A PUBLIC HEALTH ISSUE RELATED TO COLLATERAL SEISMIC HAZARDS: THE VALLEY FEVER OUTBREAK TRIGGERED BY THE 1994 NORTHRIDGE, CALIFORNIA EARTHQUAKE

RANDALL W. JIBSON
U.S. Geological Survey, Box 25046, MS 966, Denver Federal Center, Denver, CO 80225, USA
E-mail: jibson@usgs.gov

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Abstract. Following the 17 January 1994 Northridge, California earthquake (**M** = 6.7), Ventura County, California, experienced a major outbreak of coccidioidomycosis (CM), commonly known as valley fever, a respiratory disease contracted by inhaling airborne fungal spores. In the 8 weeks following the earthquake (24 January through 15 March), 203 outbreak-associated cases were reported, which is about an order of magnitude more than the expected number of cases, and three of these cases were fatal. Simi Valley, in easternmost Ventura County, had the highest attack rate in the county, and the attack rate decreased westward across the county. The temporal and spatial distribution of CM cases indicates that the outbreak resulted from inhalation of spore-contaminated dust generated by earthquake-triggered landslides. Canyons North East of Simi Valley produced many highly disrupted, dust-generating landslides during the earthquake and its aftershocks. Winds after the earthquake were from the North East, which transported dust into Simi Valley and beyond to communities to the West. The three fatalities from the CM epidemic accounted for 4 percent of the total earthquake-related fatalities.

Keywords: coccidioidomycosis, collateral seismic hazards, earthquakes, landslides, valley fever

1. Introduction

Much recent effort in the seismic hazards community has been focused on collateral or multiple hazards: geologic hazards triggered by other geologic hazards. Earthquakes can trigger collateral hazards such as liquefaction, landslides, seiches, and tsunamis. Studies following the 1994 Northridge, California earthquake documented an interesting and instructive case of a sequence of collateral hazards that were not previously recognized (Schneider et al., 1997; Jibson et al., 1998). The earthquake triggered thousands of landslides, and the landslides generated dense clouds of dust that were blown by strong winds into populated areas. The dust contained fungal spores that, when inhaled, can cause an infectious disease called coccidioidomycosis (CM), commonly referred to as valley fever. Coccidioidomycosis can cause serious illness and, in rare instances, death. The epidemic triggered by the Northridge earthquake resulted in 55 people being hospitalized, 6 of whom contracted the most serious form of the disease; 3 of these people died, accounting

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for about 4 percent of the total earthquake fatalities. This is the first documentation of an outbreak of CM associated with an earthquake.

This paper recapitulates the salient points of the epidemiological investigation of Schneider et al. (1997) and the detailed evidence associating the outbreak with dust generated by earthquake-triggered landslides presented by Jibson et al. (1998). In addition, this paper discusses those areas in the world where such an earthquake-related outbreak could occur in the future. The results of this research are far-reaching in terms of considering public-health issues in the context of collateral earthquake hazards.

2. Background on the earthquake and triggered landslides

The Northridge earthquake (**M** = 6.7) occurred at 4:31 a.m. local time on 17 January 1994. The hypocenter was 19 km beneath the Northridge area of the San Fernando Valley on a blind thrust fault striking N58°W and dipping 42° South (Wald and Heaton, 1994). Free-field peak horizontal ground accelerations greater than 1 g were recorded at some sites, and high levels of ground shaking extended over a broad region. Thousands of structures were damaged or destroyed by the strong shaking, and total direct losses were estimated at more than $20 billion.

The Northridge earthquake triggered more than 11,000 landslides over an area of about 10,000 km^2 (Harp and Jibson, 1995, 1996) that is roughly concentric with the epicenter (Figure 1). Within this broad area of scattered landslide activity is a 1,000-km^2 area of much more concentrated landsliding that lies North and North-West of the epicenter, primarily in the Santa Susana Mountains and the mountains North of the Santa Clara River valley. Landsliding was densest along the steep-walled canyons that are incised into the northern and southern flanks of the Santa Susana Mountains. In some of these areas more than 75 percent of the slope area was denuded by landslides triggered by strong shaking (Figure 2). Characteristic landslides in such areas were several decimeters to a few meters deep and consisted of dry, highly disaggregated material that cascaded downslope to flatter areas at or near the base of the steep slopes (Figure 3). These failures ranged in volume from a fraction of a cubic meter to a few hundred thousand cubic meters (Harp and Jibson, 1995, 1996).

The reason for this extraordinary concentration of landslides was twofold. First, the fault rupture extended directly beneath the Santa Susana Mountains, which probably enhanced the strong ground motion there. Throughout the Santa Susana Mountains, pervasive shattered ridge tops and boulders thrown from their sockets attest to widespread high ground accelerations. Second, the Santa Susana Mountains consist primarily of Late Miocene through Pleistocene clastic sediment having little or no cementation; this sediment is being uplifted and folded by rapid tectonic deformation. The young, weak material lacks significant tensile strength and erodes readily to form steep-walled canyons that commonly head in nearly

