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Chimney Damage in the Greater Seattle Area from the Nisqually Earthquake of 28 February 2001

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Abstract Unreinforced brick chimneys in the greater Seattle area were damaged repeatedly in the Benioff zone earthquakes of 1949, 1965, and 2001. A survey of visible chimney damage after the 28 February 2001 Nisqually earthquake evaluated approximately 60,000 chimneys through block-by-block coverage of about 50 km^2, identifying a total of 1556 damaged chimneys. Chimney damage was strongly clustered in certain areas, in particular in the neighborhood of West Seattle where prior damage was also noted and evaluated after the 1965 earthquake. Our results showed that damage produced by the 2001 earthquake did not obviously correspond to distance from the earthquake epicenter, soft soils, topography, or slope orientation. Chimney damage correlates well to instrumented strong-motion measurements and compiled resident-reported ground-shaking intensities, but it offers much finer spatial resolution than these other data sources. In general, most areas of greatest chimney damage coincide with best estimated locations of strands of the Seattle fault zone. The edge of that zone also coincides with areas where chimney damage dropped abruptly over only one or two blocks' distance. The association between shaking intensity and fault-zone structure suggests that abrupt changes in the depth to bedrock, edge effects at the margin of the Seattle basin, or localized trapping of seismic waves in the Seattle fault zone may be significant contributory factors in the distribution of chimney damage.

Introduction

In many parts of the United States, unreinforced brick chimneys are abundant, widely distributed, and readily damaged in moderate earthquakes. Although differences in chimney age and construction affect their response to seismic shaking, they have been recognized historically as useful indicators of ground-shaking intensity, in particular for moderate earthquakes in neighborhoods where alternative methods of characterizing intensity may be limited (e.g., Dengler and McPherson, 1993). The Modified Mercalli intensity (MMI) scale (Wood and Neumann, 1931) uses chimney damage to characterize several levels of shaking intensity (e.g., excerpted from Bolt, 1988):

- MMI VI (average peak acceleration, 0.06–0.07 g): Slight damage to masonry D (lowest, weakest category of masonry). Some plaster cracks or falls. Isolated cases of chimney damage.
- MMI VII (0.10–0.15 g): Masonry D cracked and damaged. A few instances of damage to Masonry C ("ordinary" masonry). Loose brickwork dislodged. Unbraced parapets and architectural ornaments may fall. Weak chimneys break.
- MMI VIII (0.25–0.30 g): Masonry C damaged, with partial collapse. Masonry B (reinforced and of good workmanship) damaged in some cases. Chimneys, factory stacks brought down. Some brick veneers damaged.

Unreinforced brick chimneys, characteristic of early- to mid-twentieth century housing in the greater Seattle area, were damaged repeatedly by the Benioff zone earthquakes of 1949, 1965, and 2001. After the 1965 event, earth scientists made detailed surveys of chimney damage in the West Seattle neighborhood of the City of Seattle (Algermissen and Harding, 1965; Mullineaux *et al.*, 1967). The extensive damage in West Seattle was puzzling, given its upland location on consolidated glacial deposits and the apparent lack of soft soils or ground failure that might contribute to ground shaking.

During the 2001 Nisqually earthquake, described more fully in the next section, West Seattle again suffered significant localized chimney damage, apparently similar to that recorded in 1965. After the earthquake, we rapidly surveyed chimney-damage patterns in West Seattle and other similar neighborhoods in the greater Seattle area. Our objective was to compare the observed damage patterns with the measured ground accelerations for the 2001 earthquake, to compare our rapid surveys with damage reported to disaster-relief agencies by homeowners, to compare our results with 1965 damage in West Seattle, and to seek possible correlations between repeated chimney damage and geologic structure along the southern margin of the Seattle basin. We focused on peak ground accelerations (PGAs) for reasons of simplicity and data availability, although more sophisticated analyses using spectral values might have produced even stronger correlations. In this article, we present evidence that the spatial patterns of chimney damage in 1965 and 2001 were similar, and we suggest that the damage pattern may be related in part to edge effects along the southern margin of the Seattle basin (Johnson *et al.*, 1994), along the trace of the Seattle fault zone.

The Nisqually Earthquake and Its Geologic Setting

The Nisqually earthquake ($M_w = 6.8$) occurred at 10:54 a.m. local time on Wednesday, 28 February 2001. It occurred about 20 km northeast of Olympia, Washington (Fig. 1) at a hypocentral depth of 52 km, within the eastward-dipping Benioff zone of the subducted Juan de Fuca plate. The event ruptured a nearly north–south striking normal fault, implying down-dip extension within the subducted plate.

The earthquake caused moderate ground shaking throughout western Washington. In the central Puget Lowland, the median peak horizontal ground acceleration was 0.11 g, and only 2 of 51 stations recorded values greater than 25% of gravity (Table 1 and Fig. 2). The same broad patterns of ground motion indicated by the instrumental record (Fig. 3a) were also observed in the distribution of liquefaction and landslides (Troost *et al.*, 2001), which showed effects concentrated just south of the epicenter in the Olympia area and in the Duwamish River valley south of downtown Seattle. Normally consolidated late-glacial deposits, modern river alluvium, or fill underlay these areas. Areas of liquefiable soils that did not display evidence of ground failure, notably the Port of Tacoma, also had quite low instrumented ground motion (station TBPA; see Table 1).

Modified Mercalli intensities in the Puget Lowland displayed broad spatial patterns constrained by the limited availability of reported observations (Dewey *et al.*, 2002) (Fig. 3b). Most of Seattle, from the northern edge of downtown south to the city limits, experienced intensity VII, with a narrow band of VII to VIII extending along the lower valley of the Duwamish River. Broad areas of intensity VI

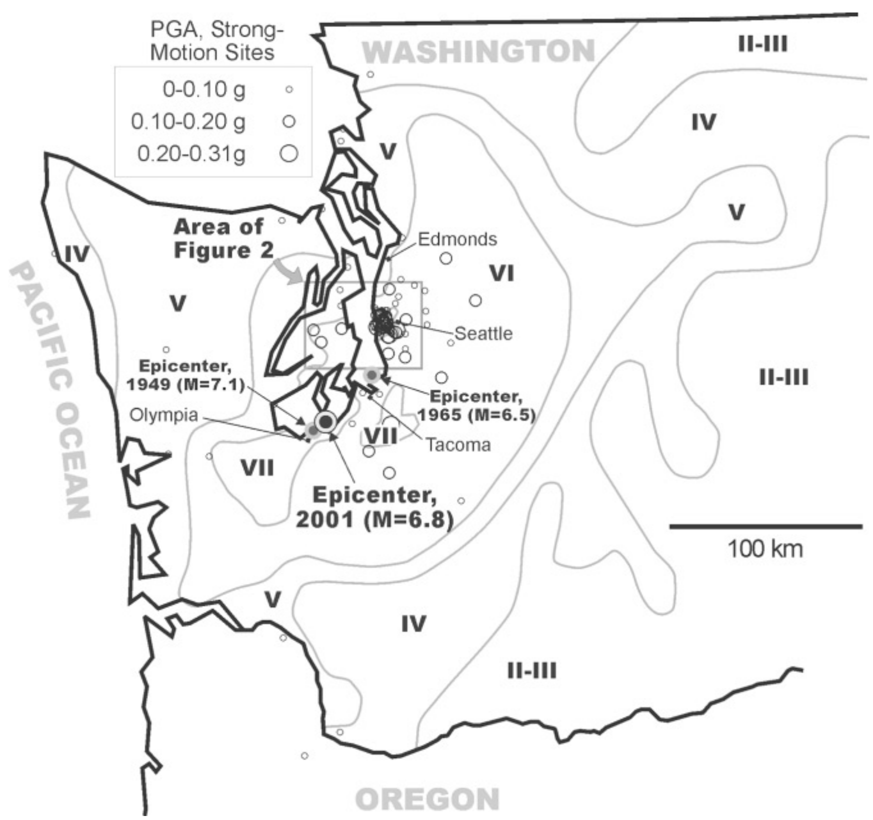


Figure 1. Index map of epicenters from the 1949 (Olympia), 1965 (Tacoma), and 2001 (Nisqually) earthquakes; contours of Modified Mercalli intensities reported by community surveys (Dewey *et al.*, 2002); strong-motion instrument sites plotted from data compiled in Table 1.

