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Modified Mercalli Intensities for Nine Earthquakes in Central and Western Washington Between 1989 and 1999

Open-File Report 2017–1104

U.S. Department of Interior
U.S. Geological Survey

Cover: Damage to the cupola of the Grays Harbor County Courthouse in Montesano, Washington, resulting from the July 1999 Satsop earthquake. Photograph courtesy of Grays Harbor County.

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RYAN K. ZINKE, Secretary

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Modified Mercalli Intensities for Nine Earthquakes in Central and Western Washington Between 1989 and 1999

By Thomas M. Brocher,[1] James W. Dewey,[1] and John F. Cassidy,[2]

Abstract

We determine Modified Mercalli (Seismic) Intensities (MMI) for nine onshore earthquakes of magnitude 4.5 and larger that occurred in central and western Washington between 1989 and 1999, on the basis of effects reported in postal questionnaires, the press, and professional collaborators. The earthquakes studied include four earthquakes of *M*5 and larger: the *M*5.0 Deming earthquake of April 13, 1990, the *M*5.0 Point Robinson earthquake of January 29, 1995, the *M*5.4 Duvall earthquake of May 3, 1996, and the *M*5.8 Satsop earthquake of July 3, 1999. The MMI are assigned using data and procedures that evolved at the U.S. Geological Survey (USGS) and its Department of Commerce predecessors and that were used to assign MMI to felt earthquakes occurring in the United States between 1931 and 1986. We refer to the MMI assigned in this report as traditional MMI, because they are based on responses to postal questionnaires and on newspaper reports, and to distinguish them from MMI calculated from data contributed by the public by way of the internet. Maximum traditional MMI documented for the *M*5 and larger earthquakes are VII for the 1990 Deming earthquake, V for the 1995 Point Robinson earthquake, VI for the 1996 Duvall earthquake, and VII for the 1999 Satsop earthquake; the five other earthquakes were variously assigned maximum intensities of IV, V, or VI. Starting in 1995, the Pacific Northwest Seismic Network (PNSN) published MMI maps for four of the studied earthquakes, based on macroseismic observations submitted by the public by way of the internet. With the availability now of the traditional USGS MMI interpreted for all the sites from which USGS postal questionnaires were returned, the four Washington earthquakes join a rather small group of earthquakes for which both traditional USGS MMI and some type of internet-based MMI have been assigned. The values and distributions of the traditional MMI are broadly similar to the internet-based PNSN intensities; we discuss some differences in detail that reflect differences in data-sampling procedure, differences in the procedure used to assign intensity numbers from macroseismic observations, and differences in how intensities are mapped.

Introduction

Macroseismic intensities characterize the strength of shaking produced by an earthquake at a specific location, by considering the effects of the shaking on people, manmade structures, and natural features at the location. Since 1931, the U.S. Geological Survey (USGS) and its predecessors in the U.S. Department of Commerce (National Oceanic and Atmospheric Administration, 2016) have assigned macroseismic intensities to U.S. earthquakes based on the Modified Mercalli Intensity (MMI) scale (Wood and Neumann, 1931; table 1, this report).

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[2]Natural Resources Canada.

Modified Mercalli Intensities for U.S. earthquakes that occurred in the period 1931–1986 were reported, and critical macroseismic effects documented, in the publication U.S. Earthquakes, now scanned and available online (for example, U.S. Geological Survey, 2016a). The MMI values that were published in U.S. Earthquakes for 1931–1985 (but not those of 1986) are also available online in a database that is maintained by the National Oceanic and Atmospheric Administration (2016). The traditional MMI for U.S. earthquakes of 1931–1986 are, for most communities, based on postal questionnaires sent to government entities such as post offices and returned to the USGS or its predecessor agency. MMI assignments for some communities and earthquakes in 1931–1986 were based on observations documented in press or engineering reports, and on observations reported to the USGS and its predecessors by collaborators at academic institutions, state agencies, and Canadian geoscience agencies.

Beginning in mid-1998 with California earthquakes and in mid-2000 for earthquakes in the rest of the nation, U.S. earthquakes have been characterized by USGS Community Internet Intensities (CII), also known as "Did You Feel It?" intensities (DYFI). CII and DYFI are based on macroseismic observations volunteered over the internet, and they are calibrated so as to be equivalent on average to MMI (Wald and others, 1999, 2011). The CII/DYFI of felt Washington earthquakes occurring after mid-2000 may be viewed online at the "Search Earthquake Catalog" from the USGS earthquake website (U.S. Geological Survey, 2016b).

The principal purpose of the present report is to document traditional MMI associated with earthquakes of magnitude 4.5 and larger that occurred in Washington during the time-period between the 1986 date of the last U.S. Earthquakes volume and the mid-2000 beginning of USGS CII/DYFI coverage of Washington state; the nine shocks that meet the *M*4.5 magnitude criterion occurred in the period 1989–1999. We note that the *M*6.8 Nisqually earthquake of 2001 (fig. 1) has already been characterized by traditional MMI in addition to CII/DYFI (Dewey and others, 2002).

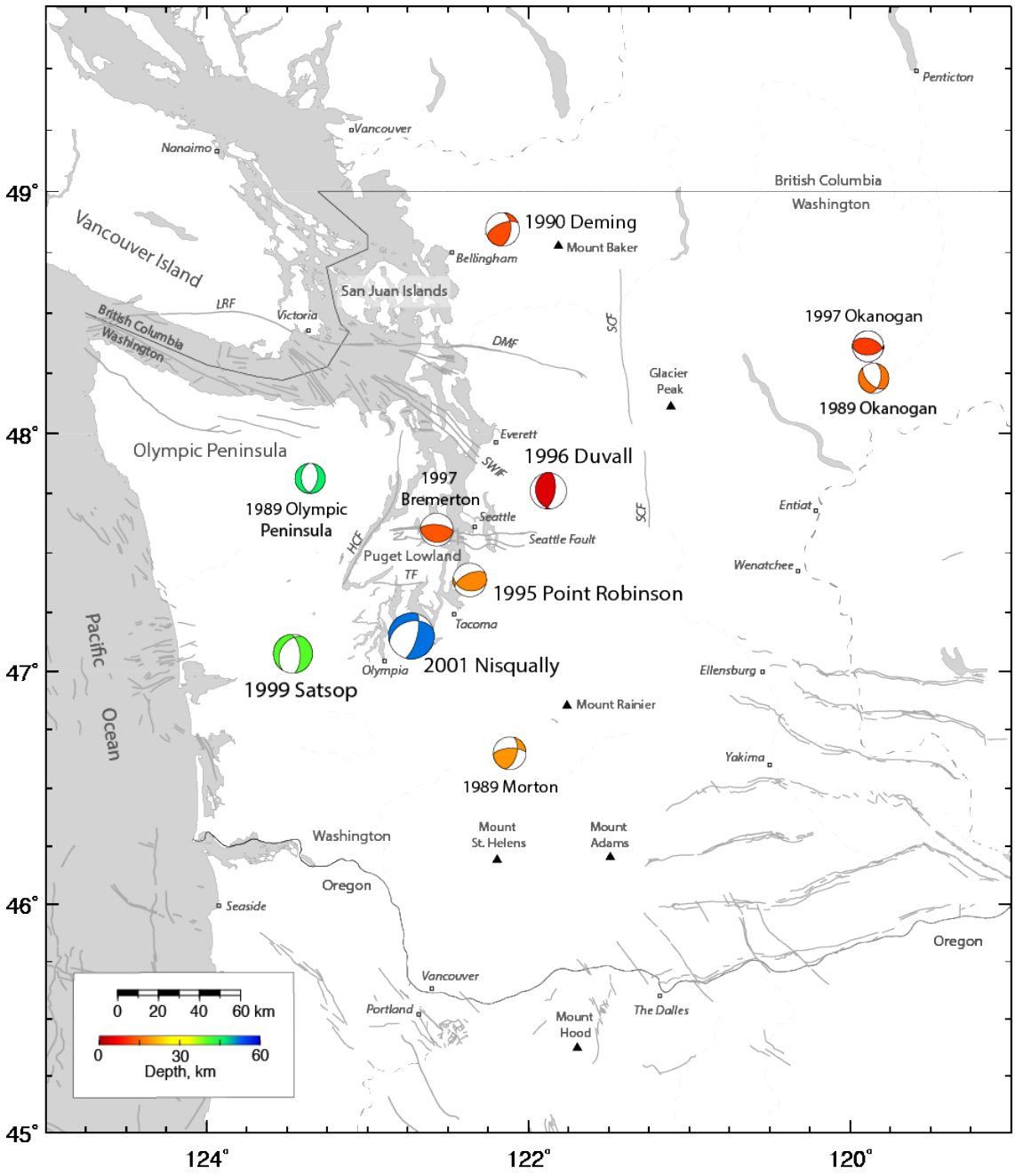


Figure 1. Map showing locations (from table 2) and focal mechanisms for the nine earthquakes studied in this report and that of the 2001 Nisqually earthquake, the largest earthquake in the region in the past half century. With the exception of the 1997 Bremerton and 1997 Okanogan earthquakes, plotted focal-mechanisms are those given in Pacific Northwest Seismic Network (2017). As elaborated in the text, focal-mechanisms plotted for the 1997 earthquakes are those for the moment-tensor solutions calculated at Oregon State University. Gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. DMF, Devils Mountain Fault; HCF, Hood Canal Fault; LRF, Leech River Fault; SCF, Straight Creek Fault; SWIF, Southern Whidbey Island Fault; TF, Tacoma Fault.

Table 1. Modified Mercalli Intensity Scale of 1931, as originally abridged by Wood and Neumann (1931), with additional effects (in italics) from their unabridged intensity scale that have proven to be particularly useful in assigning MMI. As discussed in the text, we do not use reports of human reactions to justify assigning intensities higher than V. The non-abridged version of the scale is given in its entirety by Wood and Neumann (1931) and is reproduced by Stover and Coffman (1993).

Scale	Description
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Knocked pictures against wall, or swung them out of place. Moved small objects, furnishings, the latter to slight extent. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Persons made to move unsteadily. Broken dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; Fall of plaster, loose bricks, stones, tiles, cornices, unbraced parapets, architectural ornaments; some chimneys broken. Noticed by persons driving motorcars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Frame houses moved on foundations if not bolted down. Panel walls thrown out of frame structures. Fall of many chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Conspicuously moved very heavy furniture. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed [slopped] over banks.
XI	Few, if any, [masonry] structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Traditional USGS Postal Canvasses and Interpretation of MMI

During the period in which the USGS conducted postal canvasses following earthquakes that were large enough to have been felt, questionnaires were mailed to government entities (mostly post offices) in communities situated within a circle extending from the epicenter out to a distance thought to be sufficient to define the extent of the area over which the earthquake was felt. The density of canvassing decreased with distance from the epicenter, with all classes of post-offices being canvassed close to the epicenter and only post offices in county seats being canvassed in the outer regions of the canvassed area.

