A balanced cross-section of the 1994 Northridge earthquake, southern California

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THE Northridge earthquake of 17 January 1994[1] was the latest in a series of very damaging, thrust-fault-generated earthquakes to strike California, following the San Fernando[2] 1971, Coalinga[3] 1983, and Whittier Narrows[4,5] 1987 events. Like the last two of these, the Northridge event occurred along a fault that did not reach the surface and which had not been detected by traditional seismic-hazard methods[6,7]. Balanced cross-sections[8,9], which flatten and remove the crustal deformation, can be used to identify and quantify the seismic hazard posed by thrust faults. Here we present a balanced cross-section through the Northridge portion of the Transverse Ranges fold-and-thrust belt[10], which shows that the earthquake occurred on what we call the Pico thrust. A cross-section of this sort constructed before the earthquake would have revealed the fault, although it would not have predicted the earthquake. Cross-sectional modelling of the Pico thrust yields an average slip rate of 1.4–1.7 mm yr^{-1} and a recurrence interval of Northridge-sized (M_w 6.7) earthquakes every 1,500–1,800 years. We show that the Pico thrust is the back thrust to the 170-km Elysian Park thrust[3,4] which underlies some of the most densely urbanized portions of the Los Angeles basin.

Belts of crustal convergence (fold-and-thrust belts), active and ancient, have been the focus of much study by structural geologists during the past 80 years[11] and developing techniques that can forecast the subsurface structure in these belts has considerable economic importance for the exploration of oil and gas reserves[9,12]. These techniques have focused on methods of cross-section balancing which kinematically restore the crust to an undeformed state (following the classical mechanics principle of conservation of mass) to test the validity of the interpretation[13]. Balanced cross-section construction is further constrained by geometric and kinematic theories and field observations of the origin of fault-related folds. The geometry of folds is most important because it is a direct result of fault geometry and slip at depth and is the most commonly available and continuous data set in fold-and-thrust belts. The balanced cross-section and seismological data from the Northridge earthquake presented here indicate that the present crustal structure, developed over several million years, and the recent earthquake are the result of displacement along a common fault deep below the surface.

The Northridge earthquake occurred at a depth of 18.0 km on a previously unknown thrust fault (Fig. 1). The focal mechanism and aftershocks of the earthquake indicate that the causative fault dips ~40° to the south[5] and that the upper plate moved northwards. The causative fault did not rupture to the surface[14] although the Santa Susana Mountains were uplifted ~380 mm (ref. 15).

Subsurface projection of surface geology[16] and data from oil wells show that the earthquake occurred beneath the San Fernando Valley synclinorium which lies between the Santa Monica Mountains and Santa Susana Mountains anticlinoria (Fig. 2*a*, *b*). The northeast limb of the Santa Susana Mountains anticlinorium consists of a panel of beds 2–3 km wide, dipping 60°–

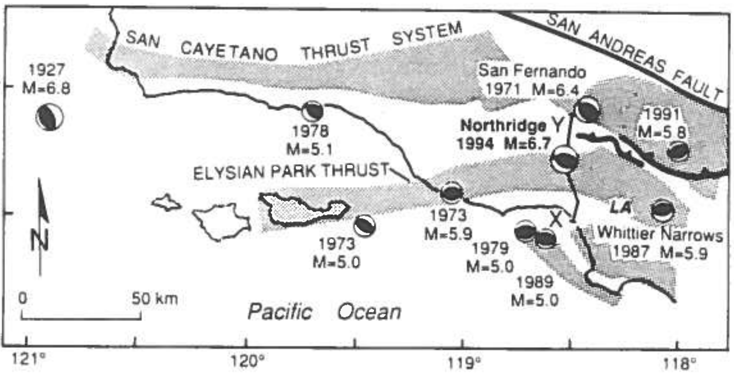

FIG. 1 Epicentres, focal mechanisms and local or moment magnitudes M of the Northridge 1994 earthquake[5] and other significant thrust earthquakes of southern California. Stipple pattern shows the location of major thrust ramps in the western Transverse Ranges[3,10] which have been the source of many of the significant thrust earthquakes. LA, downtown Los Angeles; X–Y, line of cross-section in Fig. 2.

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70 to the north. Field mapping following the earthquake showed activation of a discontinuous set of bedding-plane faults with slip directions consistent with coseismic growth of the anticlinorium[17]. Integration of deep oil-well data reveals the enormous vertical dimensions of the anticlinorium which has more than 6 km of structural relief (Fig. 2*b*). The gently dipping south limb shows that the anticlinorium is asymmetric to the north.

Coseismic uplift of the Santa Susana Mountains anticlinorium and surface disruptions characteristic of folding[17] indicate it is a fault-related fold. We interpret the Santa Susana Mountains anticlinorium to be a fault-propagation fold[18] based on its asymmetric geometry. In this type of thrust-related fold, an asymmetric anticline forms above a propagating thrust ramp with fault slip terminating in the synclinal axis in front of the fold (Fig. 2*b*). We refer to the causative fault of the Northridge earthquake and the Santa Susana Mountains anticlinorium as the Pico thrust, because the large Pico anticline occurs as a secondary structure along the northeast limb of the anticlinorium[16]. This interpretation also provides a kinematic explanation of the zone of shallow aftershocks as flexural-slip faulting, fold axis migration into the Santa Clara synclinorium, and incipient propagation of the Pico thrust up the synclinal axis (Fig. 2*a*). These secondary processes are commonly observed in the front limbs of fault-propagation folds[18] and are consistent with the discontinuous surface disruptions observed in the Santa Clara synclinorium[14,17].