Table 1
List of Strong-Motion Sites

Station	Latitude (°N)	Longitude (°W)	Peak Acceleration (% of g)	
720	47.655	− 122.322	7.30	*
727	47.548	− 122.277	7.81	*
1416	47.584	− 122.383	15.20	*
2147	47.665	− 122.397	6.40	*
2194	47.214	− 123.101	9.97	
7026	48.243	− 122.455	7.47	
7027	47.548	− 122.277	7.36	*
7028	47.913	− 124.635	1.91	
7029	48.134	− 122.766	5.67	
7030	47.450	− 122.302	19.77	*
7031	47.997	− 122.199	3.82	
7032	47.584	− 122.383	16.18	*
7033	48.512	− 122.613	2.67	
7034	47.569	− 122.628	18.72	*
7035	46.972	− 123.826	8.29	
7039	47.468	− 123.847	1.83	
7040	47.856	− 122.584	4.97	
ALCT	47.647	− 122.038	4.31	
ALK	47.575	− 122.418	4.47	*
ALO	47.627	− 122.314	10.30	*
ALST	46.109	− 123.033	7.57	
BHD	47.586	− 122.316	16.30	*
BOE	47.524	− 122.300	18.90	*
BRI	47.548	− 122.283	9.10	*
BRKS	47.755	− 122.288	10.40	*
CRO	47.637	− 122.351	11.70	*
CSEN	47.800	− 122.210	3.87	
CTR	47.621	− 122.351	7.70	*
EARN	47.741	− 122.044	6.94	
ELW	47.494	− 121.871	5.63	
ERW	48.454	− 122.625	0.95	
EVA	47.656	− 122.351	5.50	*
FINN	47.720	− 122.232	6.09	*
GNW	47.564	− 122.825	15.92	*
HAL	47.642	− 122.362	7.70	*
HAR	47.584	− 122.350	21.70	*
HIG	47.629	− 122.364	13.00	*
HOLY	47.565	− 122.384	9.54	*
KDK	47.595	− 122.334	18.80	*
KEEL	45.550	− 122.895	1.44	
KIMB	47.575	− 122.302	13.54	*
KIMR	47.503	− 122.767	16.30	*
KINR	47.752	− 122.643	7.55	*
KITP	47.675	− 122.630	4.93	*
LAP	47.639	− 122.351	10.20	*
LAWT	47.657	− 122.389	10.48	*
LEOT	47.768	− 122.116	7.55	*
LON	46.750	− 121.810	3.75	
MAR	47.605	− 122.334	12.80	*
MBPA	47.899	− 121.889	15.46	
MPL	47.469	− 122.185	9.77	*
MURR	47.120	− 122.560	6.91	
NOR	47.601	− 122.332	21.80	*
NOWS	47.687	− 122.256	8.77	*
PCEP	47.112	− 122.290	21.35	
PCFR	46.990	− 122.441	13.10	
PCMD	46.889	− 122.300	15.78	
PIE	47.633	− 122.380	12.90	*
PNLK	47.582	− 122.034	6.30	
QAW	47.632	− 122.354	11.39	*
RAW	47.337	− 121.931	17.26	
RBEN	47.435	− 122.186	10.98	*
RHAZ	47.540	− 122.184	4.54	*
ROSS	45.662	− 122.657	2.54	
RWW	46.965	− 123.542	7.53	
SBES	48.768	− 122.415	0.63	
SDN	47.586	− 122.332	18.80	*
SDS	47.583	− 122.332	21.40	*
SDW	47.584	− 122.333	22.10	*
SEA	47.654	− 122.308	7.06	*
SEU	47.608	− 122.318	9.80	*
SEW	47.550	− 122.250	16.90	*
SP2	47.556	− 122.248	30.76	*
SQM	48.078	− 123.046	3.82	
TBPA	47.258	− 122.367	6.49	
THO	47.621	− 122.319	11.60	*
TKCO	47.537	− 122.300	27.21	*
TTW	47.695	− 121.689	11.18	
UNK	47.610	− 122.334	13.00	*
UPS	47.264	− 122.484	6.08	
WEK	47.575	− 122.384	22.60	*
WISC	47.609	− 122.174	11.35	*

Data sources include the Pacific Northwest Seismograph Network (http://www.ess.washington.edu/SEIS/PNSN/welcome.html) and the U.S. Geological Survey Seattle Urban Hazards Seismic Array (Carver *et al.*, 2001; Frankel *et al.*, 2002).
*Stations that are displayed in the area of Figure 3.

and VII characterize the more sparsely populated Kitsap Peninsula and areas adjacent to Lake Washington. Earthquake damage in older unreinforced masonry buildings, wood-frame structures, and some concrete structures occurred primarily in the cities of Olympia, Seattle, Bremerton, and at SeaTac Airport 20 km south of downtown Seattle (Nisqually Earthquake Clearinghouse Group, 2001).

Although the Nisqually earthquake occurred deep in the subducting Juan de Fuca plate, the crust of the overriding North America plate also influenced ground response. In this upper plate, a prominent structure is the Seattle fault, which extends across the Puget Lowland to the Cascade Range foothills through the cities of Bremerton, Bainbridge Island, west and central Seattle, and northern Mercer Island. It consists of several strands, forming a zone about 5 km wide recognized in both seismic-reflection and geologic data (Yount and Gower, 1991; Johnson *et al.*, 1999; Blakely *et al.*, 2002; Troost *et al.*, in press) and produced late-Holocene surface rupture (see Bucknam *et al.*, 1992; Nelson *et al.*, 2002). Within 5–10 km of the ground surface, the fault likely has a moderate dip of 40–50° to the south with a reverse sense of motion (Pratt *et al.*, 1997; Johnson *et al.*, 1999; Brocher *et al.*, 2001; ten Brink *et al.*, 2002). The fault zone separates the 10-km-deep Seattle basin to the north from the Seattle uplift to the south (Johnson *et al.*, 1994). The Quaternary basin fill, north of the fault, reaches depths of at least

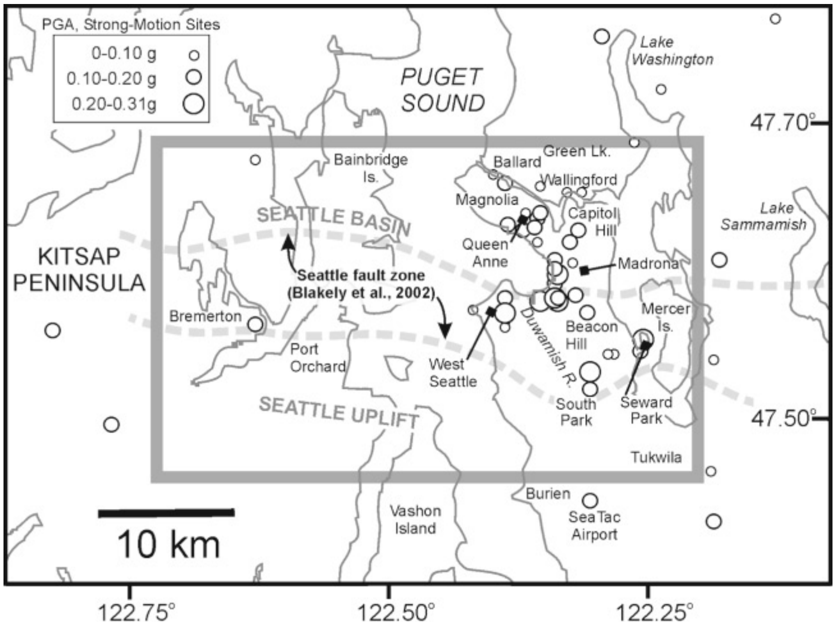


Figure 2. Index map of study area (inner box) and strong-motion instrument sites (Table 1). The Seattle fault zone separates the structurally low Seattle basin (north) from the Seattle uplift (south).

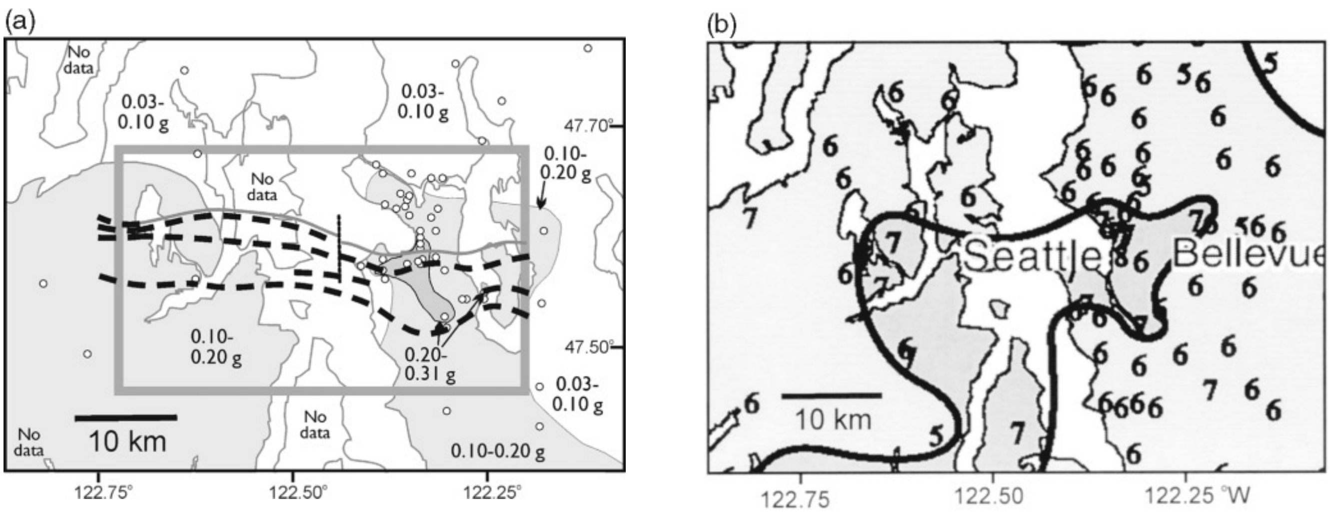


Figure 3. (a) Contoured peak horizontal ground accelerations from the strong-motion instruments of Table 1 (small dots). Zones of equivalent ground acceleration (0.10–0.20 g and 0.20–0.31 g) are indicated by shading. Location of the mapped strands (dashed) and deformation front (solid) of the Seattle fault from Blakely *et al.* (2002). (b) Contoured Modified Mercalli intensities from community damage reports (Dewey *et al.*, 2002) over the same area as for Figure 3a. MMI values are compiled by zip code and displayed at the geometric center of each zip-code area, independent of actual damage locations.