Experience with the MMI scale in the decades since its introduction in 1931 showed that some criteria of the MMI scale are more reliable than others as indicators of the level of ground shaking. Moreover, building construction methods changed appreciably since the scale was introduced. Assigning USGS MMI values to earthquakes occurring in later decades of the period 1931–1986 therefore involved use of the original criteria of Wood and Neumann (1931) with amendments and modifications that were developed after 1931. In assigning intensities to the nine Washington earthquakes, we followed amendments and modifications that are summarized by Stover and Coffman (1993) and that were used by the USGS to assign MMI for earthquakes occurring in the last several decades of the 20th century (for example, Dewey and others, 1995). Notably, we do not use reports of human reactions as a basis for assigning traditional USGS MMI higher than IV (for most reports) or V (for reports of people having difficulty standing or leaving buildings). Similar to Stover and Coffmann (1993) and Dewey and others (1995), and contrary to the 1931 wording of the scale, the USGS has, in recent decades, not generally assigned intensities of VIII or above on the basis of reports of ground failure, or on effects (such as rupture of gas and water mains) that are likely due to ground failure, because post-1931 experience has shown that ground failures can be induced in susceptible soil by levels of ground-motion that do not produce shaking damage characteristic of intensity VIII and higher.

The assigning of traditional USGS MMI from a set of macroseismic observations is a classification scheme similar to that used for many macroseismic intensities (for example, Gruenthal, 1998), though not for CII/DYFI or the PNSN internet intensities. In assigning traditional USGS MMI, the various macroseismic effects reported for a community are considered collectively in light of the effects that are defined in the Modified Mercalli Intensity Scale of 1931 (table 1), and in light of post-1931 experience with the scale, as characteristic of different intensity levels. The selected intensity is that for which, in the judgment of the seismologist, the ensemble of macroseismic effects described in the scale best matches the ensemble of observed effects. In this report we usually follow a widely used seismological tradition of representing the integer values of traditional MMI by Roman numerals. Note, as is traditional, we have made no adjustment or account for site conditions in assigning MMI.

There is commonly not a one-to-one match between all the effects that are defined in the MMI scale as characteristic of a particular intensity level and the macroseismic observations obtained for a community from postal questionnaires or media reports, even after accounting for post-1931 adjustments in application of the scale. For most moderate-sized earthquakes, there are some communities for which the available macroseismic observations may be interpreted by different seismologists as implying different MMI values. It is the custom, therefore, to document at least the observations that the assigner views as critical for assigning the higher values of MMI associated with an earthquake. In the present report, for communities experiencing the larger MMI's associated with each earthquake, we document both the observations contained in postal questionnaires that were critical for assigning the MMI and other observations from the questionnaires that we did not view as diagnostic of the MMI for that community but that provide a flavor of the responses. For the *M*4.5 1989 Olympic Peninsula earthquake and *M*5.0 1995 Point Robinson earthquake, details of the postal

questionnaire responses are provided for communities that were assigned intensities IV or V. For the other seven earthquakes, details of the postal questionnaire responses are provided for communities that were assigned intensities V and higher.

For communities for which we provide details of postal questionnaire responses, we also note (in parentheses following the observation) the intensity that would be implied by some of the individual observed effects, if those individual effects were considered in isolation rather than as part of an ensemble and if those individual effects are commonly useful in assigning intensity at some level. Most of these effects are summarized in the modified abridged scale of table 1; a few of the effects are not listed in table 1 but are given in the non-abridged scale of Wood and Neumann (1931). We use a notation having the general form "≥MMI," where "MMI" is an intensity value, to indicate that the effect, considered in isolation from other reported effects but in the context of the design of the questionnaire on which it was reported, would be consistent with both the stated "MMI" and with intensities higher than "MMI". This situation arises when the reported effect is the strongest of its type in the questionnaire, so that the questionnaire does not permit documentation of a stronger effect of the same type on people or objects. For a few effect types, the questionnaire used for the 1999 Satsop earthquake contains more levels of impact than the questionnaires used for the earlier earthquakes, so that an effect that would be characterized as an "≥MMI" effect for the earlier earthquakes might be characterized as simply an "MMI" effect for the 1999 earthquake. Finally, it will be noted that the intensities corresponding to individual effects frequently differ from the community intensity that is assigned by consideration of the ensemble of effects.

Nine Washington State Earthquakes Between 1989 and 1999

The hypocenters, origin times, and magnitudes cited for the nine onshore Washington earthquakes (table 2) are those listed as authoritative in the online U.S. Geological Survey Comprehensive Catalog as of August 2016 (U.S. Geological Survey, 2016b). For the region of our study, the USGS Comprehensive Catalog protocols treat locations and magnitudes provided by the Pacific Northwest Seismic Network as authoritative. For all of the 1989–99 earthquakes we studied, the PNSN magnitude considered authoritative was a duration magnitude (M_D), calculated from a measure of the duration of the signal as recorded by local stations. Other magnitude-types have been calculated, which, because they are based on different measures of the size of the earthquake than the duration upon which M_D is based, may have numerical values that differ from the reported M_D. Here we list values of moment-magnitudes calculated by the Global Centroid Moment Tensor Project (2017) when these have been calculated for an earthquake; these are denoted M_w(GCMT). We also list values of moment-magnitudes that were associated with moment-tensors calculated for the earthquakes occurring between 1995 and 1999 by scientists at Oregon State University; these moment-magnitudes are denoted M_w(OSU). According to participating scientist Jochen Braunmiller (written commun., February 2017), the methodology used for the M_w(OSU) is that described by Braunmiller and others (1995) and Nábělek and Xia (1995). We give references to individual M_w(OSU) values along with the values themselves. Finally, we list the values of USGS short-period body-wave magnitude m_b(USGS) calculated for these earthquakes; these are obtained by clicking on the "Magnitudes" tab that is associated with the USGS origin at U.S. Geological Survey (2016b).

Table 2. Earthquake origin date and time, hypocenter, magnitudes, and maximum assigned Modified Mercalli Intensities (MMI). Throughout this paper, we typically refer to earthquakes by their year of occurrence and a geographic reference that is either a prominent geomorphic feature in the region in which the earthquake occurred or a town near the earthquake's epicenter.

[UTC, coordinated universal time; km, kilometers; M_D, duration magnitude]

Geographic reference	Date Month/Day/ Year (UTC)	Time Hours: Minutes: Seconds (UTC)	Latitude (N)	Longitude (W)	Depth (km)	M_D	Maximum MMI
Olympic Peninsula	3/5/1989	6:42:01	47.813	123.357	45.3	4.5	IV
Okanogan	5/9/1989	18:28:46	48.230	119.854	14.6	4.5	VI
Morton	12/24/1989	8:45:59	46.650	122.116	17.3	4.9	V
Deming	4/14/1990	5:33:27	48.845	122.160	11.9	5.0	VII
Point Robinson	1/29/1995	3:11:22	47.387	122.364	15.4	5.0	V
Duvall	5/3/1996	4:04:22	47.761	121.876	3.8	5.4	VI
Bremerton	6/23/1997	19:13:27	47.598	122.570	13.3	4.9	VI
Okanogan	6/24/1997	14:23:13	48.364	119.888	10.2	4.6	V
Satsop	7/3/1999	1:43:54	47.074	123.464	40.0	5.8	VII

Information on the canvass radii and numbers of questionnaires sent and returned is listed for all nine earthquakes in table 3. Canvass radii increased during the 1990s. Typically, 75–85 percent of the questionnaires were completed and returned.

Table 3. Postal questionnaire canvass information.

[km, kilometers; M_D, duration magnitude; MMI, Modified Mercalli Intensity]

Earthquake	M_D	Survey radius (km)	Number sent	Number of responses	Percent returned	Maximum MMI
1989 Olympic Peninsula	4.5	125	124	83	67	IV
1989 Okanogan	4.5	100	47	42	89	VI
1989 Morton	4.9	250	326	240	74	V
1990 Deming	5.0	175	100	84	84	VII
1995 Point Robinson	5.0	350	151	118	78	V
1996 Duvall	5.4	350	311	248	80	VI
1997 Bremerton	4.9	300	255	190	75	VI
1997 Okanogan	4.6	250	112	95	85	V
1999 Satsop	5.8	450	487	369	76	VII

The questionnaires received for the 1989 and 1990 earthquakes were of the type illustrated in figures 2*A* and *B*. The vast majority of the questionnaires received for the 1995, 1996, and 1997 earthquakes were of the type illustrated in figures 3*A* and *B*. The version of the postal questionnaire from which most of the 1999 Satsop earthquake data were obtained is illustrated in figures 4*A* and *B*. A few questionnaires from earlier eras were returned by individuals of the general public or by U.S.