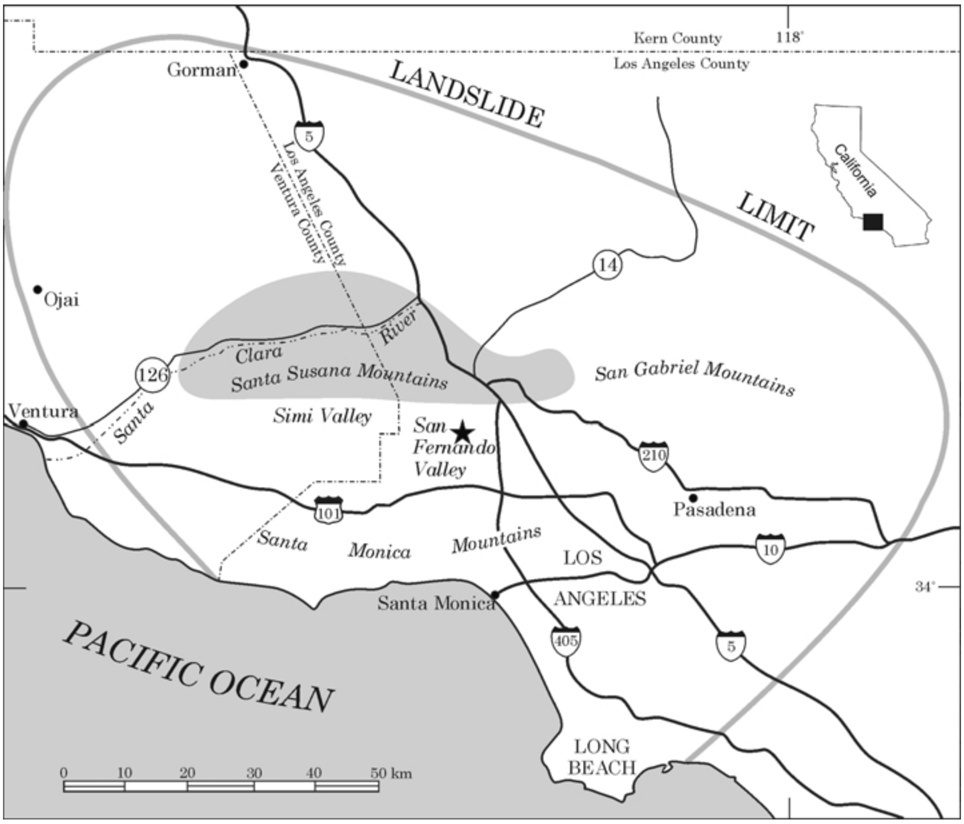

Figure 1. Map showing epicenter (star) of 1994 Northridge earthquake (**M** = 6.7) and areas affected by landslides. Heavy gray line shows maximum limit of triggered landslides; area of greatest landslide concentration is shaded. Solid lines are major roads, dash-dot lines are county boundaries, and dash-double-dot lines are rivers.

vertical slopes. The combination of young, weak sediment and steep relief reaching elevations of 1,000 m above sea level makes this area extremely susceptible to failure during seismic shaking.

3. Background on coccidioidomycosis

Coccidioidomycosis (locally known as valley fever, desert fever, or desert rheumatism) occurs only in the western hemisphere. It is endemic to parts of South and Central America as well as the semi-arid South-West of North America, particularly parts of Arizona, California, Nevada, New Mexico, Texas, Utah, and northern Mexico (Drutz and Catanzaro, 1978; Pappagianis, 1988). CM is a reportable disease (any diagnosed case must be reported to public-health authorities) in California and several other U.S. states in which the disease is endemic. Within

Figure 2. Slopes denuded by earthquake-triggered landslides in the Santa Susana Mountains. Virtually all the light-colored areas failed during the earthquake.

Figure 3. Highly disrupted landslide in the Santa Susana Mountains just North of Simi Valley. The weak sediment disaggregated into individual sediment grains and cascaded down the steep slopes. The landslide source extends approximately 1 km along the ridge top.

California it is highly endemic in the southern San Joaquin valley and less endemic in the epicentral area of the Northridge earthquake (Edwards and Palmer, 1957; Fiese, 1958). CM is caused by infection with *Coccidioides immitis* spores, a dimorphic, saprophytic fungus that grows in the upper 10–20 cm of semi-arid soils (Drutz and Catanzaro, 1978). Infection results from inhaling airborne dust containing the spores, and CM is not transmitted from person to person (Drutz and Catanzaro, 1978; Pappagianis, 1988). The incubation period for CM ranges from 8–21 days; the median is 14 days (Smith et al., 1946; Stevens, 1995).

An estimated 100,000 CM cases occur each year in the United States resulting in about $20 million in medical expenses and 50–70 fatalities (Stevens, 1995). About 60 percent of infected persons are asymptomatic; the remaining 40 percent have symptoms suggesting a flu-like respiratory illness. About 0.5 percent of infected persons develop disseminated coccidioidal disease, in which the infection spreads to different organs and body systems (Drutz and Catanzaro, 1978; Einstein and Johnson, 1993; Stevens, 1995). Because CM symptoms are similar to those of other common illnesses, definitive diagnosis requires isolation of the organism or serological testing. Therefore, the number of diagnosed cases probably underestimates total actual cases because most infected persons are either asymptomatic or have what appears to be a mild, flu-like illness. For example, Einstein and Johnson (1993) estimated that the number of serologically confirmed cases represents only 8-10 percent of total infections. Almost all infected persons acquire lifetime immunity to the disease (Drutz and Catanzaro, 1978; Einstein and Johnson, 1993). Previous exposure to the infection can be determined by skin testing.

In endemic areas, people who are exposed to high levels of airborne dust in their work environments are at higher risk for infection with *Coccidioides immitis* than the population in general. People working in agriculture, construction (particularly excavation), archaeology, and field geology are particularly at high risk for contracting CM (Pappagianis, 1988).

