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Seismic Waves Generated by Aircraft Impacts and Building Collapses at World Trade Center, New York City

PAGES 565, 570–571

Seismologists sometimes do their work of data acquisition and analysis against a tragic background. Usually, the context is fieldwork far from home, in an area subjected to the natural but sometimes devastating effects of an earthquake. But in the present case, we are in our own New York City area; that is, the Lamont-Doherty Earth Observatory of Columbia University, in Palisades, N.Y.; and the context is inhuman actions against people and the fabric of our society.

As the appalling events of September 11 unfolded, we found that we had recorded numerous seismic signals from two plane impacts and building collapses of the two World Trade Center (WTC) towers, often at times different than those being reported elsewhere. Collapses of the two WTC towers generated large seismic waves, observed in five states and up to 428 km away. The north tower collapse was the largest seismic source and had local magnitude M_L 2.3. From this, we infer that ground shaking of the WTC towers was not a major contributor to the collapse or damage to surrounding buildings. But unfortunately, we also conclude that from the distance at which our own detections were made (the nearest station is 34 km away at Palisades) it is not possible to infer (with detail sufficient to meet the demands of civil engineers in an emergency situation) just what the near-in ground motions must have been.

Signals at Palisades from Impacts and Collapses

Figure 1 shows seismic signals at Palisades, N.Y. (PAL) for the impacts and collapses, which are labeled by their arrival time order. Note that impact 1 and collapse 2 relate to the north tower, and impact 2 and collapse 1 apply to the south tower. Computed origin times and seismic magnitudes are listed in Figure 1. Origin times with an uncertainty of 2 s were calculated from the arrival times of Rg waves at PAL using a velocity of 2 km/s. The collapse of 7 WTC at 17:20:33 EDT was recorded but is not shown. Three other small signals shown in Figure 1 and ones at 12:07:38 and 12:10:03 EDT may have been generated by additional collapses.

Surface waves were the largest seismic waves observed at various stations. The presence of seismic body waves is questionable even at Palisades for the two largest collapses; they are not observed at other stations. Local magnitudes M_L, like those defined originally by Richter for southern California but with distance correction factors appropriate for eastern North America [*Kim*, 1998], were computed for the two impacts and the three largest collapses. For collapses 1 and 2, values of M_L determined from E-W components are 2.1 and 2.3. M_L is 0.1 to 0.2 units smaller on the vertical, an observation that we associate later with multipath propagation.

Amplitude spectra for PAL data are shown at the right of Figure 1 for the impacts and the collapses of the twin towers. The spectra of collapses 1 and 2 are above the noise for frequencies from 0.2 to 10 Hz. The two spectra are similar, but the second shows a more pronounced peak near 1 Hz. Seismic signals from both impacts are characterized by relatively periodic motion and their spectra are above the noise only for frequencies from about 1.3 to 1.6 Hz. Those frequencies are more than 10 times the frequency of the lateral fundamental mode of each tower.