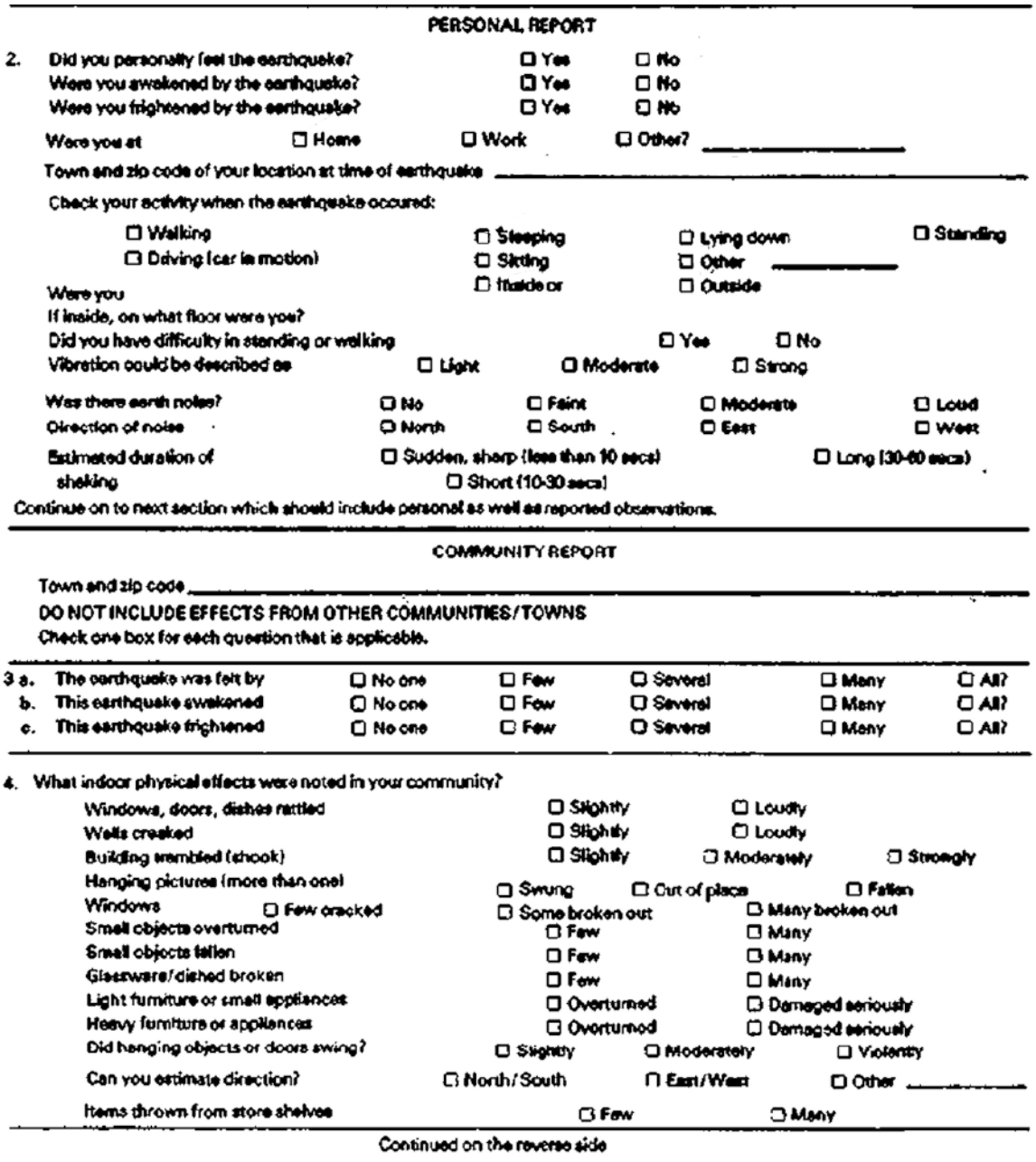
government agencies whom we had not included in the postal canvass but who had those questionnaires on hand. All questionnaires contained a personal report section in which the respondent indicated his/her personal experience as well as a community report section in which the respondent summarized impacts on his/her community (figs. 2–4). In some cases, the respondent's personal report pertained to a different community than the respondent's community report. In this situation, we assigned intensities to both communities, according to the effects reported, although we note here that the questions asked in the personal report do not permit resolution of MMI higher than V, using the USGS conventions for assigning MMI in recent decades. In some cases, the community report described effects in a different zip code than the zip code of the post office to which the questionnaire was sent. In this situation, we assign the intensity to the zip code for which the effects are described.

In the relatively few cases where multiple responses for the same zip code were received, we summarize those that we judge to be most diagnostic of the strength of shaking.

The vast majority of intensities are plotted at geographic coordinates that we obtained from a legacy computer file of zip codes, community names, and geographic coordinates that was used by USGS seismologists during the years in which they were assigning traditional USGS MMI. These coordinates lie within the zip code for which effects are described in the questionnaires, but the plotted locations may differ by kilometers from locations at which some, or all, of the reported effects were observed. In the case of zip code regions that include large areas of lightly populated territory, the locations at which intensity symbols are plotted might differ by tens of kilometers from some of the locations at which reported effects were observed. Plotted symbols in the intensity maps that correspond to communities named in press reports may likewise be some kilometers from the locations within the communities at which the reported effects were observed.

The estimate of hypocentral distance, commonly associated with observations of an earthquake's effects in a community, corresponds to the straight-line distances between the focus of the earthquake at depth and a location to which we assigned intensity on the basis of macroseismic observations reported in both the "Personal Report" and "Community Report" sections of a postal questionnaire. We calculate hypocentral distance from the epicenter and focal depth that we list for each earthquake. The source dimensions of the *M*4.5 to *M*5.8 earthquakes documented in this report may be reasonably approximated as point sources, so the use of hypocentral distance as the measure of source-to-community distance is equivalent to the use of distance-to-fault as a distance measure (for example, Atkinson and Wald, 2007). For each level of intensity we summarize the range of hypocentral distances for the observations as well as the median hypocentral distance. Interpretations of hypocentral distances have to be tempered by consideration of possible errors of several kilometers in the epicenters and possible errors approaching 10 km in focal depths of some earthquakes; errors of this magnitude are suggested by differences between independent estimates of the epicenters and focal-depths that are encountered on various pages of the PNSN and USGS websites that are cited for each earthquake. Interpretation of the hypocentral distances also has to be tempered by consideration of the imprecision of knowledge of the location to which the intensity is assigned, discussed in the previous paragraph.

A.



PERSONAL REPORT

2. Did you personally feel the earthquake? ☐ Yes ☐ No
Were you awakened by the earthquake? ☐ Yes ☐ No
Were you frightened by the earthquake? ☐ Yes ☐ No

Were you at ☐ Home ☐ Work ☐ Other? _____

Town and zip code of your location at time of earthquake _____

Check your activity when the earthquake occured:

☐ Walking ☐ Sleeping ☐ Lying down ☐ Standing
☐ Driving (car in motion) ☐ Sitting ☐ Other _____
☐ Inside or ☐ Outside

Were you

If inside, on what floor were you?

Did you have difficulty in standing or walking ☐ Yes ☐ No

Vibration could be described as ☐ Light ☐ Moderate ☐ Strong

Was there earth noise? ☐ No ☐ Faint ☐ Moderate ☐ Loud
Direction of noise ☐ North ☐ South ☐ East ☐ West

Estimated duration of shaking ☐ Sudden, sharp (less than 10 secs) ☐ Long (30-60 secs)
☐ Short (10-30 secs)

Continue on to next section which should include personal as well as reported observations.

COMMUNITY REPORT

Town and zip code _____

DO NOT INCLUDE EFFECTS FROM OTHER COMMUNITIES/TOWNS

Check one box for each question that is applicable.

3 a. The earthquake was felt by ☐ No one ☐ Few ☐ Several ☐ Many ☐ All
b. This earthquake awakened ☐ No one ☐ Few ☐ Several ☐ Many ☐ All
c. This earthquake frightened ☐ No one ☐ Few ☐ Several ☐ Many ☐ All

4. What indoor physical effects were noted in your community?

Windows, doors, dishes rattled ☐ Slightly ☐ Loudly
Walls creaked ☐ Slightly ☐ Loudly
Building trembled (shook) ☐ Slightly ☐ Moderately ☐ Strongly
Hanging pictures (more than one) ☐ Swung ☐ Out of place ☐ Fallen
Windows ☐ Few cracked ☐ Some broken out ☐ Many broken out
Small objects overturned ☐ Few ☐ Many
Small objects fallen ☐ Few ☐ Many
Glassware/dishes broken ☐ Few ☐ Many
Light furniture or small appliances ☐ Overturned ☐ Damaged seriously
Heavy furniture or appliances ☐ Overturned ☐ Damaged seriously
Did hanging objects or doors swing? ☐ Slightly ☐ Moderately ☐ Violently
Can you estimate direction? ☐ North/South ☐ East/West ☐ Other _____
Items thrown from store shelves ☐ Few ☐ Many

Continued on the reverse side

Figure 2. *A*. Personal report and first two sections of community report from the questionnaire that was used in postal canvasses for the 1989 and 1990 earthquakes. *B*. Last six sections of community report from the questionnaire that was used in postal canvasses for the 1989 and 1990 earthquakes.

B.

5. Indicate effects of the following types to interior walls if any:

Plaster/stucco	☐ Hairline cracks	☐ Large cracks (many)	☐ Fell in large amounts
Dry wall	☐ Hairline cracks	☐ Large cracks (many)	☐ Fell in large amounts

6. What outdoor physical effects were noted in your community?

Trees and bushes shaken	☐ Slightly	☐ Moderately	☐ Strongly
Standing vehicles rocked	☐ Slightly	☐ Moderately	
Moving vehicles rocked	☐ Slightly	☐ Moderately	
Water splashed onto sides of lakes, ponds, swimming pools	☐ Yes	☐ No	
Elevated water tanks	☐ Cracked	☐ Twisted	☐ Fallen (thrown down)
Tombstones	☐ Displaced ☐ Fallen	☐ Cracked	☐ Rotated
Chimneys	☐ Cracked ☐ Broken at roof line	☐ Twisted	☐ Fallen ☐ Bricks fallen
Railroad tracks bent	☐ Slightly	☐ Greatly	
Stone or brick fences/walls	☐ Open cracks	☐ Fallen	☐ Destroyed
Underground pipes	☐ Broken	☐ Out of service	
Highways or streets	☐ Large cracks	☐ Large displacements	
Sidewalks	☐ Large cracks	☐ Large displacements	

7a. Check below any structural damage to buildings.

Foundation	☐ Cracked		☐ Destroyed
Interior walls	☐ Split	☐ Fallen	☐ Separated from ceiling or floor
Exterior walls	☐ Large Cracks		☐ Bulged outward
	☐ Partial collapse		☐ Total collapse

b. What type of construction was the building that showed this damage?

☐ Wood	☐ Stone	☐ Brick veneer	☐ Other _____
☐ Brick	☐ Cinderblock	☐ Reinforced concrete	☐ Mobile home

c. What was the type of ground under the building?