The steep north limb and gentle south-dipping back limb of the anticlinorium requires a south-dipping thrust, but the back limb only constrains the dip of the fault to a range of 25°–45°

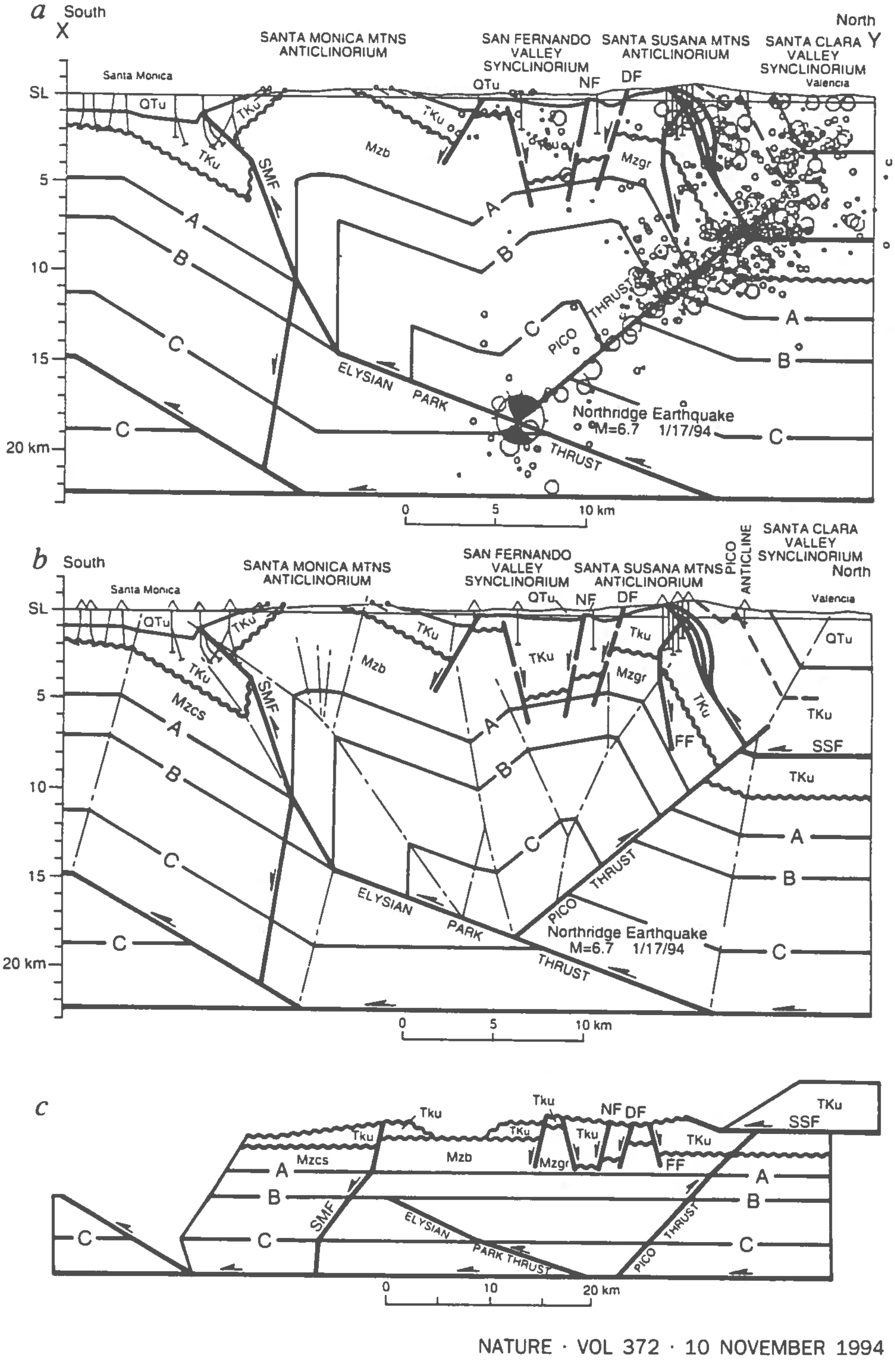

FIG. 2 *a*, Balanced cross-section across the Northridge portion of the Transverse Range fold-and-thrust belt with focal mechanism[5] and aftershock distribution[5] from the Northridge 1994 earthquake superimposed. Main event and aftershocks below 5 km occurred along the Pico thrust. Shallower aftershocks are the result of fold growth (flexural-slip faults) and propagation of the fold hinge into the Santa Clara synclinorium. Thick black lines show faults, wavy lines show unconformities. *b*, Balanced cross-section showing the Santa Susana Mountains and Santa Monica Mountains anticlinoria as crustal-scale fault-propagation folds above the Pico and Elysian Park thrusts, respectively. Assuming that the Northridge earthquake is the characteristic event for the Pico thrust, then it would take ~1,300 events to make the present-day Santa Susana Mountains anticlinorium. Location of wells are shown (triangles) with bore holes, and long-short dashed lines are fold hinges. *c*, Restoration of the cross-section shows that it balances and is therefore a viable solution[13]. The Santa Monica Mountains and Santa Susana Mountains anticlinoria are unfolded, and slip on the Elysian Park and Pico thrusts is restored to the pre-growth setting (~2–3 Myr ago). High-angle faults are older Miocene- and Pliocene-age normal faults that formed before regional convergence. Abbreviations: NF, Northridge Hills fault; DF, Devonshire fault; FF, Frew fault; SSF, Santa Susana fault; SMF, Santa Monica fault; QTu, Upper Pliocene and Quaternary rocks; TKu, Lower Pliocene to Upper Cretaceous rocks; Mzcs, Catalina Schist; Mzb, Mesozoic age metamorphic and plutonic rocks; Mzgr, Mesozoic age granite. A, B and C, form lines showing Late Cenozoic convergent structure in the undifferentiated crystalline basement.

and only generally constrains the fault depth. Integration of seismological data on the hypocentre, mainshock focal mechanism and distribution of aftershocks establishes the exact dip and depth of the Pico thrust.

Our interpretation indicates a pairing of the Santa Susana Mountains anticlinorium uplift and the deeply buried Pico thrust. The lateral extent of the latter can therefore be defined by the lateral extent of the Santa Susana Mountains anticlinorium which is recorded by surface geology and subsurface well data to be 30–40 km in length. More work is needed to elucidate the detailed geometry of the anticlinorium to define more precisely the regional geometry and extent of the seismically active Pico thrust.

The Pico thrust is shown to be a backthrust off the north-dipping Elysian Park thrust ramp. The Elysian Park thrust is rooted in a mid-crustal detachment at ~22 km depth. Mid-crustal detachments have been proposed by numerous workers[3,10,19–21] to underlie the western Transverse Ranges and are a basic component of fold-and-thrust belts[8,9,13]. The restored cross-section (Fig. 2*c*) shows the structural geometry before folding and faulting, and provides a check that the cross-section is balanced.