Even within highly endemic areas, *Coccidioides immitis* distribution in soils is spotty. The fungal spores thrive in sandy, alkaline soils rich in carbonized organic material and salts (Elconin et al., 1967; Swatek et al., 1967; Drutz and Catanzaro, 1978; Einstein and Johnson, 1993). Pappagianis (1988) noted a particular affinity of *Coccidioides immitis* to soils developed on marine sediment. Endemic areas are characterized by a semi-arid climate that facilitates the airborne distribution of *Coccidioides immitis* spores: rainy winters having few freezes enhance germination and fungal growth, and hot, dry summers cause the fungal growths to become brittle and easily detached by surface winds (Smith et al., 1946; Drutz and Catanzaro, 1978; Pappagianis, 1988). Previously reported epidemics of CM in the San Joaquin valley of California have been linked to periods of drought and periods of increased dust from disturbance of the ground surface from activities such as farming and construction (Smith et al., 1946; Centers for Disease Control and Prevention, 1994). Arroyos and dry washes are especially conducive to *Coccidioides immitis* concentration because of prolonged periods of moist soil conditions during the rainy season (Pappagianis, 1988); furthermore, *Coccidioides immitis* is hydrophobic and thus floats, which enhances transport and deposition along arroyo walls during seasonal runoff periods (Swatek et al., 1967).

4. Epidemiology of the coccidioidomycosis outbreak

During the first few weeks following the Northridge earthquake, Ventura County public health officials noted a large increase in reporting of CM cases as compared to previous years. Between 24 January and 15 March 1994 – a period of just 8 weeks – 203 outbreak-associated cases of CM were identified (Schneider et al., 1997). By contrast, fewer than 60 CM cases were reported annually in both 1992 and 1993 in Ventura County. Fifty-five (27 percent) of the diagnosed patients required hospitalization, the median duration of which was 7.5 days. Six patients (3 percent) developed disseminated coccidioidal disease, and three persons (1.5 percent) died (Schneider et al., 1997). No significant increase in reported CM cases occurred in Los Angeles County, where the earthquake epicenter was located.

5. Temporal correlation of the epidemic with the earthquake

The temporal correlation between the abrupt increase in CM cases and the occurrence of the earthquake is striking. Figure 4 shows the temporal distribution of the onset of CM symptoms for 213 cases in Ventura County diagnosed from 1 January through 15 March 1994; 203 of these cases met the case definition for being outbreak associated, and the remaining 10 cases probably represent the normal background occurrence of the disease. From 1 January through 17 January (the day of the earthquake), one case was reported, which is consistent with similar time periods in 1991 and 1992. Immediately after the earthquake, an increase in reporting of CM cases occurred. A sharp peak in the temporal distribution occurred two weeks after the earthquake; this time interval corresponded exactly to the median incubation period of CM (Smith et al., 1946; Stevens, 1995). Following this peak, the number of cases tailed off through 15 March.

Figure 4 shows a clear temporal relationship between the onset of the epidemic and the time of the earthquake. The question that remains to be answered, however, is what the earthquake did that triggered the epidemic. We address this question by analyzing the spatial distribution of the reported CM cases.

6. Spatial distribution of coccidioidomycosis cases

Although the temporal association of the earthquake and the onset of the CM epidemic is evident, the spatial distribution of the cases is more complex. The earthquake was centered in the San Fernando Valley of Los Angeles County (Figure 1),

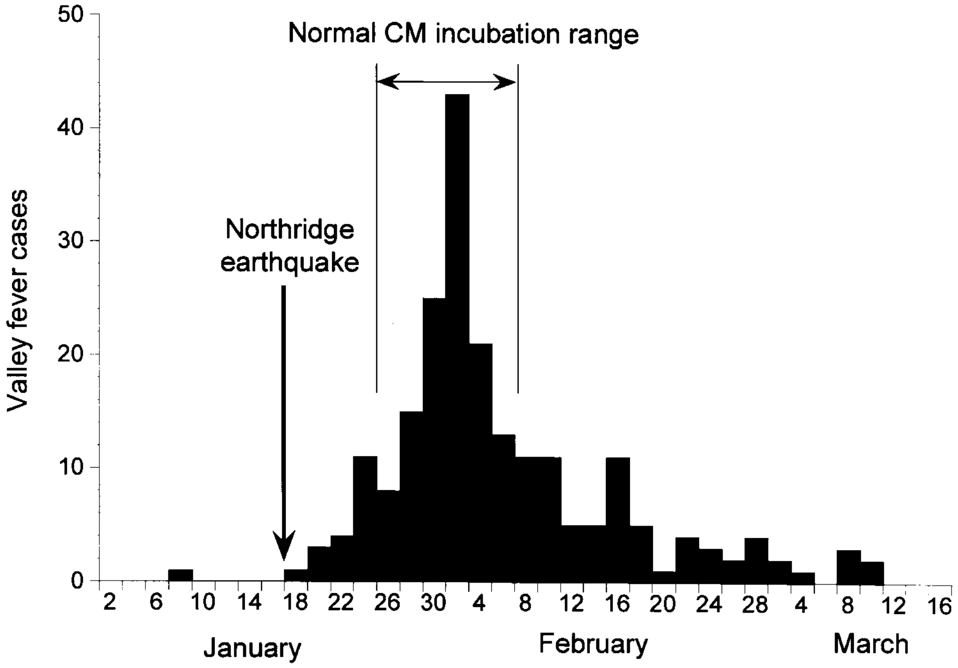

Figure 4. Epidemic curve for Ventura County, California, 1 January through 15 March 1994 (adapted from Schneider et al., 1997). The epidemic curve is a histogram showing the temporal distribution of diagnosed CM cases; the peak of the histogram is two weeks following the earthquake, which is the median incubation period for CM. The normal range of CM incubation measured from the time of the earthquake encompasses the peak of the outbreak.

and strong ground shaking and damage were greatest there. The CM outbreak, however, occurred in Ventura County and was concentrated primarily in Simi Valley, which lies at the eastern edge of the county and tens of kilometers West of the epicenter. Figure 5 shows the distribution of post-earthquake CM cases, and the distribution is clearly non-random at a regional scale.