☐ Don't know	☐ Sandy soil	☐ Marshy	☐ Fill
☐ Hard rock	☐ Clay soil	☐ Sandstone, limestone, shale	

d. Was the ground: ☐ Level ☐ Sloping ☐ Steep?

e. Check the approximate age of the building:

☐ Built before 1946 ☐ Built 1946-65 ☐ Built after 1965

8. Check below any structural damage to

Bridges/Overpasses	☐ Concrete	☐ Wood	☐ Steel	☐ Other
Damage was	☐ Slight	☐ Moderate		☐ Severe
Dams	☐ Concrete	☐ Large earthen		
Damage was	☐ Slight	☐ Moderate		☐ Severe

9. What geologic effects were noted in your community?

Ground cracks	☐ Wet ground	☐ Steep slopes	☐ Dry and level ground
Landslides	☐ Small	☐ Large	
Slumping	☐ River bank	☐ Road fill	☐ Land fill
Were springs or well water disturbed?		☐ Level changed ☐ Muddied	☐ Flow disturbed ☐ Don't know
Were rivers or lakes changed?		☐ Yes ☐ No	☐ Don't know

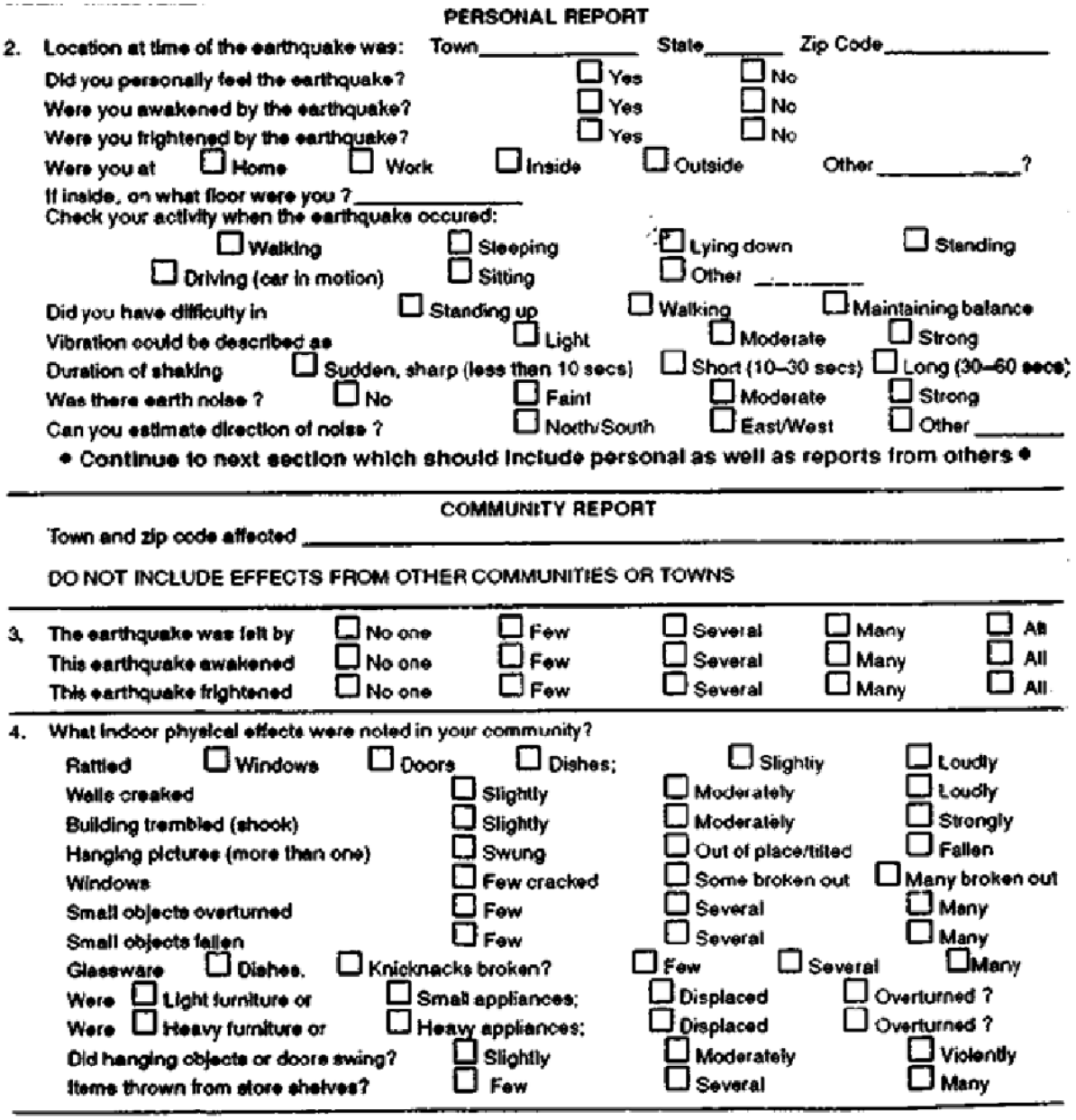
10a. What percentage of buildings were damaged?

Within 2 city blocks of your location	☐ None ☐ Many (about 50%)	☐ Few (about 5%) ☐ Most (about 75%)
b. In area covered by your zip code	☐ None ☐ Many (about 50%)	☐ Few (about 5%) ☐ Most (about 75%)

Thank you for your time and information. Refold this card and tape for return mail.

Figure 2.—Continued

A.



PERSONAL REPORT

2. Location at time of the earthquake was: Town_____ State_____ Zip Code_____
Did you personally feel the earthquake? ☐ Yes ☐ No
Were you awakened by the earthquake? ☐ Yes ☐ No
Were you frightened by the earthquake? ☐ Yes ☐ No
Were you at ☐ Home ☐ Work ☐ Inside ☐ Outside Other _____?
If inside, on what floor were you ?_____
Check your activity when the earthquake occured:
☐ Walking ☐ Sleeping ☐ Lying down ☐ Standing
☐ Driving (car in motion) ☐ Sitting ☐ Other _____
Did you have difficulty in ☐ Standing up ☐ Walking ☐ Maintaining balance
Vibration could be described as ☐ Light ☐ Moderate ☐ Strong
Duration of shaking ☐ Sudden, sharp (less than 10 secs) ☐ Short (10–30 secs) ☐ Long (30–60 secs)
Was there earth noise ? ☐ No ☐ Faint ☐ Moderate ☐ Strong
Can you estimate direction of noise ? ☐ North/South ☐ East/West ☐ Other _____

• Continue to next section which should include personal as well as reports from others •

COMMUNITY REPORT

Town and zip code affected _____

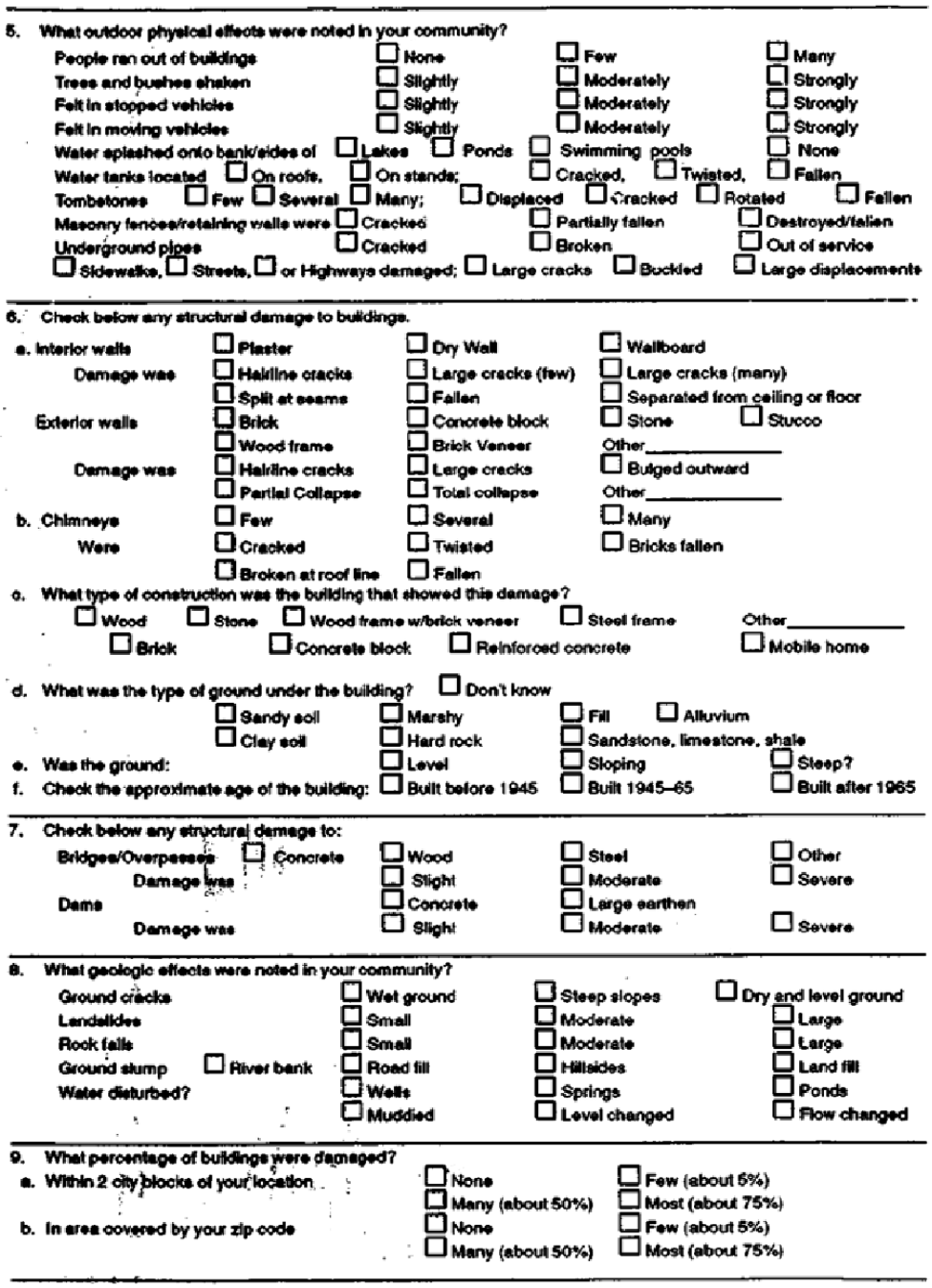
DO NOT INCLUDE EFFECTS FROM OTHER COMMUNITIES OR TOWNS

3. The earthquake was felt by ☐ No one ☐ Few ☐ Several ☐ Many ☐ All
This earthquake awakened ☐ No one ☐ Few ☐ Several ☐ Many ☐ All
This earthquake frightened ☐ No one ☐ Few ☐ Several ☐ Many ☐ All

4. What indoor physical effects were noted in your community?
Rattled ☐ Windows ☐ Doors ☐ Dishes; ☐ Slightly ☐ Loudly
Walls creaked ☐ Slightly ☐ Moderately ☐ Loudly
Building trembled (shook) ☐ Slightly ☐ Moderately ☐ Strongly
Hanging pictures (more than one) ☐ Swung ☐ Out of place/tilted ☐ Fallen
Windows ☐ Few cracked ☐ Some broken out ☐ Many broken out
Small objects overturned ☐ Few ☐ Several ☐ Many
Small objects fallen ☐ Few ☐ Several ☐ Many
Glassware ☐ Dishes, ☐ Knicknacks broken? ☐ Few ☐ Several ☐ Many
Were ☐ Light furniture or ☐ Small appliances; ☐ Displaced ☐ Overturned ?
Were ☐ Heavy furniture or ☐ Heavy appliances; ☐ Displaced ☐ Overturned ?
Did hanging objects or doors swing? ☐ Slightly ☐ Moderately ☐ Violently
Items thrown from store shelves? ☐ Few ☐ Several ☐ Many

Figure 3. *A*. Personal report and first two sections of community report from the questionnaire that was used in postal canvasses for the 1995 Point Robinson, 1996 Duvall, and 1997 Bremerton and Okanogan earthquakes. *B*. Last five sections of community report from the questionnaire that was used in postal canvasses for the 1995 Point Robinson, 1996 Duvall, and 1997 Bremerton and Okanogan earthquakes.

