Ranges, *in* Davis, T. L., and Namson, J. S. eds., Structural Evolution of the Western Transverse Ranges: *Pacific Section of Society of Economic Mineralogists and Paleontologists, Guidebook 48A*, 29-41, 1987.

Namson, J., and T. Davis, A structural transect of the western Transverse Ranges, California: Implications for lithospheric kinematics and seismic risk evaluation, *Geology, 16*, 675-679, 1988.

Perkins, G., Data report for the 1987 seismic calibration/refraction survey, Whittier, California, U.S. Geol. Surv., Menlo Park, CA, 29 pp., 1988.

Reasenberg, P. A., and L. M. Jones, Earthquake hazard after mainshocks in California, *Science, 243*, 1173-1176, 1989.

Shakal, A., M. J. Huang, and T.Q. Cao, CSMIP Strong motion data, *Earthquake Spectra, 4*, 75-100, 1988.

Singh, S. K., E. Mena, R. Castro, and C. Carmona, Empirical prediction of ground motion in Mexico City from coastal earthquakes, *Bull. Seismol. Soc. Am, 77*, 1862-1867, 1987.

Stein, R.S., Coalinga's Caveat, *Eos Trans. AGU, 65*, 794-795, 1984.

Stein, R.S., and G.C.P. King, Seismic potential revealed by surface folding: 1983 Coalinga, California, earthquake, *Science, 224*, 869-872, 1984.

Trifunac, M. D., Note on peak accelerations during the 1 and 4 October earthquakes, *Earthquake Spectra, 4*, 101-114, 1988.

Vidale, J. E., Influence of focal mechanism on peak accelerations of strong motions of the Whittier Narrows, California, earthquake and an aftershock, *J. Geophys. Res.*, this issue.

Wald, D., P. G. Somerville, and L. J. Burdick, Simulation of recorded accelerations, *Earthquake Spectra, 4*, 139-156, 1988.

Ziony, J. I., and R. F. Yerkes, Evaluating earthquake and surface-faulting potential, in *Evaluating Earthquake Hazards in the Los Angeles Region: An Earth-Science Perspective*, edited by J. I. Ziony, *U.S. Geol. Surv. Prof. Pap. 1360*, 43-91, 1985.

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(Received February 20, 1989;
accepted February 22, 1989)