Simi Valley, located near the base of the Santa Susana Mountains, had 56 percent of the reported outbreak-associated (24 January–15 March) CM cases despite having less than 15 percent of the county's population. The attack rate (number of persons who had CM divided by the number of persons at risk for infection) in Simi Valley was 114 cases per 100,000 people as compared to 30 cases per 100,000 in Ventura County as a whole. Figure 6 shows the attack rate for several communities; Simi Valley had by far the highest attack rate, and rates decreased in communities to the West and South. In westernmost Ventura County, the attack rate was only 3 per 100,000 population. Analysis of the attack rate by census tract showed large variability even within Simi Valley, where the attack rate ranged from 27 to 473 cases per 100,000 population (median: 97 per 100,000). The highest attack rate

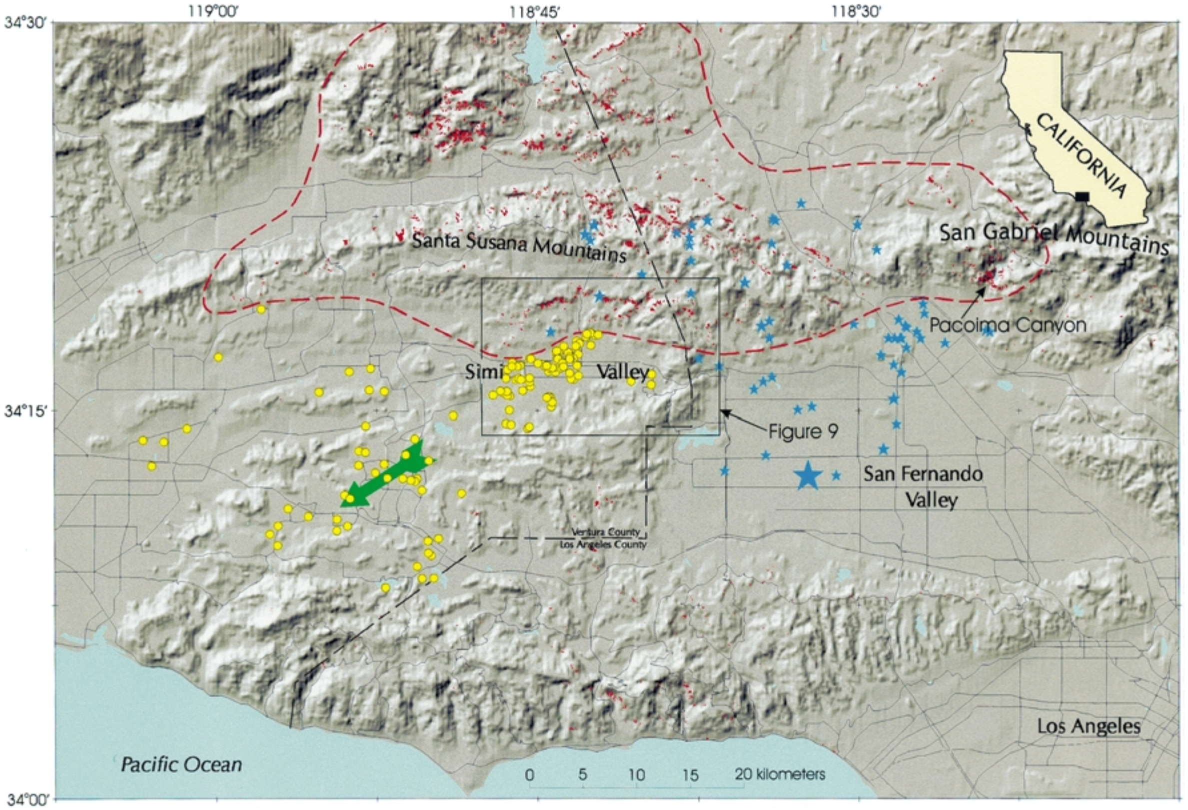

Figure 5. Map showing spatial distribution of CM cases (yellow dots) in Ventura County following the Northridge earthquake. Earthquake-triggered landslides are in red, and the area of greatest landslide concentration is outlined (dashed red line). Green arrow shows the predominant wind direction during the three days following the earthquake as measured by a National Weather Service anemometer in Thousand Oaks. Large blue star is mainshock epicenter; small blue stars are prominent aftershocks (adapted from Schneider et al., 1997). Area shown in Figure 9 is outlined.