B.



5. What outdoor physical effects were noted in your community?

People ran out of buildings	☐ None	☐ Few	☐ Many
Trees and bushes shaken	☐ Slightly	☐ Moderately	☐ Strongly
Felt in stopped vehicles	☐ Slightly	☐ Moderately	☐ Strongly
Felt in moving vehicles	☐ Slightly	☐ Moderately	☐ Strongly

Water splashed onto bank/sides of ☐ Lakes ☐ Ponds ☐ Swimming pools ☐ None

Water tanks located ☐ On roofs, ☐ On stands; ☐ Cracked, ☐ Twisted, ☐ Fallen

Tombstones ☐ Few ☐ Several ☐ Many; ☐ Displaced ☐ Cracked ☐ Rotated ☐ Fallen

Masonry fences/retaining walls were	☐ Cracked	☐ Partially fallen	☐ Destroyed/fallen
Underground pipes	☐ Cracked	☐ Broken	☐ Out of service

☐ Sidewalks, ☐ Streets, ☐ or Highways damaged; ☐ Large cracks ☐ Buckled ☐ Large displacements

6. Check below any structural damage to buildings.

a. Interior walls ☐ Plaster ☐ Dry Wall ☐ Wallboard

Damage was ☐ Hairline cracks ☐ Large cracks (few) ☐ Large cracks (many)

☐ Split at seams ☐ Fallen ☐ Separated from ceiling or floor

Exterior walls ☐ Brick ☐ Concrete block ☐ Stone ☐ Stucco

☐ Wood frame ☐ Brick Veneer Other_____

Damage was ☐ Hairline cracks ☐ Large cracks ☐ Bulged outward

☐ Partial Collapse ☐ Total collapse Other_____

b. Chimneys ☐ Few ☐ Several ☐ Many

Were ☐ Cracked ☐ Twisted ☐ Bricks fallen

☐ Broken at roof line ☐ Fallen

c. What type of construction was the building that showed this damage?

☐ Wood ☐ Stone ☐ Wood frame w/brick veneer ☐ Steel frame Other_____

☐ Brick ☐ Concrete block ☐ Reinforced concrete ☐ Mobile home

d. What was the type of ground under the building? ☐ Don't know

☐ Sandy soil ☐ Marshy ☐ Fill ☐ Alluvium

☐ Clay soil ☐ Hard rock ☐ Sandstone, limestone, shale

e. Was the ground: ☐ Level ☐ Sloping ☐ Steep?

f. Check the approximate age of the building: ☐ Built before 1945 ☐ Built 1945–65 ☐ Built after 1965

7. Check below any structural damage to:

Bridges/Overpasses ☐ Concrete ☐ Wood ☐ Steel ☐ Other

Damage was ☐ Slight ☐ Moderate ☐ Severe

Dams ☐ Concrete ☐ Large earthen

Damage was ☐ Slight ☐ Moderate ☐ Severe

8. What geologic effects were noted in your community?

Ground cracks	☐ Wet ground	☐ Steep slopes	☐ Dry and level ground
Landslides	☐ Small	☐ Moderate	☐ Large
Rock falls	☐ Small	☐ Moderate	☐ Large
Ground slump ☐ River bank	☐ Road fill	☐ Hillsides	☐ Land fill
Water disturbed?	☐ Wells	☐ Springs	☐ Ponds
	☐ Muddied	☐ Level changed	☐ Flow changed

9. What percentage of buildings were damaged?

a. Within 2 city blocks of your location ☐ None ☐ Few (about 5%)

☐ Many (about 50%) ☐ Most (about 75%)

b. In area covered by your zip code ☐ None ☐ Few (about 5%)

☐ Many (about 50%) ☐ Most (about 75%)

Figure 3.—Continued

A.

PERSONAL REPORT

DID YOU PERSONALLY FEEL AN EARTHQUAKE NEAR THE DATE AND TIME INDICATED ON THE OPPOSITE PAGE?

☐ No ☐ Yes If no, please go to **COMMUNITY REPORT.**

Date _____ Time _____ ☐ a.m. ☐ p.m. ☐ Standard time ☐ Daylight time

2. Your location at time of the earthquake?

City _____ State _____ Zip code _____

Your reaction was ☐ Little reaction ☐ Excitement ☐ Some fright ☐ Great fright ☐ Terror
Did you have difficulty ☐ Standing up ☐ Walking ☐ Maintaining balance
Were you awakened by the earthquake? ☐ No ☐ Yes

Vibration could be described as ☐ Weak ☐ Mild ☐ Moderate ☐ Strong ☐ Violent
Duration of shaking ☐ Sudden, sharp (1–10 secs) ☐ Short (10–30 secs) ☐ Long (30–60 secs)
Direction of shaking ☐ North/South ☐ East/West ☐ Other _____
Earth noise ☐ None ☐ Faint ☐ Moderate ☐ Strong

Were you at ☐ *Home* ☐ *Work* ☐ Inside ☐ Outside ☐ Other _____

If inside, on what floor were you? _____

What were you doing when the earthquake occurred? ☐ Lying down ☐ Sitting ☐ Standing ☐ Walking
☐ Sleeping ☐ Driving (car in motion) ☐ Other _____

COMMUNITY REPORT

DID OTHERS IN YOUR COMMUNITY FEEL THE EARTHQUAKE? ☐ No ☐ Yes
If no, please return the card anyway—"Not felt" reports delimit the felt area.

PLEASE DESCRIBE BELOW EFFECTS FOR *ONLY ONE* COMMUNITY.
I am reporting effects at the community to which this card is addressed ☐ No ☐ Yes
If no, where did these effects occur?

City _____ State _____ Zip code _____

3. This earthquake was felt by ☐ No one ☐ A few ☐ Several ☐ Many ☐ All
This earthquake awakened ☐ No one ☐ A few ☐ Several ☐ Many ☐ All
This earthquake greatly frightened ☐ No one ☐ A few ☐ Several ☐ Many ☐ All

4. Check effects that were noted in your community
☐ *Windows* ☐ *Doors* ☐ *Dishes* rattled ☐ Slightly ☐ Loudly
Walls creaked ☐ Slightly ☐ Moderately ☐ Loudly
Buildings trembled, shook, or rocked ☐ Slightly ☐ Moderately ☐ Strongly

Hanging objects or doors swung ☐ Slightly ☐ Moderately ☐ Violently
Hanging pictures (more than one) ☐ Left out of place/tilted ☐ Fell

Small objects overturned ☐ A few ☐ Several ☐ Many ☐ In some buildings, almost all
Small objects fell ☐ A few ☐ Several ☐ Many ☐ In some buildings, almost all
Dishes or knickknacks broke ☐ A few ☐ Several ☐ Many ☐ In some buildings, almost all
Items thrown from store shelves ☐ A few ☐ Several ☐ Many ☐ In some buildings, almost all

Appliances (TV's, computers, mixers, etc.) ☐ Shifted ☐ Overturned ☐ Fell to floor
Large furniture ☐ Shifted ☐ Overturned
Heavy appliances (ranges, refrigerators) ☐ Contents fell out ☐ Shifted by inches
☐ Shifted by a foot or more ☐ Overturned

Please continue on the reverse side

Figure 4. *A*. Personal report and first two sections of community report from the questionnaire that was used in postal canvasses for the 1999 Satsop earthquake. *B*. Final six sections of community report from the questionnaire that was used in postal canvasses for the 1999 Satsop earthquake.

B.

5. Check outdoor effects that were noted in your community

People ran out of buildings ☐ None ☐ A few ☐ Many
Felt in stopped vehicles ☐ Slightly ☐ Moderately ☐ Strongly
Felt in moving vehicles ☐ Slightly ☐ Moderately ☐ Strongly

Trees and bushes shook ☐ Lightly ☐ Moderately ☐ Strongly
☐ *A few* ☐ *Several* ☐ *Many* Tombstones ☐ Displaced ☐ Cracked ☐ Rotated ☐ Fell
Masonry fences ☐ Cracked ☐ Partially fell ☐ Destroyed/fell
Retaining walls ☐ Cracked ☐ Partially fell ☐ Destroyed/fell
Water splashed onto bank/sides of ☐ Lakes ☐ Ponds ☐ Swimming pools

6. Check damage to buildings that was noted in your community

Windows ☐ A few cracked ☐ Some broke out ☐ Many broke out

Interior walls ☐ *Plaster* ☐ *Drywall* ☐ Hairline cracks ☐ Large cracks (few) ☐ Large cracks (many)
☐ Split at seams ☐ Fell ☐ Separated from ceiling/floor

Exterior walls, wood	☐ Hairline cracks	☐ Large cracks	☐ Bulged	☐ Partial collapse	☐ Total collapse
Exterior walls, brick veneer	☐ Hairline cracks	☐ Large cracks	☐ Bulged	☐ Partial collapse	☐ Total collapse
Exterior walls, solid brick	☐ Hairline cracks	☐ Large cracks	☐ Bulged	☐ Partial collapse	☐ Total collapse
Exterior walls, stucco	☐ Hairline cracks	☐ Large cracks	☐ Bulged	☐ Partial collapse	☐ Total collapse
Exterior walls, concrete block	☐ Hairline cracks	☐ Large cracks	☐ Bulged	☐ Partial collapse	☐ Total collapse
Exterior walls, other_____	☐ Hairline cracks	☐ Large cracks	☐ Bulged	☐ Partial collapse	☐ Total collapse