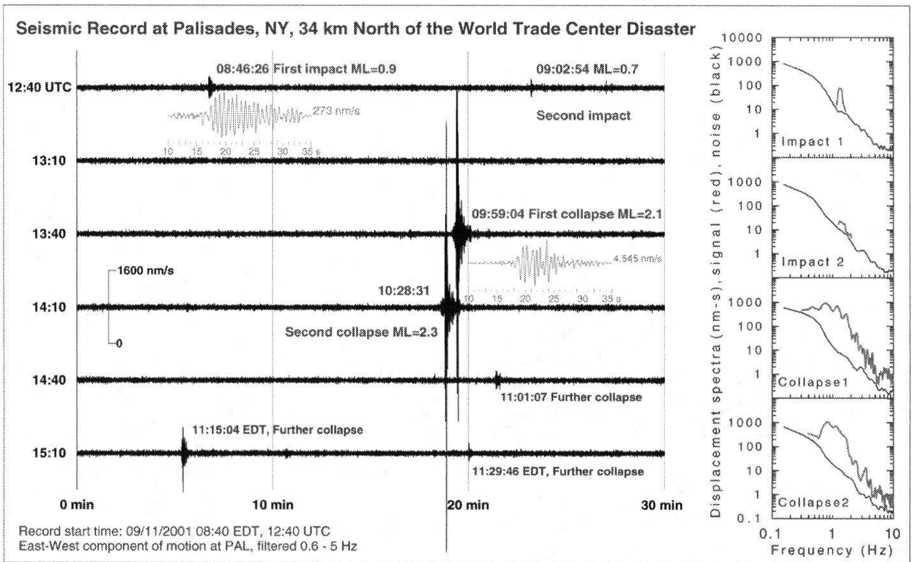

Fig. 1. Seismic recordings on E-W component at Palisades for events at World Trade Center (WTC) on September 11, distance 34 km. Three hours of continuous data shown starting at 08:40 EDT (12:40 UTC). Data were sampled at 40 times/s and passband filtered from 0.6 to 5 Hz. Two largest signals were generated by collapses of towers 1 and 2. Eastern Daylight Time (EDT) is UTC minus 4 hours. Expanded views of first impact and first collapse shown in red. Displacement amplitude spectra in nm-s from main impacts and collapses shown at right. Sampling is done for 14-second time windows starting about 17 s after origin time. Note broad-band nature of spectra for collapses 1 and 2. Their signals are similar with a correlation coefficient of about 0.9 as are those for two impacts. Original color image appears at the back of this volume.

Observations in Mid-Atlantic States and New England

Lamont-Doherty operates 34 seismograph stations in seven Mid-Atlantic and New England states. The network has been in operation since the early 1970s, but the stations, types of recording, and data transmission have changed with time. Digital data are now sent via the Internet in real time to Palisades. They are supplemented by data from the U.S. National Seismic Network. The modern stations record over a broad frequency band; some like PAL sample three components of ground motion, but others, only the vertical. Information on the stations and WTC recordings is available at www.ldeo.columbia.edu/LCSN. The data were sent to the Data Management Center, Incorporated Research Institutions for Seismology (IRIS), in Seattle, Washington.

Seismic waves from collapse 2 were recorded by at least 13 stations ranging in distance from 34 km to Lisbon, NH at 428 km. The magnitude of the event was only 2.3. The predominant signals at distances greater than 200 km are short-period surface waves, which propagate at wave speeds of about 3.5 km/s, the typical Lg group velocity observed for the largest waves from earthquakes at regional distances in eastern North America. Those observations will be published separately.

Seismic Waves in Greater New York City Area

Six stations within the greater Metropolitan New York region (Fig. 2) recorded the two tower collapses. Vertical-component records are shown in Figure 3 as a record section of distance as a function of travel time. The dotted lines indicate velocities from 1.5 to 2.5 km/s assuming propagation along straight paths from the WTC to the stations. Unlike signals at distant stations, the predominant waves are surface waves of short period (about 1 s) called Rg with group velocities between 2.3 and 1.5 km/s. GPD only recorded horizontal components.

Relatively simple and similar pulses with durations of about 5 to 6 s arrive at stations BRNJ, TBR, and ARNY starting at a group velocity of 2.0 km/s. The paths to each of those stations from the WTC are mostly in the low-velocity sedimentary rocks of the Newark Basin (N.B. in Fig. 2), the region of low topography west of the Hudson River and southeast of that of higher topography in the Hudson Highlands (Reading Prong). Since those paths cross the boundaries of the Basin at a high angle, the signals at those stations are relatively simple. The signals (not shown) at LSCT, a station in northwestern Connecticut, are also relatively simple, reflecting propagation over a distance of 125 km entirely within the high-velocity