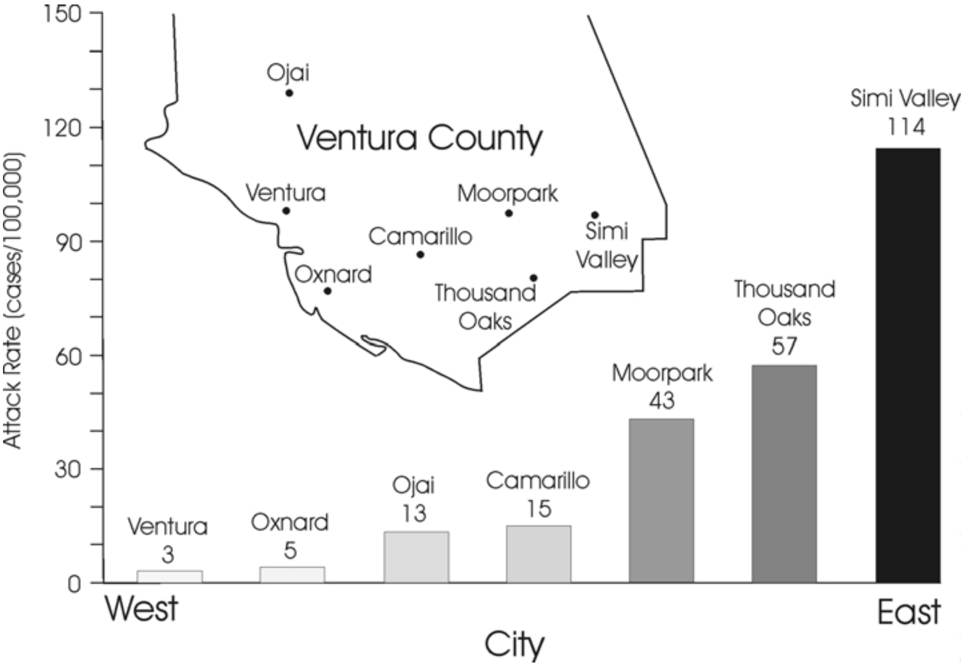

Figure 6. CM attack rate (infections per 100,000 people) by city in Ventura County (data from Schneider et al., 1997) between 24 January and 15 March 1994. Attack rate decreased markedly from East to West.

was in the census tract located closest to the mountain front (Schneider et al., 1997) and the triggered landslides.

The distribution of cases is elongated in a North East-South West direction (Figure 5). The overall pattern forms a “V” having its apex at the northern edge of the Simi Valley at the foot of the Santa Susana Mountains, and the density of cases decreases outward from the apex. As noted previously, CM is contracted almost exclusively through inhaling airborne fungal spores; therefore, this highly non-random distribution of CM cases likely resulted from a dust-generating source near the densest part of the distribution. The likely source for that dust is a dense concentration of earthquake-triggered landslides North East of the apex of the V-shaped distribution (Figure 5).

Results of the case-control study conducted by the Centers for Disease Control and Prevention (Schneider et al., 1997) showed that persons who reported being physically in a dust cloud generated by an earthquake-triggered landslide were three times more likely to be diagnosed with acute CM as those who were not in dust clouds. Among persons physically in a dust cloud, risk increased with duration of exposure. These landslides are thus the most likely source of the dust causing the densely concentrated epidemic. Validating this hypothesis requires showing that the earthquake-triggered landslides generated large amounts of airborne dust and

Figure 7. Oblique airphoto taken within a few hours of the earthquake, showing dust from earthquake-triggered landslides in the Santa Susana Mountains.

that the predominant wind direction after the earthquake would have transported the dust southwestward from the landslide area into the outbreak area.

7. Triggered landslides as a dust source

As noted previously, the Santa Susana Mountains consist of young, weak, uncemented or very weakly cemented granular sediment. In the steeply incised canyons on the flanks of the mountains, the strong shaking from the Northridge earthquake triggered abundant landslides. The landslides involved fairly shallow masses (generally 1–2 m thick) of weathered material that failed by disaggregating into individual sediment grains and cascading down the steep slopes. As documented by numerous photographs taken soon after the earthquake (Figure 7), these failures generated very dense dust clouds.

The U.S. Air Force took high-altitude (nominal scale 1:60,000) reconnaissance photos of the region about 6 h after the earthquake, and dust plumes are clearly visible in landslide areas on many of these photos (Figure 8). Likewise, sequential National Weather Service satellite images of Southern California documented earthquake-generated dust. A satellite image taken a few minutes before the 3:33 p.m. aftershock on 17 January showed no clouds present over the Santa Susana Mountains. A second image of the same area 30 minutes later (following the aftershock) showed areas of wispy clouds over the Santa Susana Mountains; these clouds were probably dust clouds because they appeared in the areas of intense landslide activity, and no nearby cloud masses are visible in the previous image that could have moved to that location during the 30-minute interval between images. If an aftershock triggered landslides that generated dust clouds visible from space, the mainshock would probably have generated much larger and more persistent dust clouds.

Even moderate-sized landslides in the weak material of the Santa Susana Mountains generated extraordinarily dense dust plumes. Persons in Simi Valley at the time of the earthquake reported that automobile drivers were using headlights while driving because of the thick dust in the air (R.A. Spiegel, Centers for Disease Control and Prevention, personal communication). Even days after the earthquake, individual landslides continued to ravel or were reactivated by aftershocks and sent thick dust plumes into the air.

No sources of significant dust related to the earthquake other than triggered landslides have been documented or reported.

8. Weather Conditions during and after the earthquake

Weather conditions at the time of the earthquake were particularly favorable for dust transport from the Santa Susana Mountains into Simi Valley, and beyond to communities to the West and South West. Little seasonal rainfall had accumulated in the region before the earthquake, and the coarse-granular surficial materials that failed were very dry. No rain fell after the earthquake for several days; thus, the dust remained dry and was easily suspended in the air.

A mild Santa Ana wind condition existed throughout the southern California region at the time of the earthquake and for the next few days. This weather pattern was characterized by moderate surface winds of 15–40 km/h blowing from the East and North East to the West and South West. Such a wind condition favored suspended-dust transport from the Santa Susana Mountains into Simi Valley. At the same time, clearing of the dust clouds from the valleys was inhibited by a mild westerly sea breeze along the coast, which caused stagnation of air in the affected valleys (Schneider et al., 1997). This weather pattern persisted through 20 January.

The arrow in Figure 5 shows the predominant wind direction at the time of the earthquake at the National Weather Service Thousand Oaks anemometer, the closest operating instrument to the densest concentration of CM cases. The wind direction aligned exactly with the elongation direction of the CM cases, and directly upwind from this cluster of outbreaks is the densest concentration of landslides on the South side of the mountain crest.