☐ *Old* ☐ *Modern*	Chimneys cracked	☐ A few	☐ Several	☐ Many
☐ *Old* ☐ *Modern*	Chimneys twisted/leaning	☐ A few	☐ Several	☐ Many
☐ *Old* ☐ *Modern*	Chimneys lost bricks	☐ A few	☐ Several	☐ Many
☐ *Old* ☐ *Modern*	Chimneys fell	☐ A few	☐ Several	☐ Many

7. Check effects on entire structures that were noted in your community

☐ *Old* ☐ *Modern*	Wood buildings	☐ Distorted/off foundation	☐ Partial collapse	☐ Total collapse
☐ *Old* ☐ *Modern*	Brick buildings	☐ Distorted/off foundation	☐ Partial collapse	☐ Total collapse
☐ *Old* ☐ *Modern*	Reinforced concrete buildings	☐ Large cracks in columns	☐ Partial collapse	☐ Total collapse
☐ *Old* ☐ *Modern*	Steel frame buildings	☐ Distorted	☐ Partial collapse	☐ Total collapse
	Mobile homes off foundation	☐ A few	☐ Several	☐ Many
☐ *Old* ☐ *Modern*	Other_____	☐ Distorted	☐ Partial collapse	☐ Total collapse

8. Check effects on lifelines that were noted in your community

Underground pipes developed leaks ☐ A few ☐ Several ☐ Many
Paved ☐ *Sidewalks* ☐ *Streets* ☐ *Highways* ☐ Large cracks ☐ Buckled ☐ Large displacements
☐ *Old* ☐ *Modern* Highway bridges ☐ Approaches settled ☐ Structural damage ☐ Span collapse

Name(s) of roads crossing over/under damaged bridge_____
Regular telephone service unusable ☐ less than one hour ☐ more than one hour ☐ more than one day
Electric power out in some areas ☐ less than one hour ☐ more than one hour ☐ more than one day

9. What geologic effects were noted in your community?

Ground cracks	☐ In wet ground	☐ On steep slopes	☐ In dry and level ground	
Landslides	☐ Small	☐ Moderate	☐ Large	
Rock falls	☐ Small	☐ Moderate	☐ Large	
Ground slump	☐ River bank	☐ Road fill	☐ Hillsides	☐ Land fill
☐ *Well* ☐ *Spring* ☐ *Pond* Water disturbed		☐ Muddied	☐ Level changed	☐ Flow changed

10. What percentage of buildings were damaged?

Within 2 city blocks of your location ☐ None ☐ Few (about 5%) ☐ Many (about 50%) ☐ Most (about 75%)
In area covered by your zip code ☐ None ☐ Few (about 5%) ☐ Many (about 50%) ☐ Most (about 75%)

Figure 4.—Continued

The 1987 to Early 2000s Gap in Reporting MMI

As previously mentioned, the nine earthquakes studied here (table 2; fig. 1) occurred in a time period, from 1987 until the early 2000s, during which the USGS collected observations by means of postal questionnaires for newsworthy earthquakes, but during which detailed analyses of macroseismic observations were published for only a relatively few, unusually high-interest, earthquakes (Dewey and Hopper, 1997). For most canvassed earthquakes during this time period, including the Washington earthquakes that are the subject of this report, preliminary intensities were assigned from the most quickly returned postal questionnaires and (or) media observations, and the largest of these MMI values reported in the Preliminary Determination of Epicenters (PDE) publications of the U.S. Geological Survey (for example, 2016c). Traditional USGS MMI for most communities experiencing these earthquakes, however, have not previously been reported. In the case of the 1996 Duvall earthquake, maximum traditional USGS MMI of V were reported in the PDE, whereas in the present study we assign traditional USGS MMI VI to four communities for which MMI were not reported in the PDE and for which, we suppose, the questionnaires must not have been returned in time to have been included in the PDE.

In Canada, the 1987–2000 time window also represents a period of transition from paper-based postal questionnaires to internet-based survey forms. For this report the data from USGS postal questionnaires are supplemented by traditional MMI observations for these earthquakes from British Columbia, derived from a variety of sources (for example, phone calls, media reports) as well as published reports (Drysdale and others, 1989, 1990) and unpublished internal reports including Drysdale and Horner (1995, 1996, 1999). At the time of the *M*5.8 1999 Satsop earthquake, the Geological Survey of Canada (Sidney office) used a web-based questionnaire form similar to one used by the PNSN at the University of Washington Seattle (described below).

Purposes of this Report

The primary purpose of this report is to document, in detail, the distributions of traditional MMI for the nine central and western Washington earthquakes between 1989 and 1999. In addition to documenting the impacts of these earthquakes on people and structures, the distributions of traditional MMI for these earthquakes—for which modern digital instrumental data are available—are important in order to calibrate inferences made from macroseismic data about earlier Washington earthquakes for which modern instrumental data are not available.

Another motivation of our study derives from the fact that four of the earthquakes were previously been characterized by MMI based on intensity data collected over the internet. Researchers of the PNSN at the University of Washington Seattle implemented an internet-based procedure for collecting macroseismic data and assigning MMI in the Pacific Northwest in the mid-1990s (Qamar and others, 1995); the procedure was a forerunner to the USGS CII/DYFI procedure (Wald and others, 1999). When first implemented for the 1995 Point Robinson earthquake, intensity reports were submitted to PNSN in three ways: (1) questionnaires printed in newspapers, filled out and mailed in by respondents, and manually entered into the database at PNSN (about 7,000 responses); (2) email versions of the same questionnaire submitted by the respondents to PNSN by email (about 1,100 responses); and (3) a web-based form submitted directly by the respondent (about 600 responses). As with the case for the USGS CII/DYFI procedure, the PNSN procedure was calibrated to produce results generally consistent with traditional MMI. As with the CII/DYFI procedure, but unlike the procedure used for traditional USGS MMI, the PNSN internet intensities were based on observations volunteered rather than solicited through a canvassing procedure, and the internet-based procedure would have

treated macroseismic data differently than the traditional USGS MMI procedure. With the availability now of the traditional USGS MMI interpreted for all the sites from which USGS postal questionnaires were returned, the four Washington earthquakes join a small group of earthquakes for which both traditional USGS MMI and some type of internet-based MMI have been assigned. We use contoured maps of internet-based MMI prepared by the PNSN both to increase understanding of the shaking produced by the four earthquakes beyond what can be inferred from the traditional USGS MMI, and to test the extent to which internet-based intensities, assigned by a procedure that is related to the CII/DYFI procedure, correspond to traditional USGS MMI.

Comparing Traditional MMI to Community Internet Intensity Reports

The PNSN community internet intensity maps are broadly consistent with the traditional USGS MMI maps for regions of moderate and strong shaking, although in these regions there are minor differences between the PNSN and USGS MMI maps. We discuss the similarities and differences in regions of moderate and strong shaking for each earthquake. A number of mechanisms have been proposed that would cause such differences (for example, Dewey and others, 2002; Wald and others, 2011). Some of the differences between the two maps almost certainly reflect situations in which either the PNSN procedure or the traditional MMI procedure collected reports of macroseismic effects for a community that do not adequately reflect the actual effects. The different procedures by which data are collected and the different manner in which the collected data are processed would cause some difference in the resulting intensities. Some apparent differences probably reflect the different methods of data-presentation—contour map versus plot of individual intensities. We also discuss a tendency for the PNSN internet intensities to be larger than traditional USGS MMI intensities near the margins of the felt area defined by traditional USGS MMI for the 1999 Satsop earthquake; we propose several possible explanations for this tendency.

Format of the Remainder of this Report

In the remainder of this report, we summarize the felt reports for the nine 1989–1999 Washington state earthquakes listed in table 2. For each earthquake there is a standard format for the discussion. First, we summarize the earthquake, its focal mechanism and tectonic significance, any significant damage produced by the earthquake, and the intensities reported for the earthquake. Then, we summarize the felt observations for each seismic intensity, starting with the highest intensity observations and ending with the lowest (not felt) intensity observations. Generally, detailed descriptions of the felt observations are restricted to MMI of V or greater, but for two of the smaller earthquakes we detail the observations for MMI IV. Zip codes are provided in some cases to help localize the intensity report. Finally, and if available, we compare maps of the USGS traditional MMI to the PNSN community internet intensity.

*M*4.5 1989 Olympic Peninsula Earthquake

UTC Date and Time: March 5, 1989 06:42:00 (UTC)
Local Date and Time: March 4, 1989 10:42:00 PM PST
Epicenter: 47.813° N., 123.357° W.
Depth: 45.3±1.9 km (28.1±1.2 miles)
Magnitude: 4.5 M_D(PNSN), 4.6 m_b(USGS)

Summary

The *M*4.5 1989 Olympic Peninsula earthquake occurred within the subducting Pacific Plate at a depth of 45 km beneath the Olympic Peninsula in western Washington (fig. 1). The PNSN focal mechanism indicates normal faulting along a north-trending fault (fig.1).

Intensity data show that the subcrustal earthquake was felt weakly throughout the Puget Lowland, San Juan Islands, and along the southeastern tip of Vancouver Island, from Sooke to Victoria to Sidney (fig. 5). The strongest shaking intensity that was well-documented on a postal questionnaire, IV, was reported at Forks, where the quake was felt by many, windows, doors, and dishes rattled, and the walls creaked. An observation (see following summary) at Port Ludlow (fig. 5) to which we assigned an intensity III might be evidence of intensity IV or V effects having occurred, but to assign such an intensity we would need more information on the circumstances of the observation or independent macroseismic observations that were consistent with intensity IV or V. There were no reports of damage or injuries associated with the earthquake.

An *M*3.1 aftershock of the *M*4.5 Olympic Peninsula earthquake occurred on March 6, 1989, which also shook windows, walls, furniture and homes in Forks, Washington, but caused no damage or injuries (Erb, 1989). According to this press report, nine Forks residents called to report the aftershock. Pictures were left askew, suggestive of an overall intensity of III to IV for the aftershock in Forks.

For the *M*4.5 mainshock, 124 postal questionnaires were sent out to a canvass radius of 125 kilometers (km) and 83 (67 percent) were returned (table 3).

Intensity IV

Forks, Washington (91 km)—Felt by many (IV), awakened few (II), frightened few (II), windows, doors, dishes rattled slightly (III), walls creaked slightly (III), no building damage within two city blocks.

Forks, Washington (press report on the *M*4.5 mainshock)—"At 10:42 p.m. Saturday an earthquake south of Blyn measuring 4.4 on the Richter scale was felt over most of the Olympic Peninsula and the Puget Sound region" (Erb, 1989).