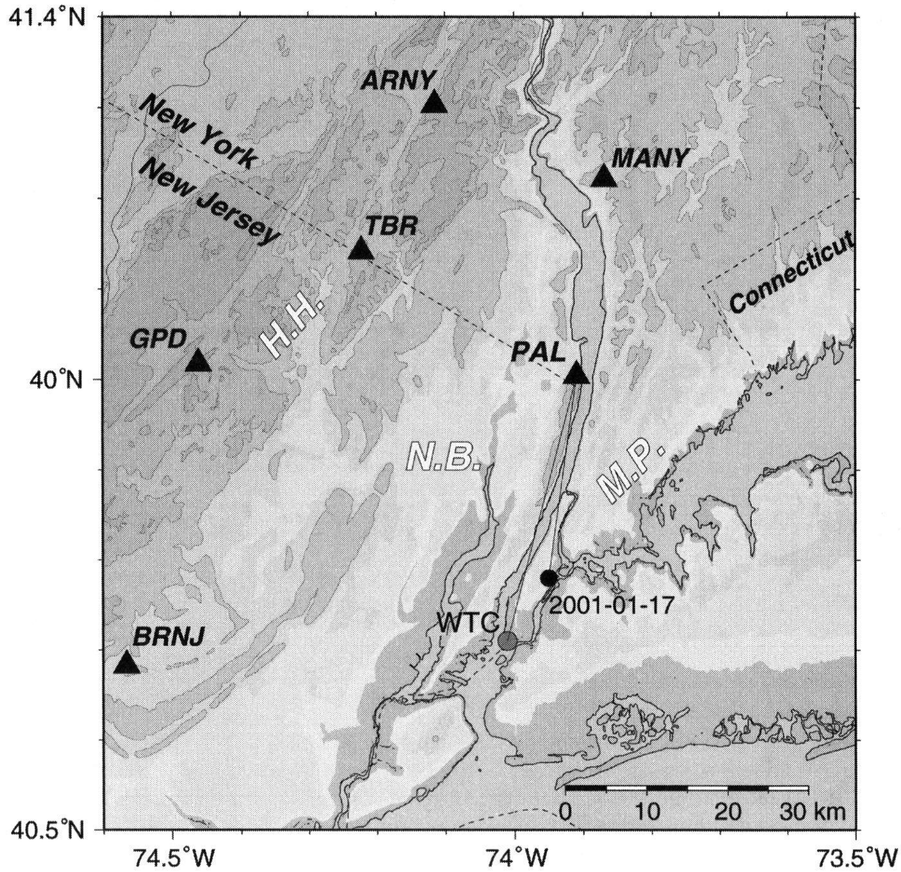

Fig. 2. Seismograph stations and topography for greater New York City area. Solid triangles indicate stations that recorded events at WTC (solid red circle); black circle, epicenter of earthquake of January 17, 2001. N.B. denotes Newark Basin; H.H., Hudson Highlands; M.P., Manhattan Prong. Original color image appears at the back of this volume.