1000 m (Jones, 1996). In contrast, the Quaternary cover to the south is typically just a few hundred meters thick, and Eocene and Oligocene sedimentary and volcanic rocks are locally exposed at the ground surface (Yount and Gower, 1991; Troost *et al.*, in press).

Overlying the faulted and folded Tertiary strata is a thick sequence of Pleistocene glacial and nonglacial deposits forming north–south ridges and troughs, the result of glacial scouring and subglacial water erosion. Across the central Puget Lowland, the ridges are generally composed of basal till overlying sand and gravel, all overconsolidated from the load imposed by the most recent advance of a 1000-m-thick ice sheet, the Puget lobe of the Cordilleran ice sheet (Booth *et al.*, 2003a). Intervening troughs commonly contain normally consolidated river and lake deposits from recessional and postglacial times (Booth, 1987). Alluvial sediment, predominantly sand, fills the major river valleys; Holocene deltas have extended from the mouths of all of the major river valleys into Puget Sound. Commercial and industrial activity on these deltas in both Seattle and Tacoma has resulted in large areas of intensive development on loose, saturated soil deposits; correspondingly, little residential construction is located in most of these areas.

Study Methods

The brick chimneys typical of the mid-twentieth century housing in the Seattle area form a crude, but broadly distributed, seismometer array. We attempted to "read" that array with a rapid Global Positioning Satellite (GPS) survey of visible chimney damage, initiated in West Seattle 3 days after the Nisqually earthquake. Piqued by an apparent concentration of damage along the recently defined trace of the Seattle fault in West Seattle, we expanded this initial survey both east–west and north–south to determine whether similar patterns of damage could be documented elsewhere. Additional neighborhoods surveyed included West Seattle, Beacon Hill, Madrona, Capital Hill, Queen Anne, Wallingford, and Ballard and parts of the cities of Mercer Island, Bremerton, Port Orchard, Burien, Seatac, and Tukwila (see Fig. 2). In the 3 weeks after the earthquake, five teams evaluated approximately 60,000 chimneys through block-by-block coverage of about 50 km^2 across a region 30 km by 50 km in lateral extent. Throughout these areas, brick chimneys are ubiquitous and housing densities vary little, ranging from a minimum of 14 houses/ha (Madrona neighborhood) to a maximum of 18 houses/ha (Wallingford and Green Lake) based on orthophoto analysis and building-outline GIS data from the City of Seattle.

We made no attempt to comprehensively delineate damaged chimneys. Instead, we wanted only a methodology that would yield equivalent results for equivalent levels of damage across a wide area using multiple field observers and that would produce those results with enough efficiency that a large area could be covered in the days immediately post-earthquake before reconstruction began in earnest. At the time of the survey, it was unclear whether any independent measures of earthquake damage, such as geocoded damage data compiled from homeowner's reports by the Federal Emergency Management Agency (FEMA), would become available to researchers.

Damaged chimneys were counted from the street by observers with binoculars on both sides of a slow-moving automobile and logged into a GPS receiver, with a typical estimated precision of about 10–15 m (city blocks in these neighborhoods are typically 150–200 m long). We did not interview homeowners or evaluate hidden damage. Observed chimney damage was divided into three classes:

1. Small cracks: cracks or displacements <2 cm, along the mortar joints or in separation from the house; chimney cap or one to two bricks from top course dislodged (Fig. 4a).
2. Large cracks/partial collapse: crack openings >2 cm cutting through the entire chimney; may involve significant rotation/translation of upper part; also includes partial collapse, with a majority of the chimney intact above the roofline (Fig. 4b).
3. Chimney destroyed above roofline: may also involve entire chimney, commonly with damage to adjacent houses (Fig. 4c).

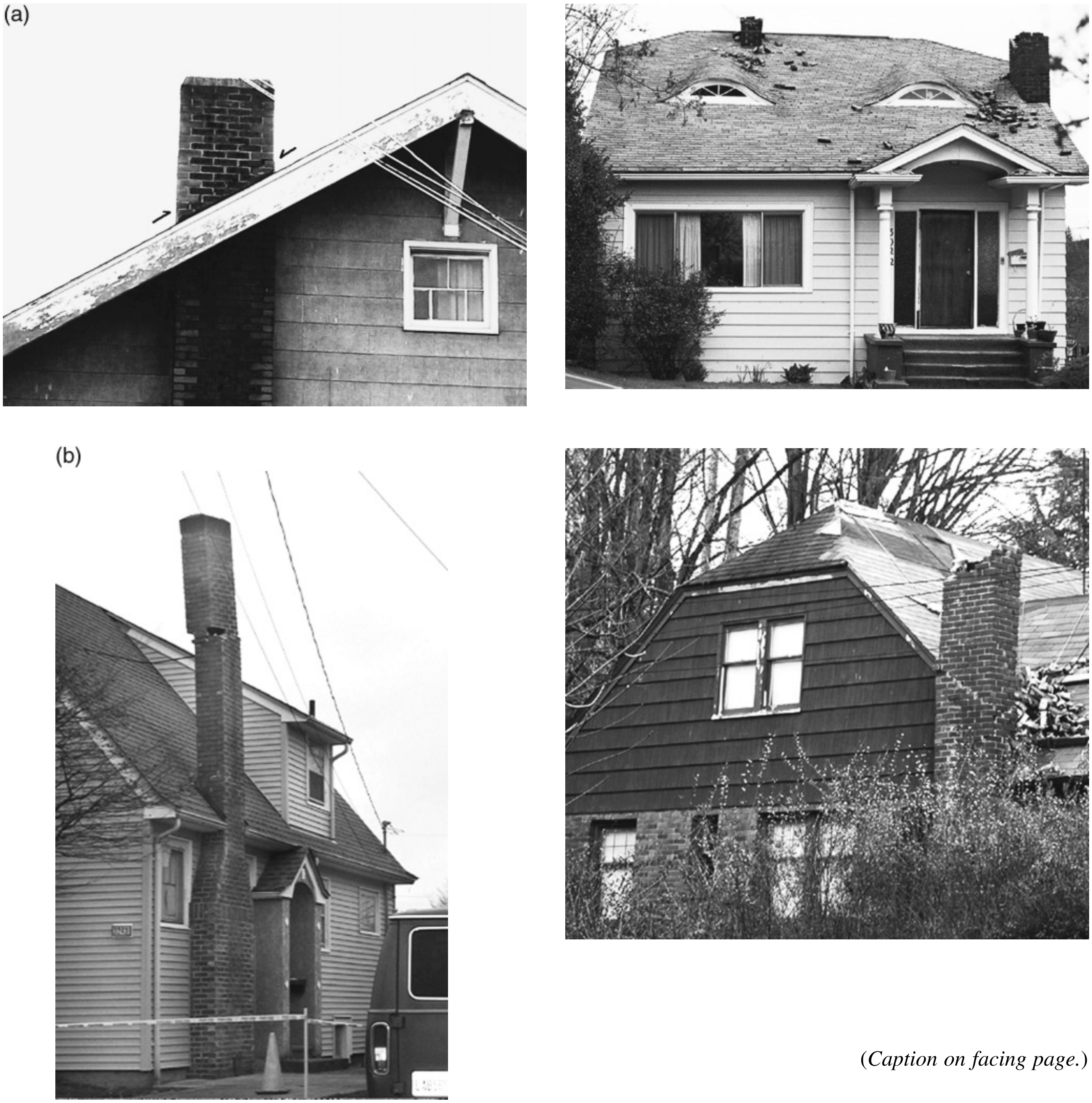
Nonrated damage included observations of discontinuous hairline cracks in mortar, a single brick missing from top course of chimney without evidence of recent loss (e.g., a nearby fallen brick), or simply a skewed clay chimney cap.

Results

In the study area, 1556 damaged chimneys were recorded (Table 2). Their locations are shown in Figure 5a, and the damage as a percentage of the housing stock is shown in Figure 5b. More than half of the area surveyed showed no damage at all; much of the balance had only widely distributed and relatively mild damage (i.e., class 1 and only a few class 2s or 3s). We did not systematically evaluate individual or neighborhood differences in chimney age or quality, although those surely exist; instead, we relied on the sheer numbers of observations to indicate whether damage tended to be uniformly distributed or locally clustered, and we confined most of our observations to neighborhoods of similar housing style and age. Chimney damage was greatest in West Seattle, with other noteworthy zones in the neighborhoods of Madrona, south Green Lake, and Bremerton. The overall patterns of damage are quite similar in spatial distribution to the generalized FEMA results that were subsequently made available to us (Fig. 5c), although greater numbers of damaged chimneys in the FEMA data suggest that significant hidden damage was reported to them by homeowners. We also compared our results with those of the U.S. Geological Survey's Community Internet Intensity Map (Fig. 5d), which also showed very good overall correspondence.