Forks, Washington (press report on a *M*3.1 aftershock on Monday, March 6, 1989)—"Forks police said there were no reports of damage or injuries." Walls were shaken, "knocking pictures askew." "After the earthquake, Forks police got five phone calls from people throughout the area who reported shaking windows, walls, furniture and homes." "Four additional people called the department Tuesday morning to report the earthquake" (Erb, 1989).

Intensity III

We assigned intensity III to seven communities. Hypocentral distances for these communities ranged between 68 and 127 km, with a median hypocentral distance of 82 km.

Felt (III) in Washington at Freeland, Graham, Port Ludlow (opened window, stove opened and ash poured out; Pacific Northwest Seismic Network, 1989), and Seattle (in the Lincoln Park neighborhood, zip code 98136).

Felt (II-III) on southern Vancouver Island, British Columbia, Canada, from Sooke to Victoria to Sidney (Drysdale and others, 1989).

Intensity II

We assigned intensity II to 12 communities. Hypocentral distances for these communities ranged between 56 and 113 km, with a median hypocentral distance of 92 km.

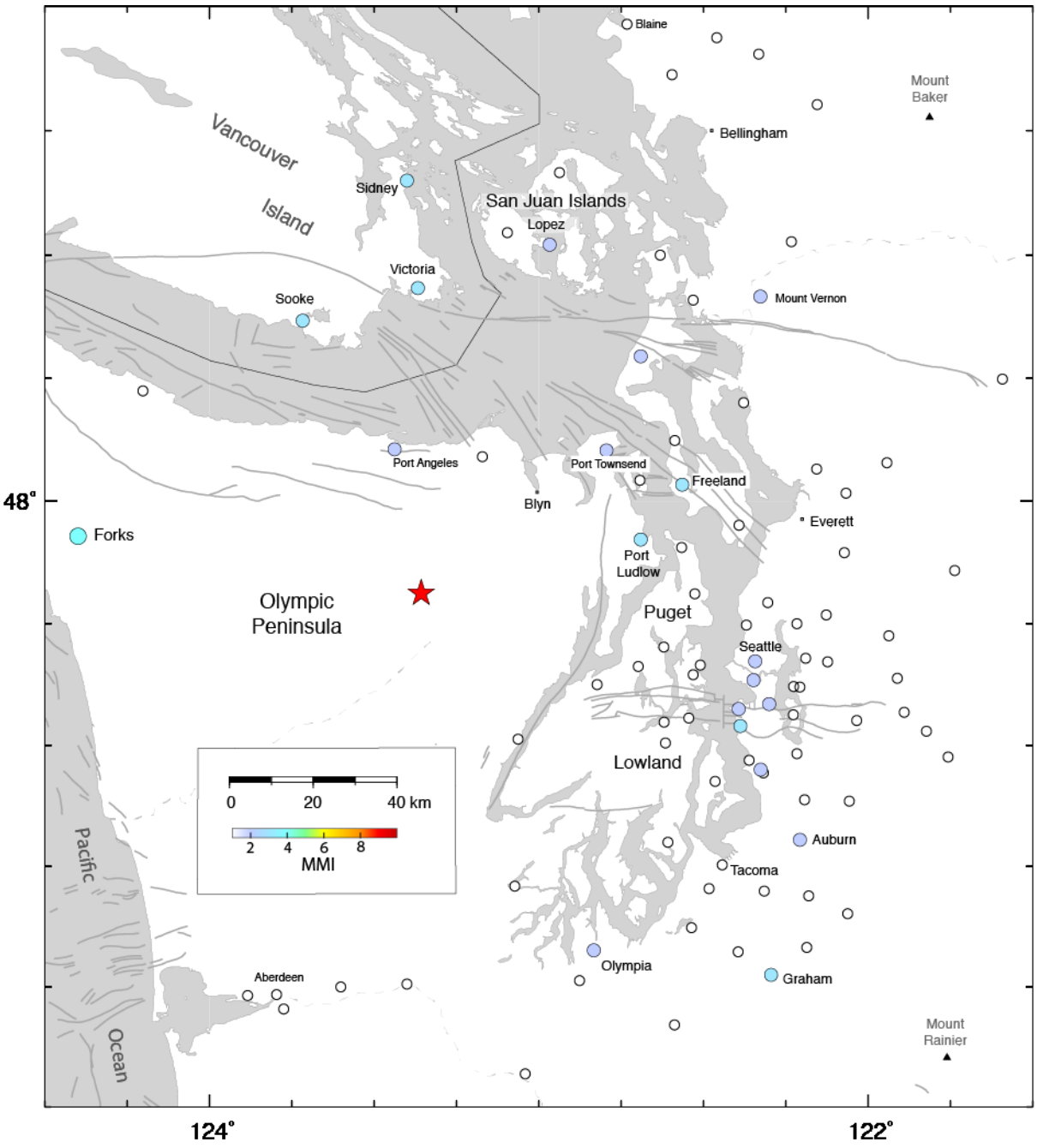


Figure 5. Modified Mercalli Intensities for the *M*4.5 1989 Olympic Peninsula earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which responses were received. Communities that reported that the earthquake was not felt are shown by smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. Gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes.

Felt (II) in Washington at Lopez and Seattle (Wallingford, 98103).

Reported felt in Washington at Auburn, Burien, Mount Vernon, Olympia, Port Angeles, Port Townsend, Seattle (Beacon Hill, Queen Anne Hill), West Seattle, and Whidbey Island. Apart from a postal questionnaire from Port Townsend, these felt observations are all from PNSN (written commun., 1989).

Not Felt (I)

We assigned intensity I (not felt) to 73 communities. Hypocentral distances for these communities ranged between 57 and 150 km, with a median hypocentral distance of 103 km.

Reported not felt (I) in 73 communities in Washington at Aberdeen, American Lake (Tacoma), Anacortes, Bainbridge Island-Winslow, Bellevue (98004), Blaine, Bothell, Buckley, Carlsborg, Carnation, Clallam Bay, Clinton, Cosmopolis, Darrington, Deming, Duvall, Eastsound, Elma, Everson, Fall City, Ferndale, Forks, Friday Harbor, Gig Harbor, Granite Falls, Greenbank, Hansville, Hoquiam, Issaquah, Kent, Keyport, Kingston, Kirkland, La Conner, Lake Stevens, Lilliwaup, Lynden, Manchester, Maple Valley, Marysville, Medina, Mercer Island, Montesano, Mountlake Terrace, Nordland, North Bend, Olympia, Orting, Port Orchard, Puyallup (west) (98371), Redmond, Renton, Retsil, Rochester, Rollingbay, Seabeck, Seahurst, Seatac, Seattle (Shoreline, 98177), Sedro Woolley, Shelton, Silverdale, Snohomish, Snoqualmie, Spanaway, Stanwood, Sultan, Sumner, Tacoma (98413), Tacoma (south) (98409), Vashon, Woodinville, and Yelm.

*M*4.5 1989 Okanogan Earthquake

UTC Date and Time: May 9, 1989 18:28:45 UTC
Local Date and Time: May 9, 1989 11:28:45 AM PDT
Epicenter: 48.230° N, 119.854° W
Depth: 14.6±2.8 km (9.1±1.7 miles)
Magnitude: 4.5 M_D(PNSN), 4.4 m_b(USGS)

Summary

The *M*4.5 1989 Okanogan earthquake occurred in north-central Washington (fig. 1). The PNSN focal-mechanism for the earthquake implies oblique-normal slip on a north-trending, east-dipping, fault or on a north-northwest-trending, southwest-dipping fault (fig. 1).

This earthquake was reported felt to a radius of at least 100 km from Wenatchee, Washington, in the south to Oroville, Washington, in the north (fig. 6). The strongest reported intensity, VI, was from Okanogan, Washington, where interior walls and chimneys were cracked and (or) split. No injuries or significant damage were reported.

There were 47 questionnaires mailed to a canvass radius of 100 km and 42 (89 percent) were returned (table 3). This canvass radius was insufficient to define the boundary between the region from which most questionnaires reported that the earthquake was felt and the region beyond where most communities did not feel the earthquake, almost all respondents reported feeling the earthquake (fig. 6).