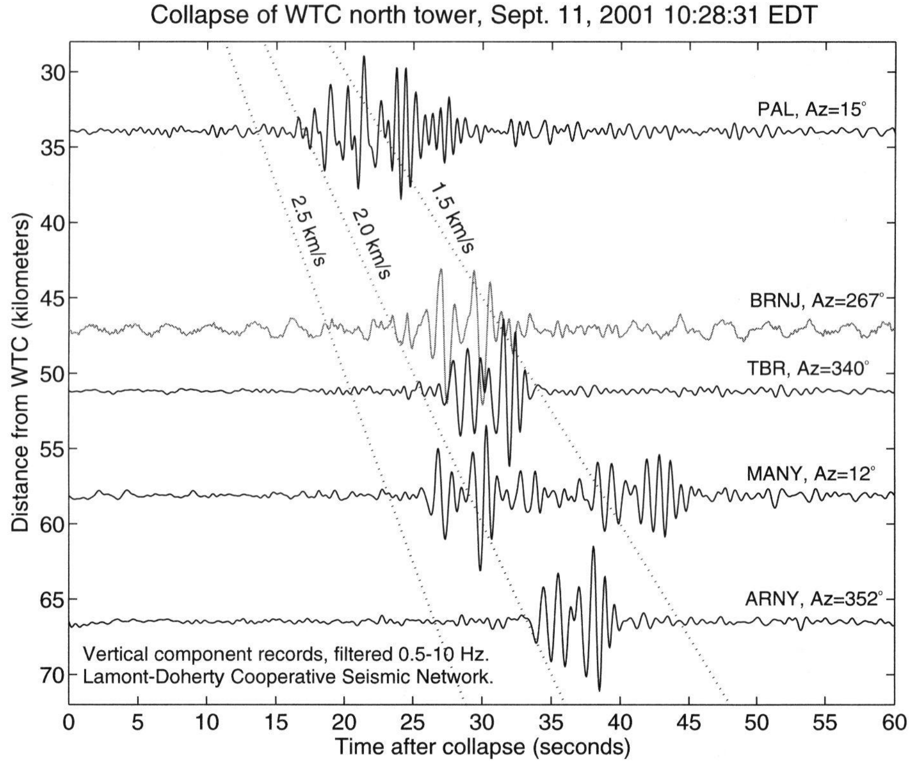

Fig. 3. Record section of vertical-component seismograms from stations in figure 2 following collapse of north tower of WTC. Zero corresponds to computed origin time of 10:28:31 EDT. Data filtered for passband 0.5 to 10 Hz. Three velocities indicated by dotted lines.

rocks of the Manhattan Prong (M.P. in Fig. 2). Their group velocity of about 3.0 km/s is consistent with Rg propagation in that faster, older terrain. Thus, we conclude that the pulse duration at those four stations reflects mainly that the generation of seismic energy from the collapse was delivered over 5–6 s. A portion of the pulse duration probably results from the dispersion of Rg waves.

Anderson and Dorman [1973] observed low egroup velocities from quarry blasts for paths that propagate mainly though the Newark Basin, and higher velocities for paths within the Manhattan Prong. Their largest arrivals also were the short-period Rayleigh wave Rg. Short-period Rg is well excited only for surface or very shallow sources, which is the case for the WTC. Since Rg propagates mainly in the upper several kilometers of the crust, it is affected strongly by rock properties in that depth range.

Anderson and Dorman also observed strong lateral refraction of Rg waves caused by the contrast in shallow rock properties at the boundary of the high and low velocity rocks of the Manhattan Prong and Newark Basin. Waves propagated to Palisades followed paths through both provinces, resulting in multiple arrivals of Rg. On the basis of polarization analysis, several of those wave packets arrived from quite different directions than those predicted for straight-line propagation. Seismic waves at PAL and MANY also are more complex than those at the other stations of Figure 3, probably indicative of arrivals refracted through the two terrains. At MANY, 10 s separates two arrivals.

The constructive interference of two Rg phases at PAL may well account for the large arrivals on the E-W component even though the azimuth of the direct path from WTC to PAL is NNE. We do not interpret them necessarily as Love waves; hence, a source with a horizontal component is not required to explain them. (We verified that the components and polarities of the digital data at PAL were correct using recordings of distant earthquakes close in time to the WTC events.)