These results are also consistent with a compilation of chimney damage from ten earthquakes in New Zealand compiled by Dowrick (1996) that compared independent measures of Modified Mercalli intensity with the number of chimneys that "fell" (his term; equivalent to class 3 of this study). Dowrick found an average of less than 1% fallen chimneys in areas of MMI VI (the typical value across the area of our survey) and between 2% and 20% (mean of 8%) fallen chimneys in areas of MMI VII, values that correspond to both reported intensities and the range of class 3 chimney damage expressed by our data.

Variations in epicentral distance, housing type, chimney maintenance, or age cannot explain all the observed clusters of damage, although these factors may be locally important. Epicentral distances across the survey area range from 45 km (Burien and south Port Orchard) to 65 km (Green Lake neighborhood and north Bremerton), but there is no corre-



(*Caption on facing page.*)

spondence between these distances and the level of damage (see Fig. 5a). Houses on Mercer Island differ from our other surveyed neighborhoods, for example, in being generally less than 30 years old and favoring a massive, blocky architectural style of chimney that provides little indication of whether ground shaking differed across the island. The high density of chimney damage in the Madrona neighborhood may also be explained in part by variations in chimney construction (see Fig. 5d). Most of the neighborhood surveys, however, were conducted in areas where the housing stock is generally 60 to 90 years old. Widespread damage in West Seattle is reminiscent of that reported in the 1965 earthquake, but qualitatively there was less expression of ground shaking in the 2001 Nisqually earthquake relative to reports of the 1965 event, both by chimney damage and by overall building damage (see also Haugerud *et al.*, 2001).

Transitions, commonly quite narrow, between areas of high and low chimney damage within the same age and character of neighborhood are evident in West Seattle and Bremerton, making chimney design or construction implausible determining factors. In West Seattle, the most intense zone of multiblock damage (over 30% of chimneys affected) changes to under 10% affected over just a few hundred meters both to the north and south (Fig. 6) without correspond-

(c)

Figure 4. (a) Examples of class 1 chimney damage (the right-hand image also shows a class 2 damaged chimney on the right side of the house). (b) Examples of class 2 chimney damage. (c) Examples of class 3 chimney damage.

Table 2
Observed Chimney Damage Totals

Damage Class	Chimneys, *n*	Damage, %
1 (minor cracking)	1030	66
2 (significant damage)	416	27
3 (total failure)	110	7
Total	1556	

The number of damaged chimneys represents about 2.5% of the total number surveyed.

ing change in neighborhood character or age. In Bremerton, typical damage levels show maxima of 10–15% per block; here as well, a transition to damage zones of 1% or less occurs over distances of only a block or two. Figure 7 shows the distribution of chimney damage in Bremerton, plotting those sites identified by our survey and also those as reported by individual homeowners to Kitsap County Emergency Management. Although the data sets show almost no correspondence on a block-to-block scale, they display a very similar overall pattern of damage, in particular the abrupt northerly reduction in damage in East Bremerton (i.e., east of station 7034).

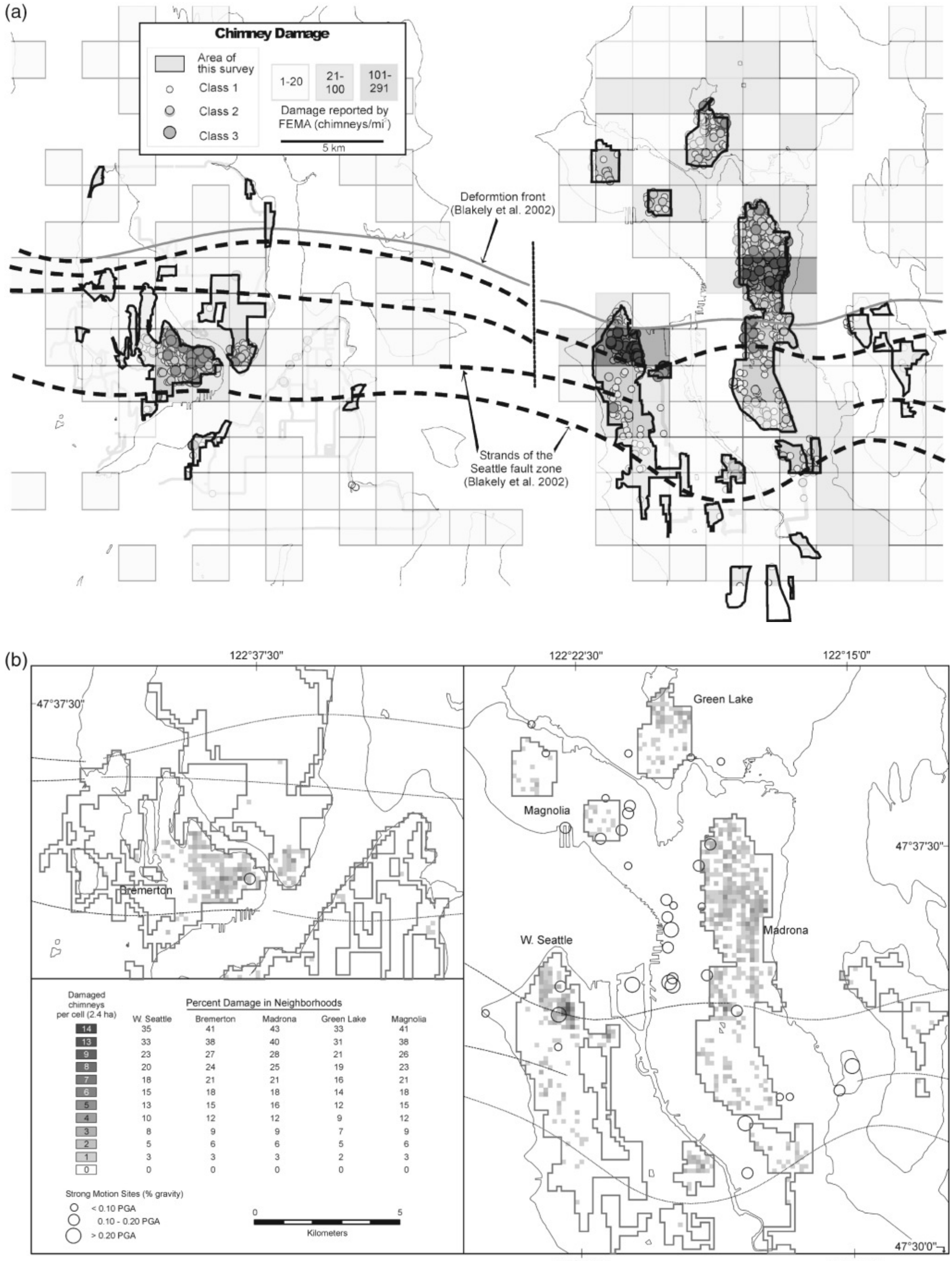
Other local pockets of a few blocks' extent with relatively high levels of chimney damage (15–30%) were identified in Madrona, Beacon Hill, and Green Lake. They are not as laterally extensive as zones in West Seattle and Bremerton, but they also display a sharp transition from relatively high to low levels of damage that cannot be explained by mapped surficial geology, building age or condition, or the limits of our survey.

Several areas display diffuse patterns of chimney-damage intensities that vary from 0% to 10% over a broad area. The most prominent is on Beacon Hill, with a zone extending some 5 km to the south over which the occurrence of damage declines only gradually to low levels. Such a pattern is also repeated farther west, in a region within the Seattle fault zone lying south of the high-intensity zone of West Seattle (Fig. 5a and b).