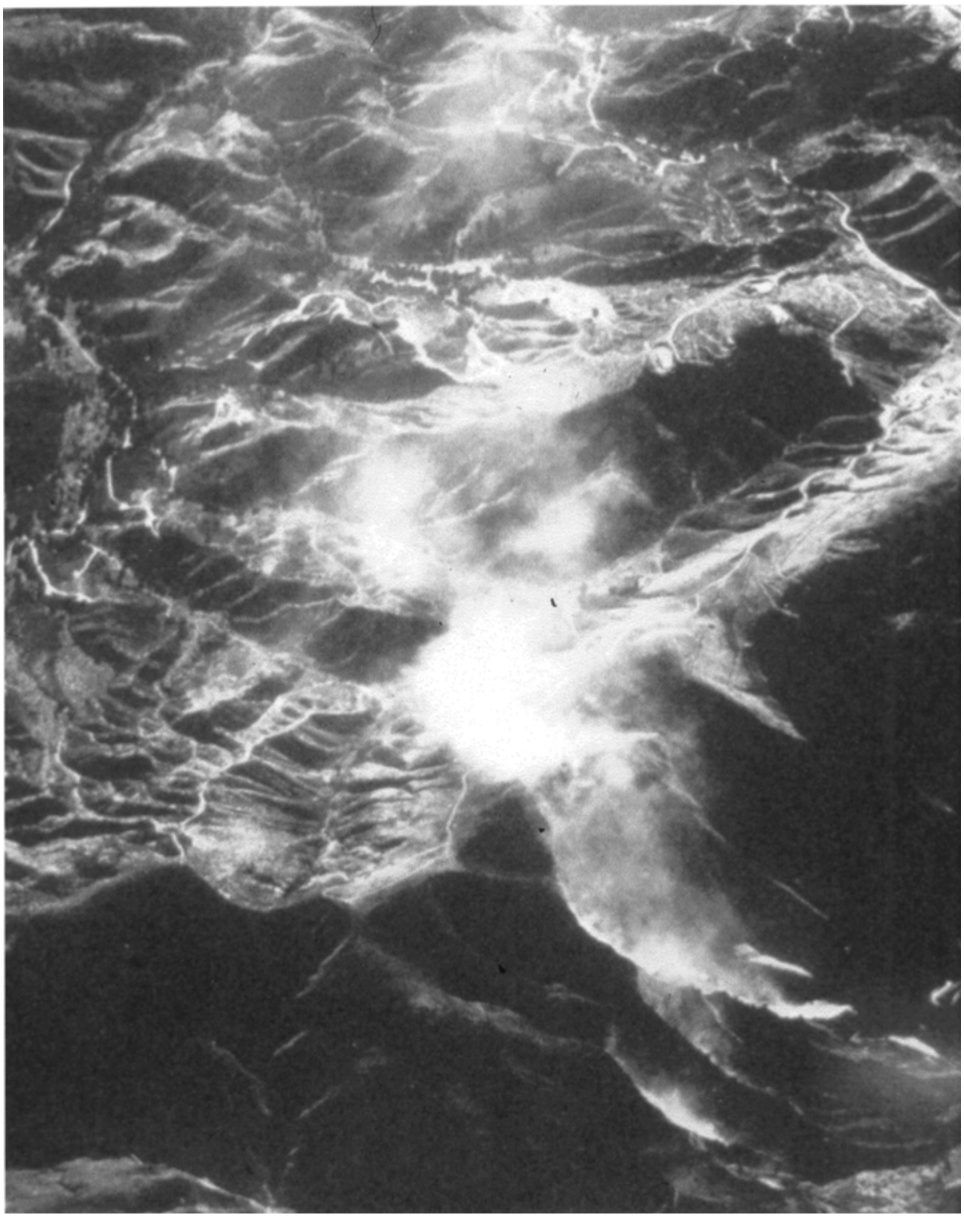

Figure 8. High-altitude U.S. Air Force photograph taken about 6 h after the earthquake, showing dust plumes from triggered landslides in the Santa Susana Mountains.

9. Discussion

The post-earthquake investigation by the Centers for Disease Control and Prevention (Schneider et al., 1997) indicated that the Ventura County CM outbreak was associated with the earthquake. This conclusion was based on (1) the epidemic curve (Figure 4); (2) the spatial distribution of outbreak-associated cases in Simi Valley; (3) the occurrence of seismically triggered, dust-generating landslides; and (4) weather conditions at the time of the earthquake. More detailed examination provides insight into how some specific geologic conditions may have affected the outbreak.

The V-shaped distribution of CM cases in Simi Valley that decreased in density away from the apex indicates a localized source for the dust containing the spores. Close examination of the map of triggered landslides (Figure 9) upwind from the CM outbreaks shows that most of the dust probably originated in Chivo and Las Llajas canyons, which extend parallel to the predominant wind direction at the time of the earthquake and the alignment of outbreaks. These canyons produced very high concentrations of disrupted landslides, and the orientation of these canyons parallel to the northeasterly winds probably enhanced airborne particulate transport into Simi Valley. The other canyons along the South flank of the Santa Susana Mountains are oriented in a more North-South direction, at an angle of about 50–60° to the wind direction. Chivo and Las Llajas canyons are arroyos incised in sandy, silty, salt-rich marine sediment, conditions that, as noted above, have been associated with enhanced *Coccidioides immitis* growth (Elconin et al., 1967; Swatek et al., 1967; Drutz and Catanzaro, 1978; Pappagianis, 1988; Einstein and Johnson, 1993).