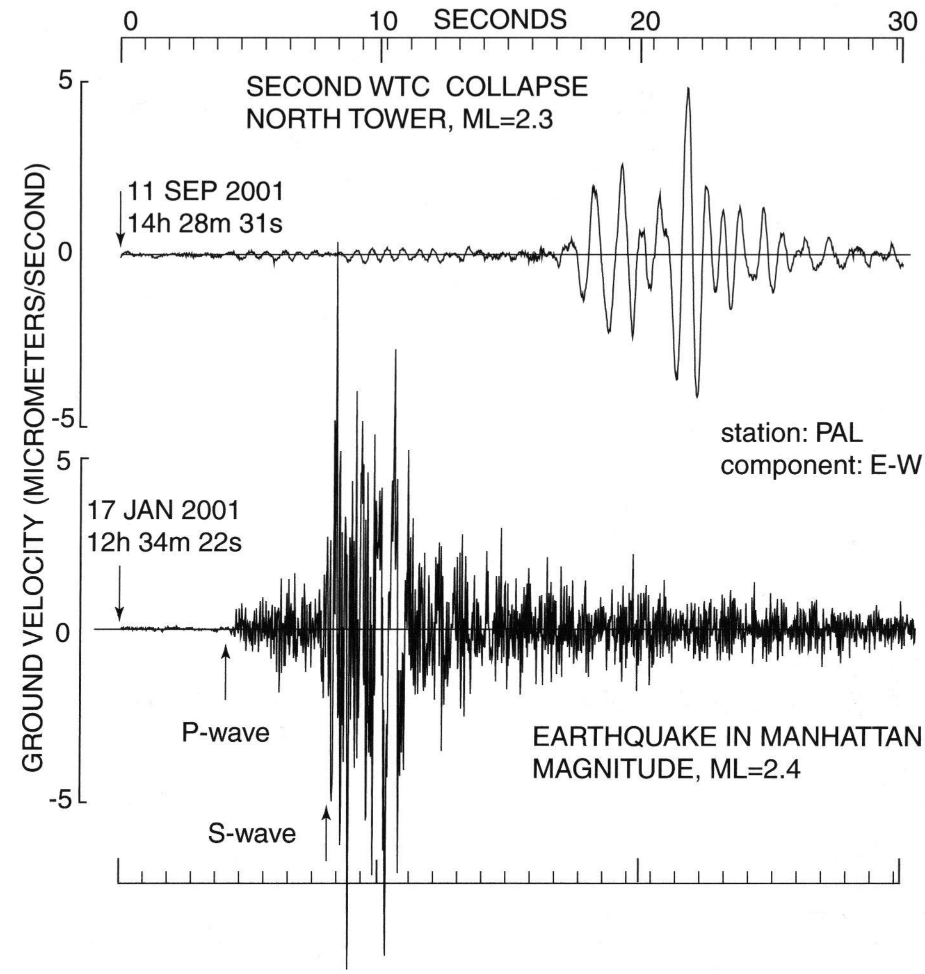

Fig. 4. Comparison of Palisades seismograms for collapse 2 and earthquake of January 17, 2001. Arrows at left indicate computed origin times.

Comparison with Signals from Earthquakes, Gas Explosion, and Mine Collapse

The signals at PAL from collapse 2 and a small felt earthquake beneath the east side of Manhattan on January 17, 2001 are of comparable amplitude and M_L (Fig. 4). The character of the two seismograms, however, is quite different. Clear *P* and *S* waves are seen only for the earthquake. The 7-km depth of the earthquake suppressed the excitation of short-period Rg, which is so prominent for the collapse. The difference in the excitation of higher frequencies also can be attributed to the short time duration of slip in small earthquakes compared to the combined source time of several seconds of the complex system of the towers and foundations responding to the impacts and collapses. The waves from the WTC events resemble those recorded by regional stations from the collapse of part of a salt mine in western New York on March 12, 1994 (M_L 3.6). That source also lasted longer than that of a small earthquake. A truck bomb at the WTC in 1993, in which approximately 0.5 tons of explosives were detonated, was not detected seismically, even at a station only 16 km away.

An explosion at a gasoline tank farm near Newark N.J. on January 7, 1983 generated observable *P* and *S* waves and short-period Rg waves (M_L 3) at PAL. Its Rg is comparable to that for WTC collapse 2. Similar arrivals were seen at station AMNH in Manhattan, which is no longer operating, at a distance of 15 km. AMNH also recorded a prominent seismic arrival at the time expected for an atmospheric acoustic wave. We know of no microbarograph recordings of either that explosion or the events at the WTC. Many people asked us if the arrivals at seismic stations from the WTC events propagated in the atmosphere. We find no evidence of waves arriving at such slow velocities. Instead, the seismic waves excited by impacts and collapses at the WTC are short-period surface waves; i.e, seismic waves traveling within the upper few kilometers of the crust.