Discussion

Comparison with Instrumented Ground Motion

On a regional scale, the largest recorded ground motions (>0.20 g) were located in a zone centered over central and southeast Seattle (Fig. 3a), which crudely follows the trend of the Holocene alluvium and artificial fill of the Duwamish River valley. Other aspects of this zone, in particular, its suggested east–west elongation into West Seattle and onto Seward Park, cannot be resolved with the paucity of strong-motion stations. The instrument record of peak ground accelerations shows no evidence of enhanced shaking over the Seattle basin as a whole, consistent with an observed lack of amplification from a subsequent distant-source earthquake (Barberopoulou *et al.*, 2002). It is also consistent with the lack of amplification of 2–8 Hz frequencies, although


(a)
Chimney Damage
Area of this survey
Class 1
Class 2
Class 3
1-20
21-100
101-291
Damage reported by FEMA (chimneys/mi²)
5 km
Deformtion front (Blakely et al. 2002)
Strands of the Seattle fault zone (Blakely et al. 2002)
(b)
122°37'30"
47°37'30"
122°22'30"
122°15'0"
Green Lake
Magnolia
47°37'30"
Bremerton
Madrona
W. Seattle
47°30'0"
Damaged chimneys per cell (2.4 ha)
Percent Damage in Neighborhoods
W. Seattle Bremerton Madrona Green Lake Magnolia
14 35 41 43 33 41
13 33 38 40 31 38
9 23 27 28 21 26
8 20 24 25 19 23
7 18 21 21 16 21
6 15 18 18 14 18
5 13 15 16 12 15
4 10 12 12 9 12
3 8 9 9 7 9
2 5 6 6 5 6
1 3 3 3 2 3
0 0 0 0 0 0
Strong Motion Sites (% gravity)
< 0.10 PGA
0.10 - 0.20 PGA
> 0.20 PGA
0
5
Kilometers
122°22'30"
122°15'0"

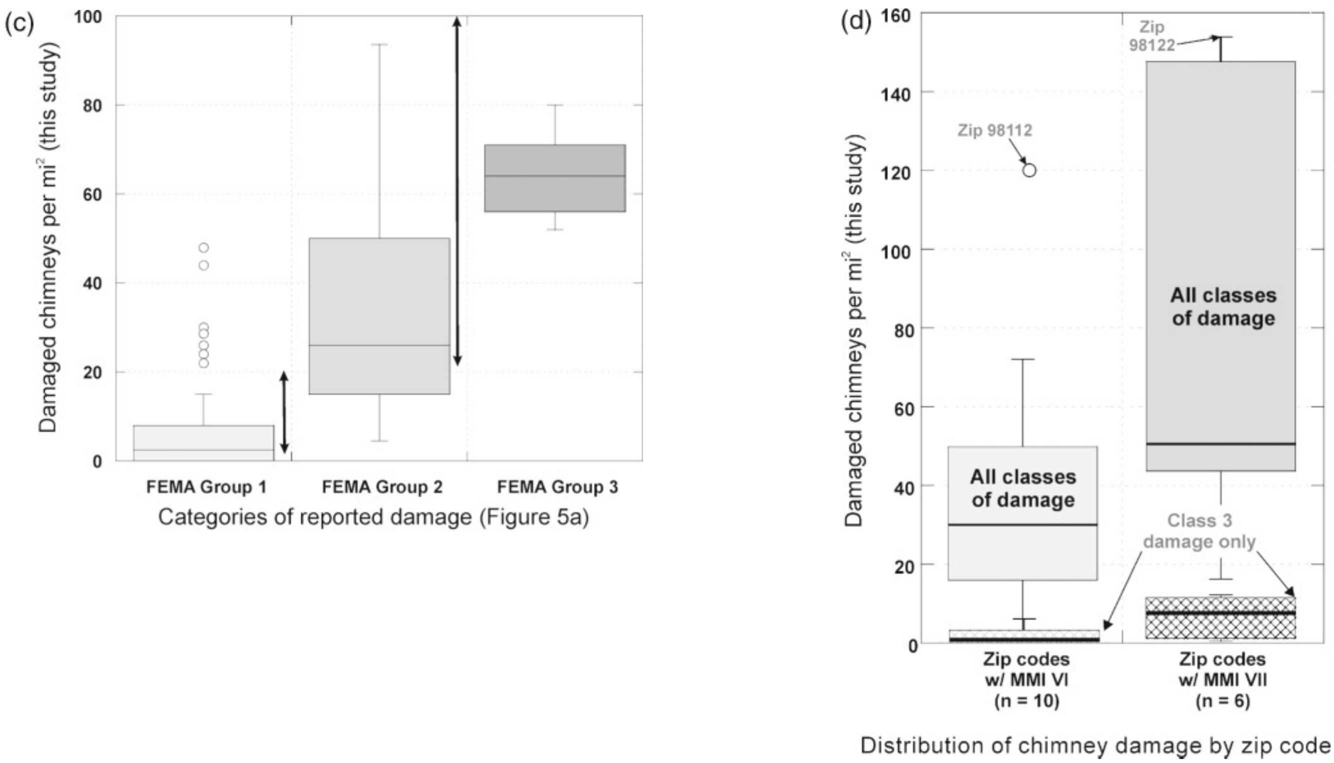


Figure 5. (a) Full survey area and distribution of damaged chimneys. Location of the mapped strands of the Seattle fault from Blakely *et al.* (2002). Shaded squares are 1.6 km (1 mile) on a side and represent the aggregated tally of claims for damaged chimneys made to FEMA as a result of the Nisqually earthquake (J. Toland, FEMA, written commun., 2003). (b) Chimney damage in the Bremerton (left) and West Seattle (right) areas, displayed as a percentage of housing stock in our survey area (outlined). Each grid cell is 155 m on a side, the average long dimension of a residential block here, with a cell area of 2.4 hectares. The number of houses per grid cell varies by neighborhood owing to modest differences in lot size. Faults (dotted lines) are from Blakely *et al.* (2002). (c) Box plots of the number of damaged chimneys observed in this study, grouped by the one-square-mile FEMA damage areas of Figure 5a and normalized by area surveyed. Top and bottom of each box mark the limits of $\pm 25\%$ of the data; median value is displayed as a line. The lines extending from the top and bottom of each box mark minimum and maximum values of the data set, with statistical outliers displayed as individual points. Heavy vertical arrows show the range of each FEMA damage group: 1–20 reported chimneys per square mile, 21–100, and 101–291 per square mile (outside of graph range). Both data sets show excellent correspondence in spatial trends, with the best correlation for areas low to moderate damage. In areas of severe damage, however, the visual survey significantly underestimates reported damage by factors of 2 to 4. (d) Box plot of damaged chimneys per square mile surveyed, tallied by zip codes and grouped by the zip code's reported Modified Mercalli intensity from the Community Internet Intensity Map (http://pasadena.wr.usgs.gov/shake/pnw/index.html). Chimney damage is included here for all zip codes where at least 10% of the area was surveyed; both combined damage classes and class 3 (total chimney collapse) are displayed. Outlier (zip code 98112), in the north part of the Madrona area, has a lower MMI and significantly less chimney damage density than its zip-code neighbor (98122) immediately south (VI vs. VII and 120 vs. 154 damaged chimneys per square mile) but a regionally higher density for its reported intensity that suggests either great spatial variability in ground shaking across the zip code (only one-third of which was surveyed) or a neighborhood of generally weaker chimneys. Box plot representation as for Figure 5c.

not with amplification of 0.5–1 Hz frequencies, determined from the detailed instrument record of the Nisqually earthquake (Frankel *et al.*, 2002).

Although only about half of the 51 strong-motion seismometers in our study area were located near residential neighborhoods (and only 10 within the chimney-survey area itself), recorded ground shaking corresponds well with chimney damage in those areas where the two data sets can be compared directly. Along with general trends (Fig. 8), specific neighborhoods display this relationship. In West Seattle, two stations record an abrupt north–south transition from some of the strongest recorded ground shaking in the study area (0.23 g at WEK) to a much more modest level (0.10 g at HOLY), a transition also recorded by an equivalent reduction in chimney damage levels (Fig. 6). In Bremerton, the one station (7034) there recorded a peak acceleration of 0.19 g, corresponding to MMI VII (Bolt, 1988) whose description includes "a few instances of damage to 'ordinary' masonry; loose brickwork dislodged; weak chimneys break." Our observed chimney damage corresponds well to