Los Angeles County, where the earthquake was centered and where most of the damage occurred, did not experience a similar increase in CM cases following the earthquake. So why did an outbreak not occur in the more densely populated, strongly shaken San Fernando Valley? Several factors are most likely responsible. Two geologic factors include the highly variable spore concentration in surficial soils (Elconin et al., 1967; Drutz and Catanzaro, 1978; Pappagianis, 1988) and the geographic distribution of triggered landslides (Figure 5). The San Gabriel Mountains, which lie North East – upwind – of the San Fernando Valley, produced only very sparse, scattered landslides, with the exception of Pacoima Canyon. Also, the San Gabriel Mountains consist of much older and somewhat stronger rock than the Santa Susana Mountains. These rocks are primarily granitic and metamorphic, and they weather to produce thinner, coarser grained soils that are likely to produce less dust than the deep, silty soils in the Santa Susana Mountains. More importantly, soils developed on granitic rocks are highly acidic and thus far less compatible with *Coccidioides immitis* growth (Pappagianis, 1988) than the alkaline soils of the Santa Susanas. Both the much sparser landslide concentration and the very different lithology and soil chemistry of the San Gabriel Mountains might account for the absence of a similar outbreak in the San Fernando Valley.

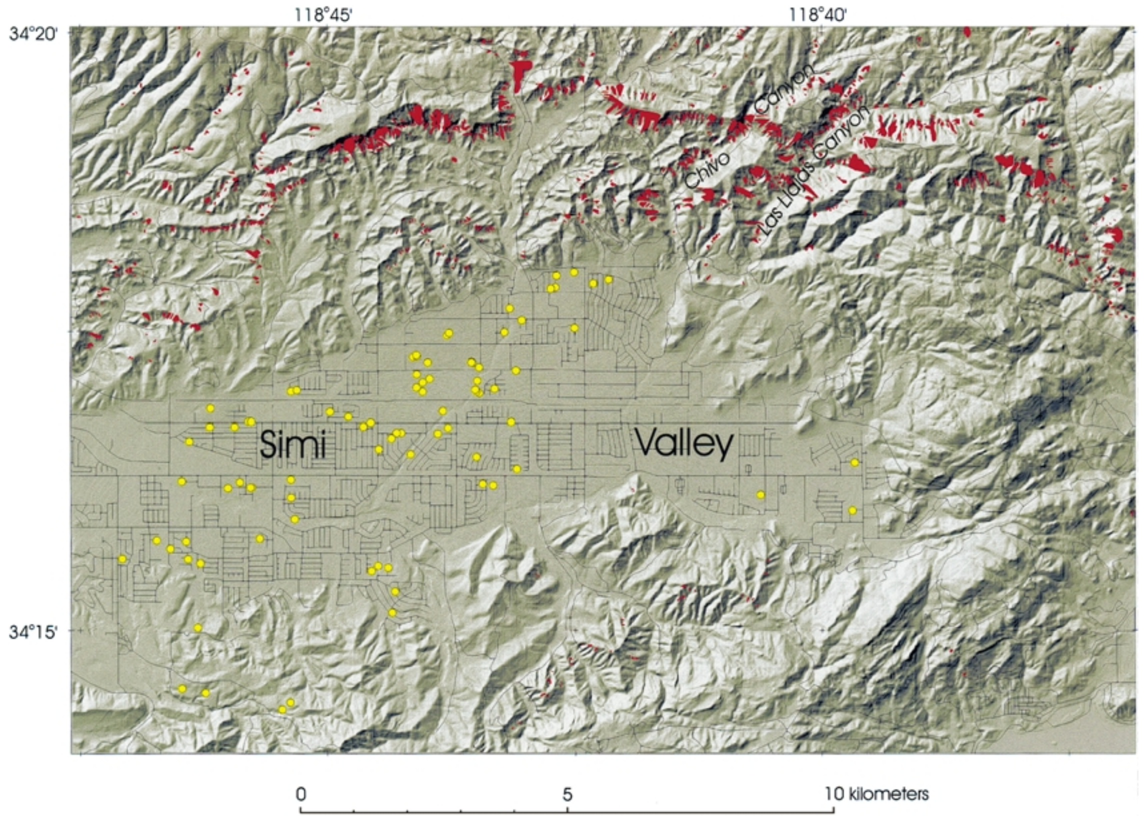

Figure 9. Map showing triggered landslides (red areas) in canyons immediately upwind of the apex of the CM concentration in Simi Valley. Chivo and Las Llajas canyons are aligned roughly parallel with the wind direction and the elongation direction of the CM distribution (yellow dots). Location shown in Figure 5.

Some measures can be taken to reduce the likelihood of contracting CM. Where dust is generated by human activities such as construction or farming, dust-control measures, including planting vegetation, wetting soil, paving dirt roads, and using face masks, have, in some instances, reduced infection rates, but the benefits of such preventive measures are temporary and incomplete (Smith et al., 1946). After a single dust-generating event such as an earthquake, instructing the public to avoid dust clouds may be beneficial in reducing exposure. Perhaps most important is educating both the general public and health-care providers regarding the risks posed by CM, ways to minimize exposure to infection, and how to recognize possible symptoms so that the disease can be rapidly diagnosed and treated. Such increased awareness of CM is particularly important for Earth scientists, who are at increased risk for infection because of occupational exposure. Earth scientists should be aware that conducting field activities in endemic areas places them at risk for contracting CM, and activities that disturb surficial materials and generate dust (such as trenching and collecting rock, soil, and fossil samples) increase risk in particular. Because initial infection confers lifelong immunity, people engaging in such work can undergo skin testing to determine if they have been infected previously or if they are at risk for initial infection.