Significance of Findings for On-Site Conditions

Unfortunately, no seismic recordings of ground motion are currently known to exist at or very close to the WTC. Plans are pending for an Advanced National Seismic System (ANSS; see *USGS* [1999]) that calls for increased urban seismic instrumentation, including New York City. The September 11 events show that such instrumentation can be valuable to serve a purpose that sometimes transcends strict earthquake applications. Since the main collapses, a major concern has been if strong shaking affected the structural stability of nearby buildings. Earthquakes of M_L 2.3 are not known to cause any structural damage in buildings. In the eastern U.S., that threshold is believed to be close to or above M_L 4 to 4.5. It is more reasonable that most of the effects of those collapses on adjacent structures and people were related to the kinetic energy of falling debris and the pressure on buildings exerted by dust- and particle-laden air mobilized by falling debris. It had, except for temperature, an effect very similar to pyroclastic ash flows that descend slopes of volcanoes. The seismic shaking associated with the impacts and the main collapses probably was small compared to those other energetic processes. The following order-of-magnitude estimates of energies involved corroborate this interpretation.

The gravitational potential energy associated with the collapse of each tower is at least 10^{11} J. The energy propagated as seismic waves for M_L 2.3 is about 10^6 to 10^7 J. Hence, only a very small portion of the potential energy was converted into seismic waves. Most of the energy went into deformation of buildings and the formation of rubble and dust. The perception of people in the vicinity of the collapses as reported in the media seems to be in full accord with the notion that ground shaking was not a major contributor to the collapse or damage to surrounding buildings. The seismic energy of a M_L 0.7 to 0.9 computed for the impacts is a tiny fraction of the kinetic energy of each aircraft, about 2 x 10^9 J. That associated with the combustion of 50 to 100 tons of fuel in each aircraft is roughly 10^{12} J, most of which was expended in the large fireballs (visible in TV images) and in subsequent burning that ignited material in each tower. Less than a millionth of the fuel energy was converted to seismic waves.

Acknowledgments

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Authors

Won-Young Kim, L. R. Sykes[1], *J. H. Armitage, J. K. Xie, K. H. Jacob, P. G. Richards*[1], *M. West*[1], *F. Waldhauser, J. Armbruster, L. Seeber, W. X. Du*[1], and *A. Lerner-Lam*[1], Lamont-Doherty Earth Observatory of Columbia University, Palisades, N.Y. 10964, USA

[1] also Department of Earth and Environmental Sciences, Columbia University, NYC.

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Surface Rupture and Behavior of Thrust Faults Probed in Taiwan

PAGES 565, 569

Taiwan's destructive Chi-chi earthquake of September 21, 1999, was a dramatic expression of active tectonic processes at a complex collisional plate boundary. It resulted in more than 2,400 causalities and tens of billions of dollars in property loss. During the earthquake, an 80-km stretch of the country's mountainous backbone moved upward and westward along the range-bounding Chelungpu thrust fault (Figure 1a). A team of earthquake geologists from the United States, in collaboration with geoscientists from Academia Sinica, National Taiwan University and the Central Geological Survey of Taiwan, worked together to address questions concerning the recurrence of large- magnitude earthquakes along reverse faults in Taiwan.

After receiving a formal letter of invitation for post-earthquake scientific assistance from Jian-Cheng Lee of the Institute of Earth Sciences, Academia Sinica, Taiwan, an international team visited Taiwan for 10 days in March 2000. The team interpreted the complex surface and sub-surface rupture and located potential paleoseismic sites. Armed with sub-surface geologic and paleoseismic techniques that characterize the timing and magnitude of past earthquakes, the group began to characterize the prehistoric seismic record of the Chelungpu and adjacent faults. This National Science Foundation-sponsored visit to the rupture convinced us that the active Chelungpu fault could have been mapped with precision before the 1999 rupture using high-resolution shaded-relief Digital Elevation Models (DEM) or Light Detection and Ranging (LIDAR) imagery.