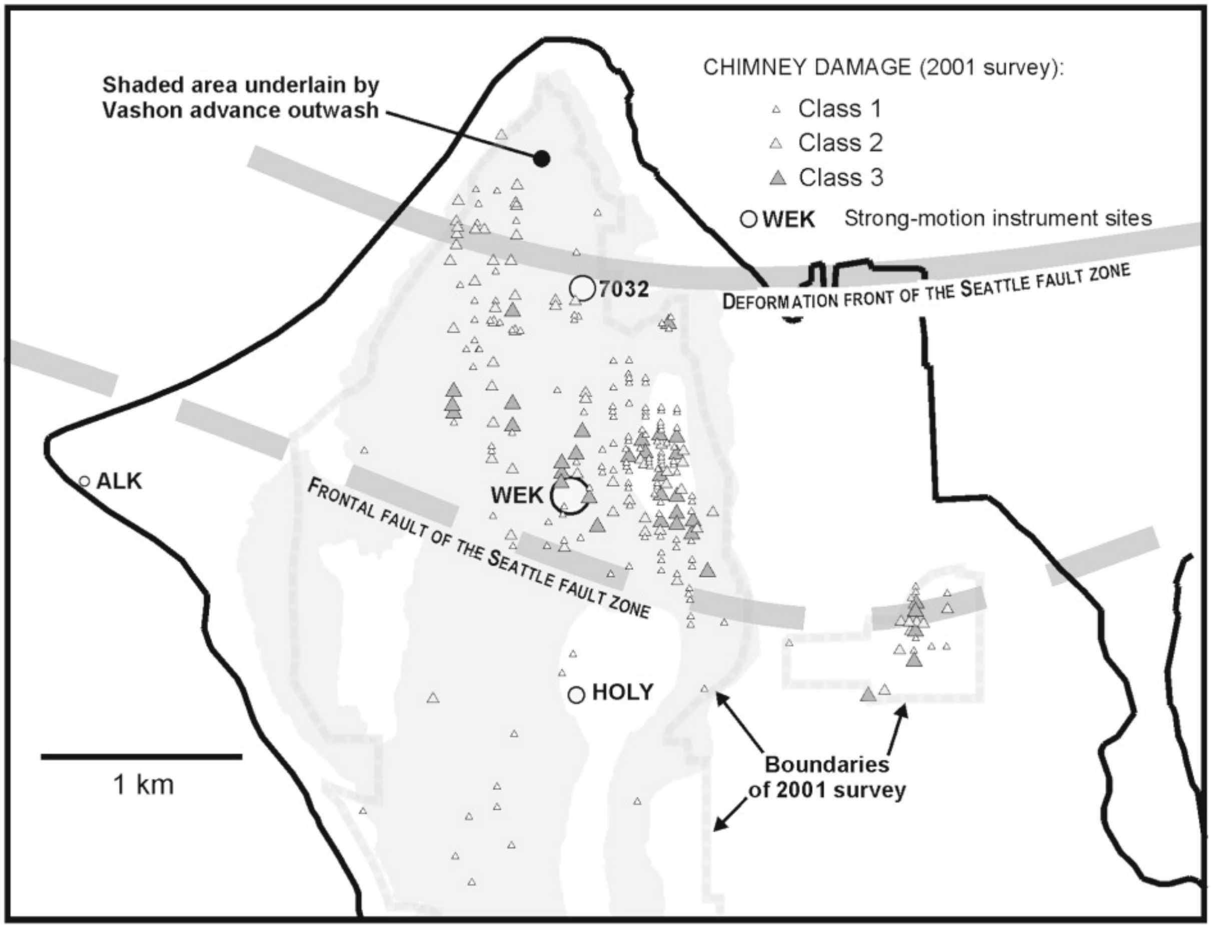


Figure 6. Observed chimney damage in West Seattle (this study). The largest recorded PGA in this area (at WEK) was 0.23 g; other values were 0.16 g at Station 7032, 0.10 g at HOLY, and 0.04 at ALK. The overconsolidated advance outwash sand of the most recent ("Vashon") glacial advance is denoted by shading; unshaded areas within the survey boundary are underlain by overconsolidated basal till from the same glacial period (Troost *et al.*, in press). Part of the high-damage area corresponds to one of the areas of till, but damage patterns more closely mirror the pattern of instrumented ground shaking and follow the trend of the Seattle fault zone (as mapped by Blakely *et al.*, 2002).

this description, with 10–20% of structures affected over a relatively broad area. In Madrona–Beacon Hill, strong-motion stations ALO, THO, and SEU were located on the western edge of the surveyed residential neighborhoods; they showed a range of values from 0.10 to 0.12 g in an area of relatively widespread chimney damage, although not as intense as in either West Seattle or Bremerton. Magnolia and Wallingford had little damage and instrumented ground shaking <0.08 g at all stations.

In some localities, however, these two data sets do not obviously correspond. One reason is resolution. The strong-motion instruments almost nowhere capture transitions between areas of high and low chimney damage, because the typical spacing between instruments was 1 to 5 km or more. In a few areas, moderate levels of instrumented ground shaking occur with only light to moderate levels of recorded chimney damage, notably at the south end of Beacon Hill (0.14 g at KIMB) and on Queen Anne Hill (0.13 g at HIG). Elsewhere, closely spaced instruments recorded irregular spatial patterns of ground shaking with no obvious cause or correlative with chimney (or other building) damage, such as in downtown Seattle or near Seward Park where two bedrock sites less than 1 km apart recorded a near 2-fold difference in PGA (0.17 g at SEW and 0.31 g at SP2).

Comparison with Chimney Surveys from the 1965 Earthquake

The 29 April 1965 earthquake was another deep (ca. 60 km) Benioff zone earthquake ($M_w = 6.8$) with an epicenter midway between Seattle and Tacoma (Noson *et al.*, 1988). After this event, two independent chimney surveys were conducted in West Seattle (Algermissen and Harding, 1965; Mullineaux *et al.*, 1967). Both recorded the location of "damaged chimneys" on a block-by-block basis and ex-

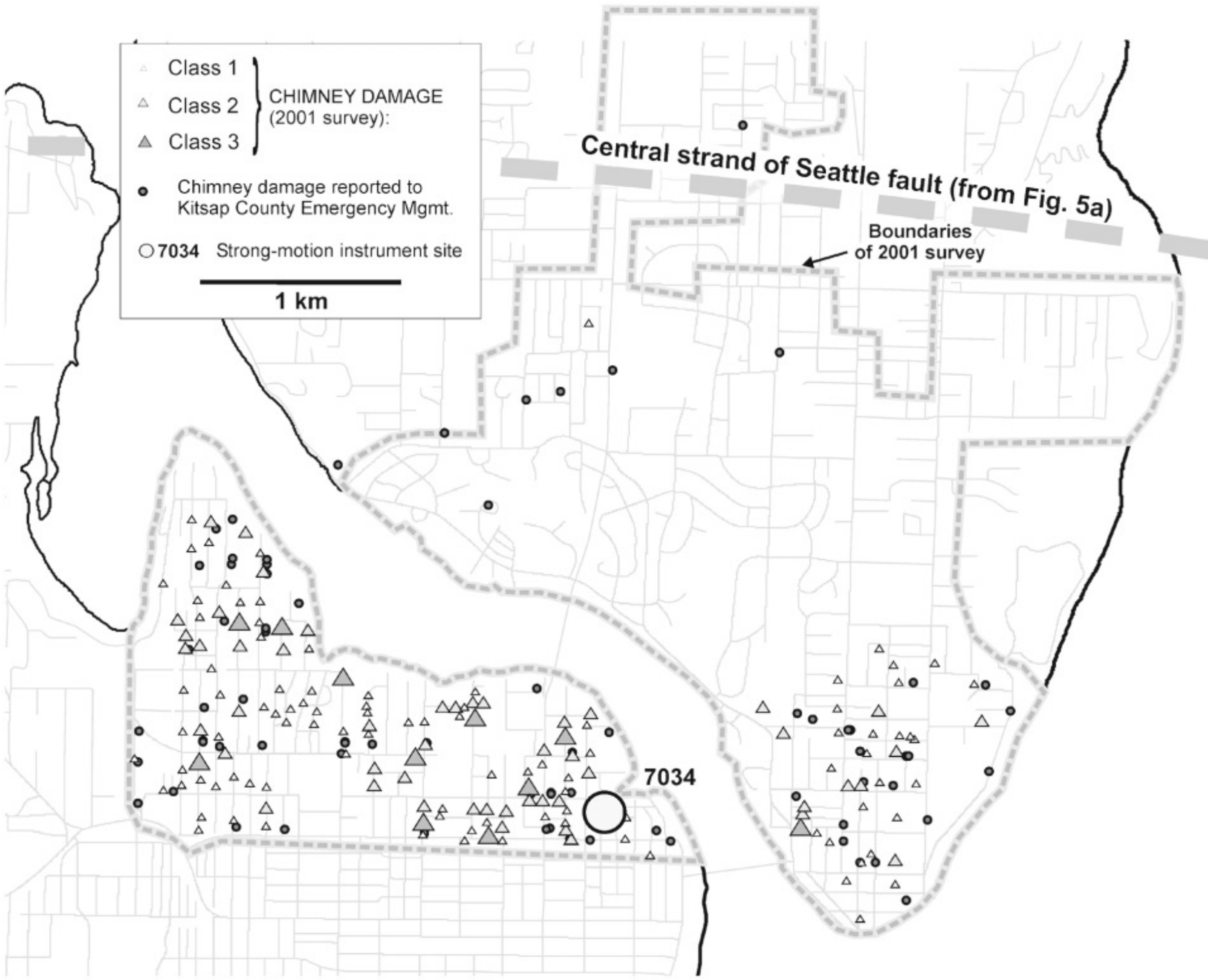


Figure 7. Bremerton-area comparison of observed chimney damage (triangles, from this study) with homeowner-reported damaged chimneys to Kitsap Emergency Management (small dots). Overall pattern of damage is very similar in both data sets, in particular the abrupt northern boundary of significant damage in east Bremerton (PGA = 0.19 g) near strong-motion instrument station 7034. Southern strand of Seattle fault lies about 0.5 km south of map edge.

pressed their results as a percentage of each block's total number of chimneys. The criteria for identifying "damage" were not specified in either report. Algermissen and Harding's (1965) criteria were likely more permissive than those of Mullineaux *et al.* (1967), insofar as the Algermissen/Harding criteria show both a greater total area of damaged chimneys and larger areas of more pervasive damage than the Mullineaux criteria (Fig. 9). Curiously, the locations of the two studies' blocks of most intense damage do not everywhere overlap; although Algermissen and Harding commonly show two to four times the density of damage for a given locale than Mullineaux *et al.*, a few blocks in the southeast part of their overlapping study areas display an inverted relationship between them.