The balanced cross-section provides information about the seismic potential of the Pico and Elysian Park thrusts. This information is especially important for the latter thrust because it underlies the most urbanized parts of the Los Angeles basin (Fig. 1). Previous balanced cross-section analysis and subsurface mapping of the Elysian Park thrust[3,22] indicate that it is over 170 km long and is a fundamental thrust fault of southern California. The Pico thrust has 3.3 km of displacement and the Elysian Park thrust has 11.8 km of displacement (Fig. 2*b*). Compressive deformation probably began 2–3 Myr ago[3] within the Transverse Range fold-and-thrust belt. Initiation of the Santa Susana Mountains anticlinorium and Pico thrust is recorded by deformation of the youngest unit, the Saugus Formation (QTu, Fig. 2), which is no older than 2.3 Myr (ref. 23). The displacement and 2.3–2.0 Myr age of fault initiation yields an average slip rate of 1.4–1.7 mm yr^{-1} for the Pico thrust. A 2.0–3.0 Myr (ref. 3) age of initiation of the Santa Monica Mountains anticlinorium yields an average slip rate of 3.9–5.9 mm yr^{-1} for the Elysian Park thrust.

Geodetic and seismic modelling suggest the Pico thrust moved ~2.5 m during the Northridge earthquake[15,24] which, divided by our slip rates, yield an average repeat time of 1,500–1,800 years. This repeat-time estimate applies to the segment of the Pico thrust involved in the earthquake, which is ~15 km long. Similar recurrence calculations can be made for the Elysian Park thrust (Fig. 1). Assuming that a Northridge-size earthquake is the characteristic event for the Elysian Park thrust trend, then our slip rate and time-of-initiation estimates yield average earthquake repeat times of 420–640 years for any 15 km segment of the thrust, or an event every 39–58 years along the trend. This repeat time is not supported by the 220 years of recorded history. This discrepancy is probably due to one or more of the following: our long-term slip rates differ from the short-term rates, some crustal shortening is taken up aseismically, the earthquake repeat time is variable, or the characteristic event is even larger and less frequent than that predicted by a Northridge-size earthquake.

Fold-and-thrust belts are tectonic systems with complicated fold and fault patterns that develop over a scale of kilometres (ref. 13). In seismically active belts, the integration of earthquake data with balanced cross-sections provides a broader view of seismic risk than traditional seismic-hazard methods. Application of the balanced cross-section technique should be the first step in evaluating the seismic risk in fold-and-thrust belts and would have predicted the presence of a young south-dipping thrust beneath the Santa Susana Mountains and San Fernando Valley before the Northridge earthquake. ☐

Received 23 February; accepted 6 October 1994

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ACKNOWLEDGEMENTS. We thank E. Duebendorfer and D. Schwartz for comments on the manuscript.