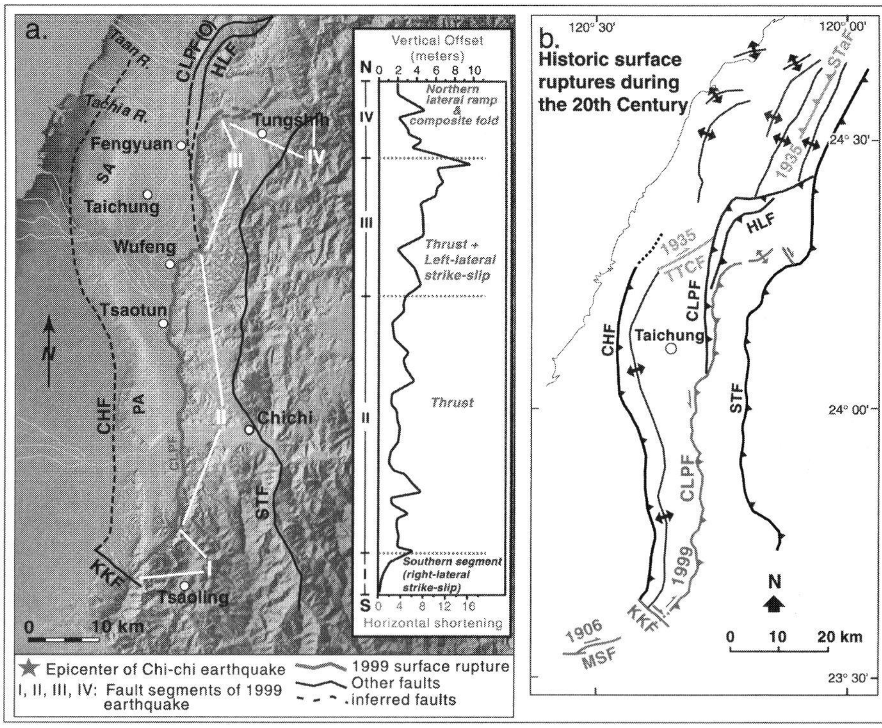
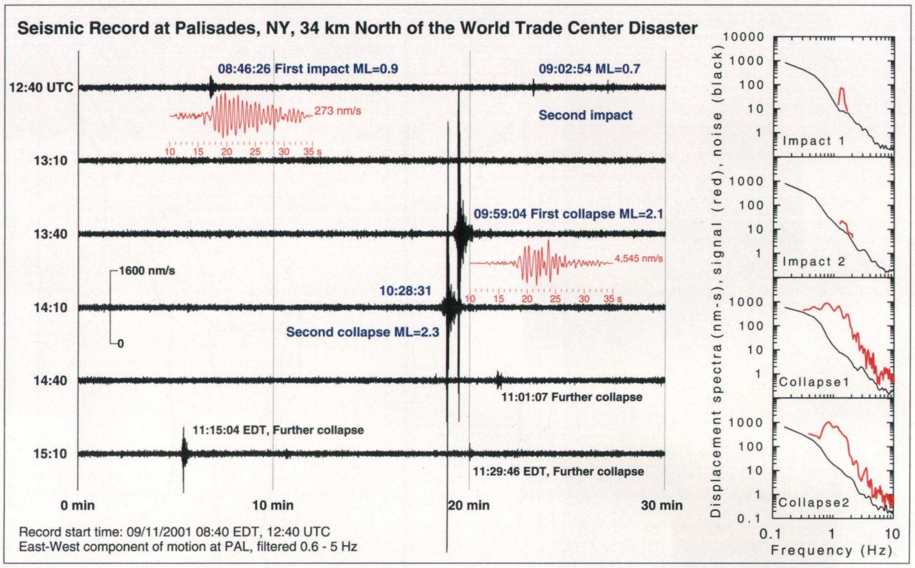