Absent stated criteria, we do not know that our current survey criteria are any more comparable with one or the other of the 1965 surveys, but the larger number of Algermissen and Harding's damaged chimneys allows the richest comparison with our data (Fig. 10a). Although the maximum and median densities of reported chimney damage in the 1965 earthquake were substantially higher than for 2001, even when using our lowest threshold for "damage" (i.e., class 1) (Fig. 10b), the zones of reported damage in the two surveys were quite similar. To the north, this spatial correspondence is largely a function of the limited distribution of houses, but to the southeast and southwest the correspondence represents a rapid decrease in percentage of damaged chimneys. The zone of greatest damage in 2001 (>30% per block) also corresponds to Algermissen and Harding's most intense damage zones; however, several other such high-damage areas scattered throughout the 1965 survey do not match any particularly intense zone of ours. Broadly, the zone of moderate damage (>30% in 1965, >5–10% in 2001) forms a west–northwest–trending belt in both surveys.

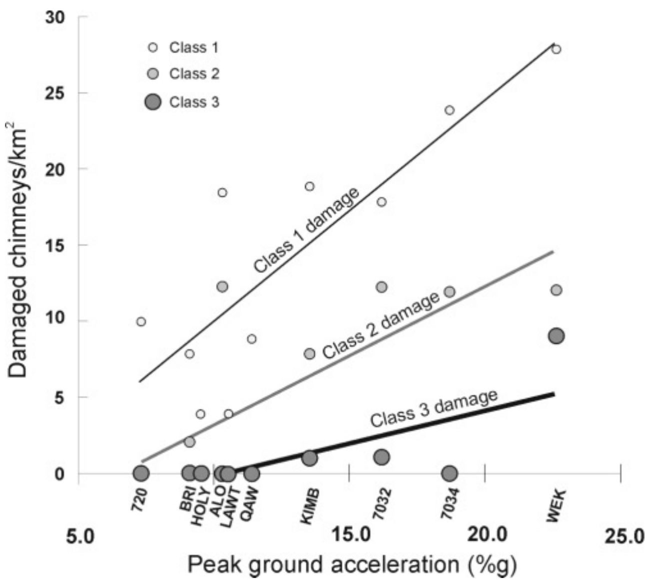


Figure 8. Density of damaged chimneys within a 1-km^2 square centered on the indicated strong-motion stations (720, Wallingford; BRI and KIMB, Beacon Hill; HOLY, WEK, and 7032, West Seattle; ALO, Capital Hill; LAWT, Magnolia; QAW, Queen Anne; 7034, Bremerton). Only those stations that fall within the chimney-surveyed area are included. Chimney damage in the three classes correlates reasonably well with peak ground acceleration, with all r^2 values on the plotted linear-regression best-fit lines >0.74.

These spatial patterns and correspondences are evident even though the two data sets were reported using different units (percentage of damaged chimneys/block in 1965, versus number of damaged chimneys/block in 2001), which cannot be simply equated because the number of houses per block varies across this neighborhood.

In summary, our comparison of the three surveys suggests:

1. Reported damage from the 1965 earthquake was greater than in 2001, although the data cannot discriminate between stronger ground shaking or weaker chimneys during the earlier earthquake.
2. The distribution of relative damage was similar, on a neighborhood scale, in both events but local discrepancies are evident.
3. Specific blocks did not uniformly share similar relative levels of damage between the two events, suggesting that neither local soils nor building-specific construction (whether original or due to reconstruction after the 1965 event) were primary determinants of damage patterns.

Geologic Controls on Shaking and Damage

Surficial Geology. In the Seattle area and across most of the Puget Lowland, upland areas are underlain by overconsolidated till and other glacial units, whereas the intervening north–south troughs are generally filled with water (e.g., Puget Sound) or Holocene alluvium (Booth *et al.*, 2003b). The residential areas of our study are nearly all located on the uplands, which are underlain by stiff, overconsolidated glacial deposits. Observed north–south variations in damage in West Seattle and the Madrona–Beacon Hill neighborhoods do not correlate with any known variations in shallow soil type or surficial deposits (Waldron *et al.*, 1961; Troost *et al.*, in press). For example, the surficial deposit underlying the zone of greatest chimney damage in West Seattle is variously overconsolidated outwash sand and basal till of the last glacial advance. Chimney damage patterns do not follow the boundaries of these geologic units (Fig. 6); indeed, damage intensity closely matches the recorded ground-shaking intensity of the nearby strong-motion instrument (WEK), although geologic contacts lie close by. In this high-damage zone, neither loose soil nor peat is described in either the published geologic maps or the more than 200 geotechnical borings archived in this area (Shimel *et al.*, 2001).

Structure. The zone of southward-decreasing chimney damage in West Seattle and Madrona correlates with the southern margin of the Seattle basin. Compared with depth-to-bedrock data (Jones, 1996), the southward drop-off in damage coincides with the steep gradient on the north side of a shallow (<100 m) bedrock high (i.e., the Seattle uplift). The high is on the upthrown side of the Seattle fault, which passes beneath West Seattle, and trends west–northwest directly beneath the transition between high and low chimney damage there (Fig. 5a). In Bremerton, the chimney damage overlies a broad northeast-plunging anticline in the volcanic basement, with depths to bedrock between a few meters and 200 m. The distribution of houses is locally limited by the shoreline, but the northward decrease in observed damage across east Bremerton apparently reflects a true local decrease in shaking intensity.

The zones of most intense chimney damage are thus located on the bedrock highs beneath Seattle and Bremerton, blocks in the Seattle fault zone with their bounding faults dipping southward toward the hypocenter of the Nisqually earthquake. Although we have no direct evidence for focusing of seismic waves, the association between shaking intensity and fault-zone structure suggests that abrupt changes in the depth to bedrock, basin-edge effects, or localized trapping of seismic waves in the Seattle fault zone may be significant contributory factors in the distribution of chimney damage. Similar high ground shaking along the margins of the Santa Monica basin of southern California during the 1994 Northridge earthquake appear to have been caused by acoustic focusing by deep geological structure and (or) the constructive interference of surface and body waves (Baher *et al.*, 2002). There is no suggestion that movement on the Seattle fault itself was the source of locally increased damage during the Nisqually earthquake.

Not every area of noteworthy damage, however, is related to the basin margin. This suggests that either (1) the

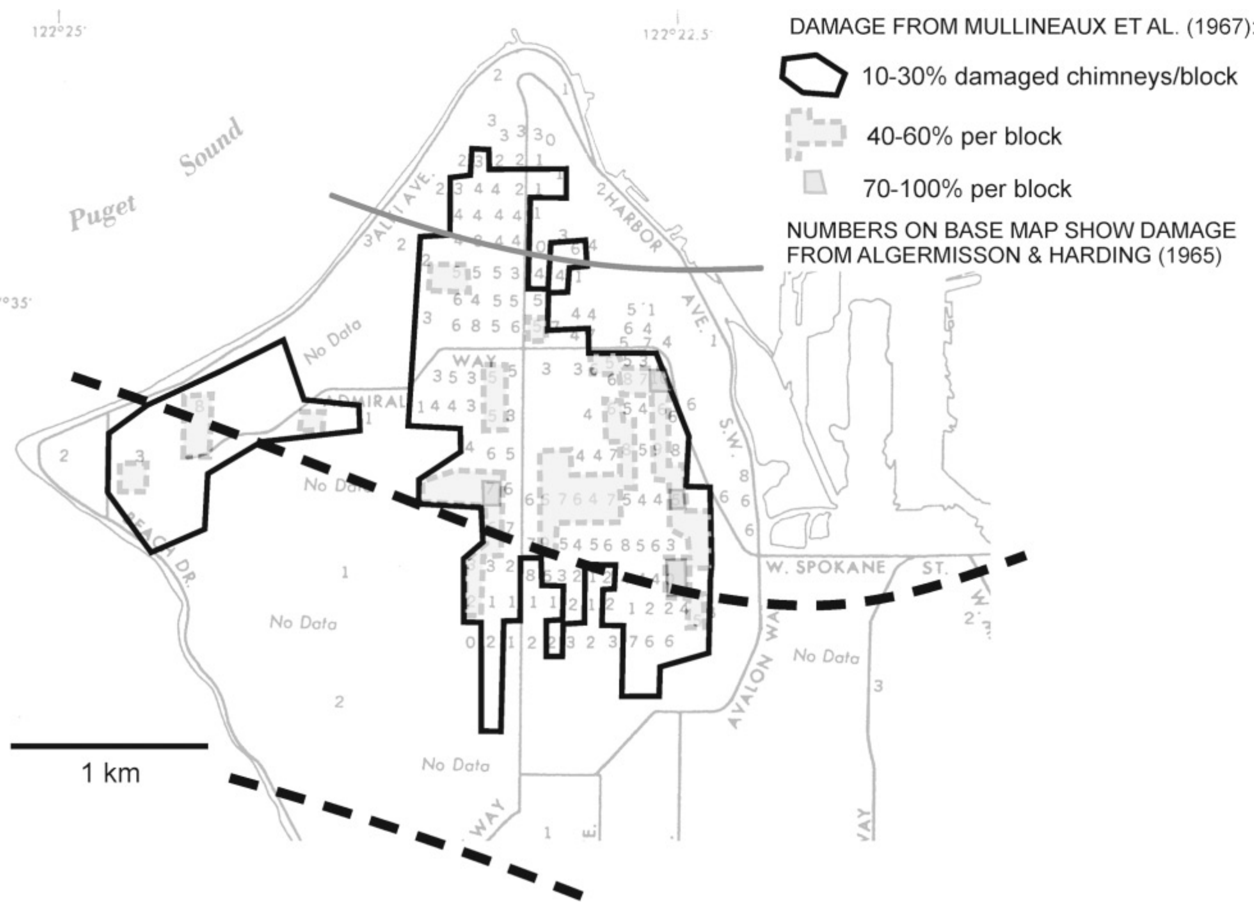


Figure 9. Comparison of damage reported from the 1965 earthquake by Algermissen and Harding (1965) and Mullineaux *et al.* (1967). Base map from the Algermissen study and shows decile of percent damaged chimney per block (e.g., "5" = 50% chimneys damaged). Contours based on equivalent data reported in the study of Mullineaux *et al.*, showing broad similarities but some local differences between the two data sets. Seattle fault strands (dashed) and deformation front (solid) from Blakely *et al.* (2002) (see Fig. 5a).

same underlying (and still unrecognized) cause of greater chimney damage predominates in all of these neighborhoods, and so the alignment of some damaged neighborhoods with the Seattle fault zone is coincidental only; or (2) a variety of subsurface and near-surface conditions can result in zones of enhanced damage, of which one (but only one) is the set of conditions associated with a major fault zone.