10. Areas where earthquakes could trigger outbreaks of coccidioidomycosis

The valley-fever outbreak associated with the 1994 Northridge earthquake was the first such outbreak to be definitively associated with an earthquake (Schneider et al., 1997). Could such earthquake-related outbreaks occur in other areas?

As stated previously, CM is known to be endemic only in the western hemisphere. Figure 10 shows areas in North and South America currently known to be endemic for CM superimposed on a base (modified from Shedlock and Tanner, 1999) showing seismic shaking hazards. In addition to the southwestern United States (the area most endemic for CM), parts of northern Mexico, Guatemala, Honduras, Venezuela, Paraguay, and Argentina also are endemic. All of these endemic areas except for the easternmost area in Argentina are in regions that could be affected by seismic shaking severe enough to trigger landslides on steep slopes. Public-health and hazard-response officials in these areas should be aware of the potential for post-earthquake outbreaks to facilitate rapid diagnosis and treatment of patients who display valley-fever symptoms following earthquakes that have triggered significant landsliding.

11. Summary and Conclusions

Strong shaking from the Northridge earthquake triggered abundant landslides in the very weak slopes of the Santa Susana Mountains. These landslides generated

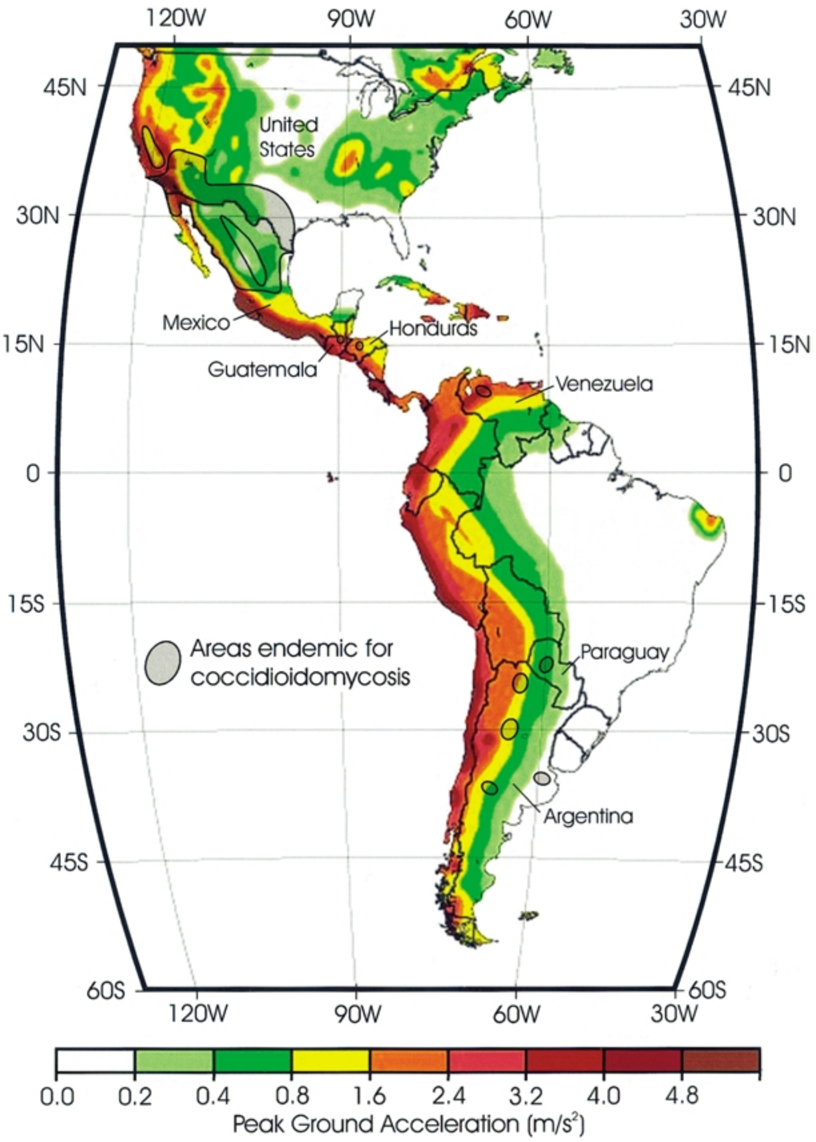

Figure 10. Areas (gray) endemic for coccidioidomycosis (modified and combined from Fisher et al., 2000; Arizona Research Laboratories, 2002; International Association of Physicians in AIDS Care, 2002). Base map shows peak ground accelerations having a 10% probability of being exceeded in 50 years (modified from Shedlock and Tanner, 1999). All endemic areas except for the easternmost area in Argentina are in regions that could experience seismic shaking sufficient to trigger landslides from steep slopes.

dense dust clouds that were transported by northeasterly winds into the Simi Valley and beyond to Thousand Oaks and other communities to the West and South. Analysis of the epidemiological data indicated a strong relationship between the earthquake, the triggered landslides, and the CM outbreak (Schneider et al., 1997). The earthquake-triggered outbreak led to three CM fatalities, which accounted for 4 percent of the total earthquake fatalities.

The results of this investigation are significant for earthquake hazard assessment and emergency preparedness in areas where CM is endemic and where landslide-generated dust clouds could occur. Such areas include the southwestern United States, northern Mexico, and parts of Guatemala, Honduras, Venezuela, Paraguay, and Argentina. Public-health officials and health-care providers in these areas must be aware of the risk factors for CM, and they should be better integrated into earthquake-preparedness planning. If such epidemics are anticipated, closer and more rapid screening of patients with CM symptoms can take place, and more rapid medical treatment may reduce the number of serious or fatal cases.

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