Fig. 1. (a) Map of the 1999 Chi-chi rupture (red), its segments (white), and the neighboring major faults. Fault segments are defined by discontinuities in the surficial fault trace (stepovers or gaps), changes in fault orientation, and changes in the geomorphology along-strike. Field observations of the vertical offsets and derived horizontal shortening assume a 30° dip for the fault plane. (b) Surface rupture of the 1999 Chi-chi earthquake showing the northern and southern segment boundary geometry. The historic surface rupture is shown in blue: MSF, Meishan fault (1906 surface rupture shown in orange); StaF, Shihtan fault (1935 surface rupture shown in green); TTCF, Tuntzuchiao fault (1935 surface rupture shown in green). CLPF, Chelungpu fault (1999 surface rupture shown in red). Other faults, CHF, Changhua fault; CLPFO, Chelungpu fault (mapped fault prior to 1999); STF, Shuangtung fault; HLF, Holi fault; KKF, Kukeng fault. Anticlines: PA, Pakuashan anticline and SA, Shalu anticline. Original color image appears at the back of this volume.



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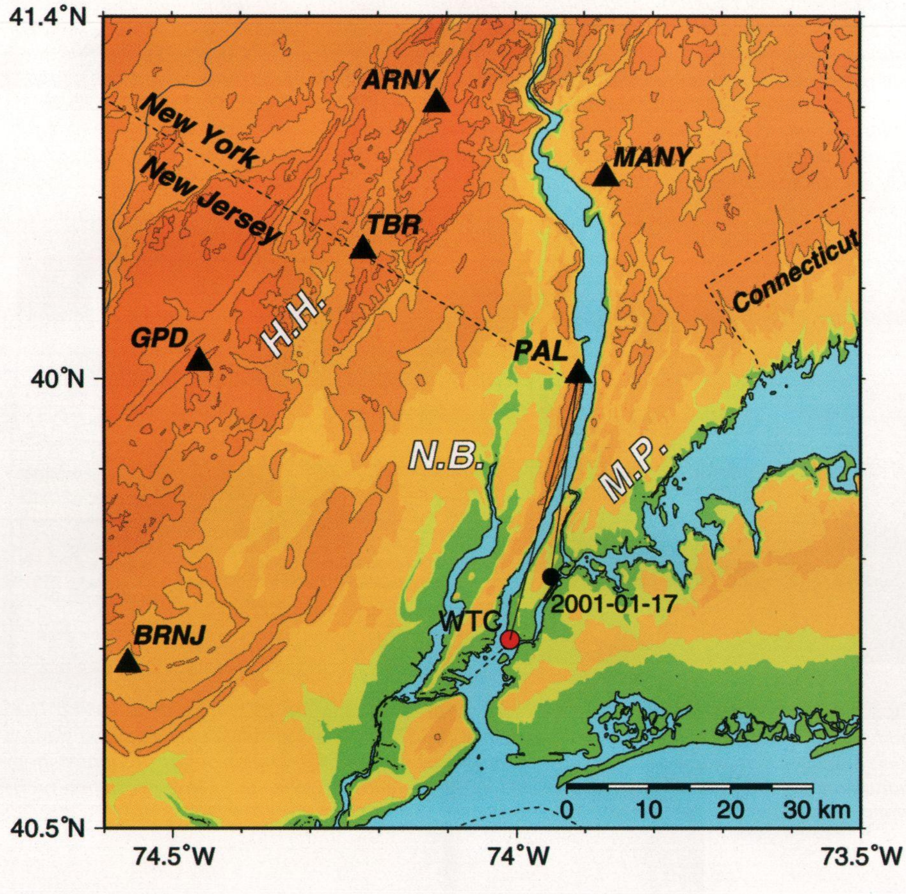

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