Conclusions

Brick chimneys are imprecise indicators of ground-shaking intensity, but they are closely spaced and widely distributed. They have a well established history of evaluation following earthquakes, and their level of damage is part of many systematic determinations of regional earthquake intensity. A rapid survey of brick-chimney damage in the central Puget Lowland after the 2001 Nisqually earthquake suggests the following:

1. Overall, chimney damage corresponds with instrumental measurements of strong motion. Chimney damage, however, can provide a record of much finer spatial resolution for moderate-intensity earthquakes than a strong-motion instrument array.
2. Damage does not obviously correspond to distance from the earthquake epicenter, soft soils, topography, or slope orientation. Although differences in the housing stock may introduce bias, patterns of strongly varying damage commonly cut across neighborhoods of similar construction and age.
3. Damage patterns reported by homeowners to government agencies (e.g., FEMA) are similar to the damage patterns observed here. Each method of identifying spatial patterns of damage has limitations and potential biases; in combination, however, they illuminate overall trends and localized variations that may be useful for understanding strong-motion processes and models.

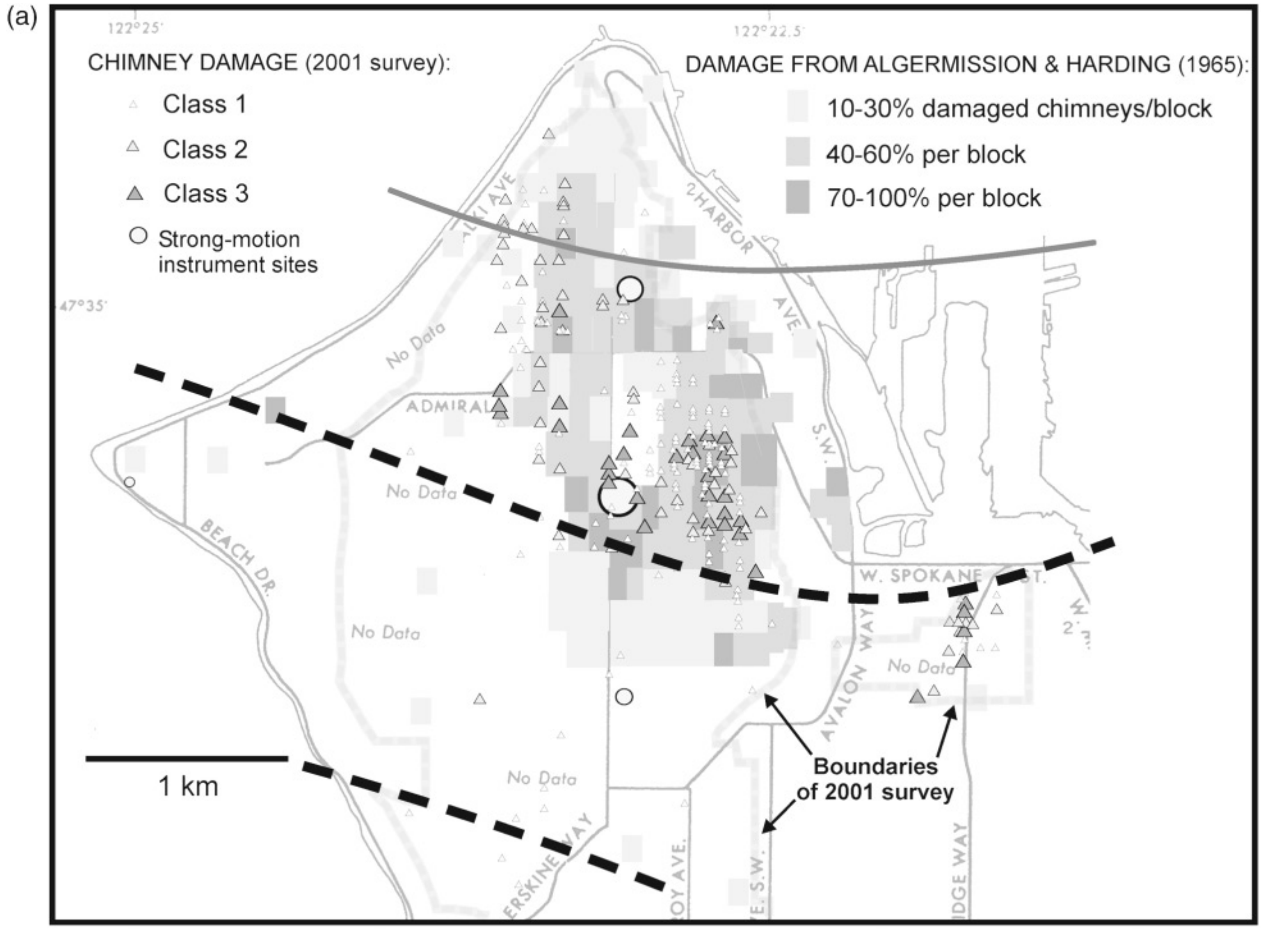
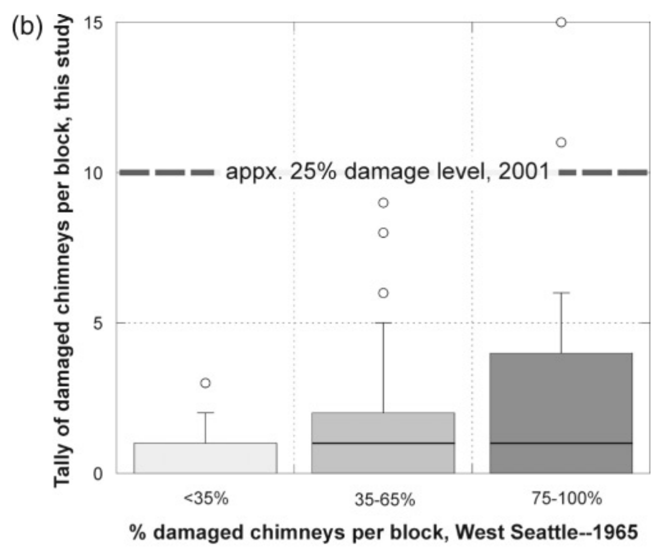


Figure 10. (a) Comparison between the results of this study (triangles) and those of Algermissen and Harding (1967). Base map as in Figure 9, but percent damage from the 1965 earthquake is represented by shaded blocks. Large circles are strong-motion instrument sites in the 2001 Nisqually earthquake. Seattle fault strands (dashed) and deformation front (solid) from Blakely *et al.* (2002) (see Fig. 5a). (b) Box plot comparing Algermisson and Harding (1965) data with those of the current study, block-by-block (see Fig. 10a). 1965 data (*x* axis) expressed in percent damaged chimneys per block; 2001 data (*y* axis) as a simple tally of damaged chimneys per block. This neighborhood has approximately 40 houses per block, based on counts of structures from GIS overlays provided by the City of Seattle (see also Fig. 5b), but differences in block size and spatial imprecision in the 1965 data make a reliable comparison of block-specific damage quantities from 1965 and 2001 impossible. Spatial correlations, however, are clear and quite similar between the two earthquakes. Box plot representation as for Figure 5c.



4. In West Seattle, damage in 2001 mirrored the general damage pattern mapped for the earthquake in 1965. The coincidence of high damage from the two earthquakes at a neighborhood scale, coupled with the absence of correlation on a block-by-block scale, suggest that fine-scale variations in ground shaking are being crudely but accurately represented by the pattern of observed chimney damage and that this area has felt larger ground accelerations than much of the surrounding region in each of the last two earthquakes.
5. The damage in West Seattle in 2001 and 1965 coincides with the recently mapped location of the Seattle fault zone. This suggests that abrupt changes in the depth to bedrock, basin-edge effects, or localized trapping of seis-

mic waves may be significant contributory factors in the distribution of chimney damage.

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