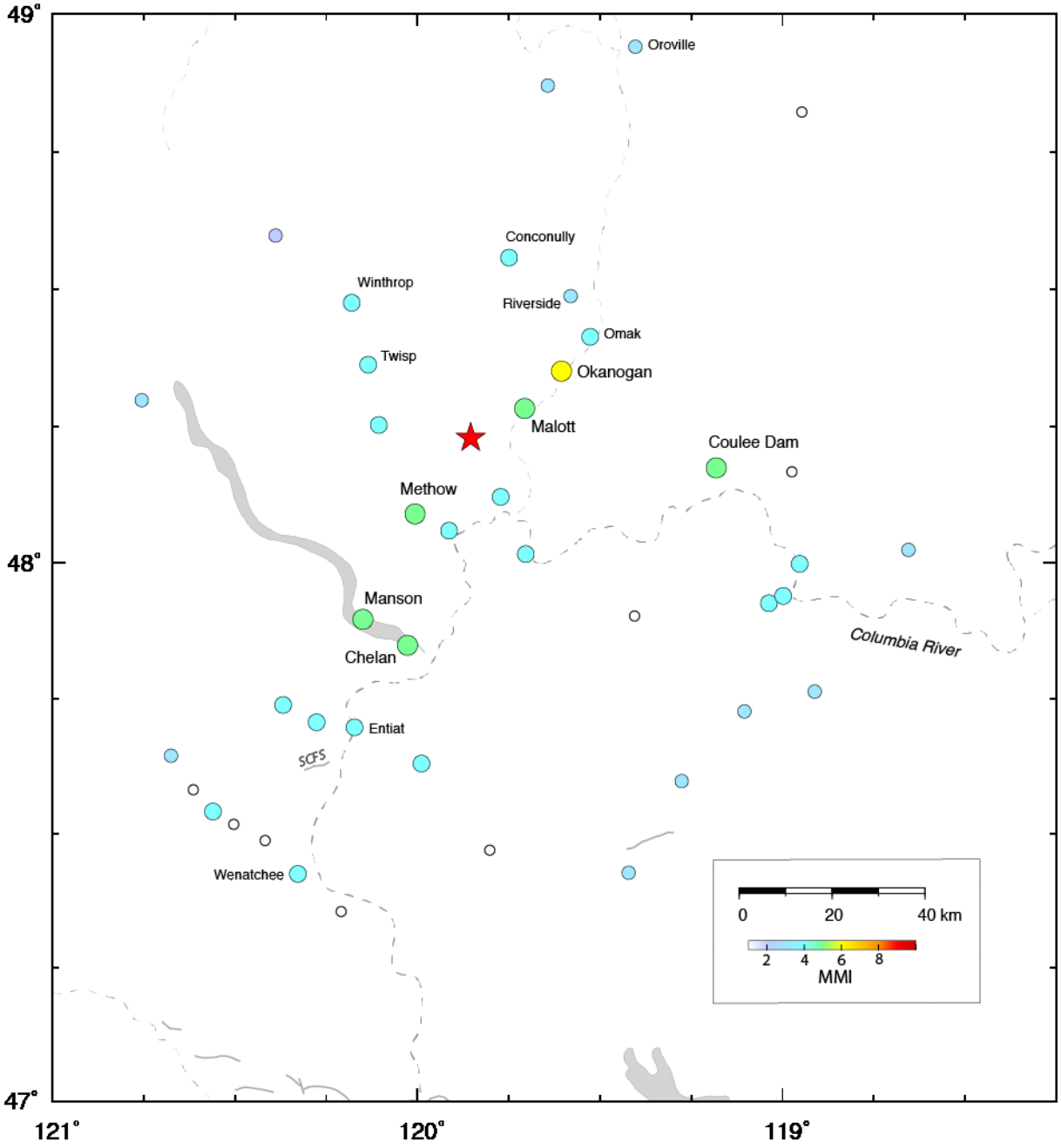


Figure 6. Modified Mercalli Intensities for the *M*4.5 1989 Okanogan earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which responses were received. Communities that reported that the earthquake was not felt are shown as smaller white circles. Spencer Canyon fault scarp (SCFS), thought to have been produced by the large December 1872 Washington State earthquake (Sherrod and others, 2015), is located southwest of Entiat.

Intensity VI

Okanogan, Washington (27 km)—Felt by many (IV), awakened no one, frightened several (III), windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects fell (V), hanging objects or doors swung slightly (III), hairline cracks in interior plaster/stucco walls (V), hairline cracks in interior dry wall (V), chimneys cracked (VI), interior walls split (VI), slight damage to concrete dams, few (about 5 percent) buildings damaged within two city blocks.

Intensity V

We assigned intensity V to five communities. Hypocentral distances for these communities ranged between 19 and 52 km, with a median hypocentral distance of 46 km.

Chelan, Washington (47 km)—Felt by many (IV), frightened several (III), windows, doors, dishes rattled loudly (IV), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), trees and bushes shaken moderately (V), standing vehicles rocked slightly (III).

Coulee Dam, Washington (52 km)—Felt by many (IV), awakened a few (II), frightened many (IV), windows, doors, dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled strongly (≥IV), a few small objects overturned (V), a few small objects fell (V), trees and bushes shaken slightly (IV), water splashed onto sides of lakes, ponds, swimming pools, no building damage within two city blocks.

Malott, Washington (19 km)—Felt by many (IV), awakened a few (II), frightened many (IV), windows, doors, dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects/doors swung slightly (III), a few items thrown from store shelves (V), questions 5 to 10 on the returned questionnaire were answered by "no damage".

Manson, Washington (46 km)—Felt by many (IV), frightened a few (II), windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), glassware/dishes broke (V).

Methow, Washington (24 km)—Felt by all (≥IV), awakened no one, frightened several (III), windows, doors, dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled moderately (IV), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes broke (V), hanging objects/doors swung slightly (III), no items were thrown from store shelves, cracks in interior walls (≥V), trees and bushes shaken slightly (IV), standing vehicles rocked slightly (III), no building damage within two city blocks. Questions 5, 6 (second half), 7, 8, 9, and 10 on the returned questionnaire were answered by "no damage" or "none".

Intensity IV

We assigned intensity IV to 17 communities. Hypocentral distances for these communities ranged between 20 and 97 km, with a median hypocentral distance of 65 km.

Felt (IV) in Washington at Ardenvoir, Brewster, Bridgeport, Carlton, Conconcully, Dryden, Electric City, Elmer City, Entiat, Grand Coulee, Omak, Orondo, Pateros, Twisp, Waterville, Wenatchee, and Winthrop.

Intensity III

We assigned intensity III to 10 communities. Hypocentral distances for these communities ranged between 38 and 96 km, with a median hypocentral distance of 85 km.

Felt (III) in Washington at Almira, Coulee City, Hartline, Keller, Leavenworth, Loomis, Oroville, Riverside, Stehekin, and Stratford.

Intensity II

Felt (II) in Washington at Mazama (59 km).

Not Felt (I)

We assigned intensity I (not felt) to eight communities. Hypocentral distances for these communities ranged between 52 and 102 km, with a median hypocentral distance of 93 km.

Reported not felt (I) in Washington at Cashmere, Malaga, Mansfield, Monitor, Nespelem, Palisades, Peshastin, and Wauconda.

There were no felt reports from Canada.

*M*4.9 1989 Morton Earthquake

UTC Date and Time: December 24, 1989 08:45:58 UTC
Local Date and Time: December 24, 1989 12:45:58 AM PST
Epicenter: 46.650° N, 122.116° W
Depth: 17.3±1.1 km (10.7±0.7 miles)
Magnitude: 4.9 M_D(PNSN), 4.3 m_b(USGS)

Summary

The *M*4.9 1989 Morton crustal earthquake was located about 38 km southwest of Mount Rainier (fig. 1). The PNSN focal mechanism shows oblique reverse-faulting on either an east- or north-trending fault (fig. 1).

The earthquake was reported as felt in Washington west of the Cascade arc, but was not reported felt as far northwest as Vancouver Island or, with one exception, as far south as Oregon (fig. 7*A*). The communities reporting the strongest shaking, intensity V, were mainly limited to the western foothills of the Cascade arc and the eastern side of the Puget Lowland (fig. 7*B*). Site response and poor design may have contributed to the cracking of windows in Kirkland, which is located on the east side of Lake Washington. No injuries or significant damage were reported.

There were 326 questionnaires mailed to a canvass radius of 250 km and 240 (74 percent) were returned (table 3).

Intensity V

We assigned intensity V to 10 communities. Hypocentral distances for these communities ranged between 23 and 116 km, with a median hypocentral distance of 69 km.

Ashford, Washington (23 km)—Felt by many (IV), awakened several (III), frightened a few (II), windows, doors, and dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place (V), a few small objects overturned (V), hanging objects or doors swung slightly (III), no building damage within two city blocks or within zip codes. Question 5 on the returned questionnaire was answered by "none I know of"; questions 6 to 9 answered as "none".

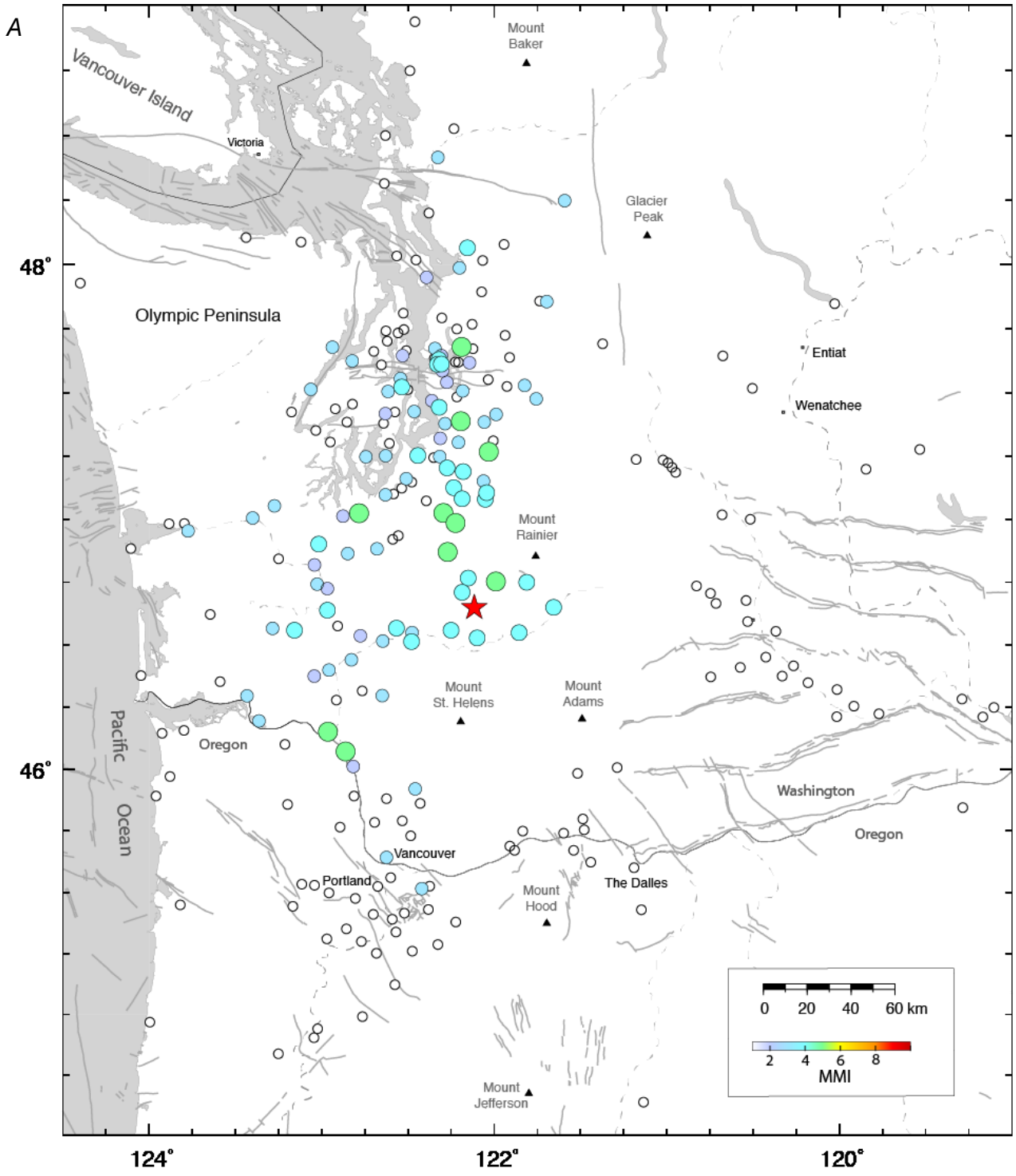


Figure 7. *A*. Modified Mercalli Intensities for the *M*4.9 1989 Morton earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which responses were received. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. *B*. Expanded view of the Modified Mercalli Intensities for the *M*4.9 1989 Morton earthquake (red star). Communities that reported that the earthquake was not felt are shown as smaller white circles. Gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes.

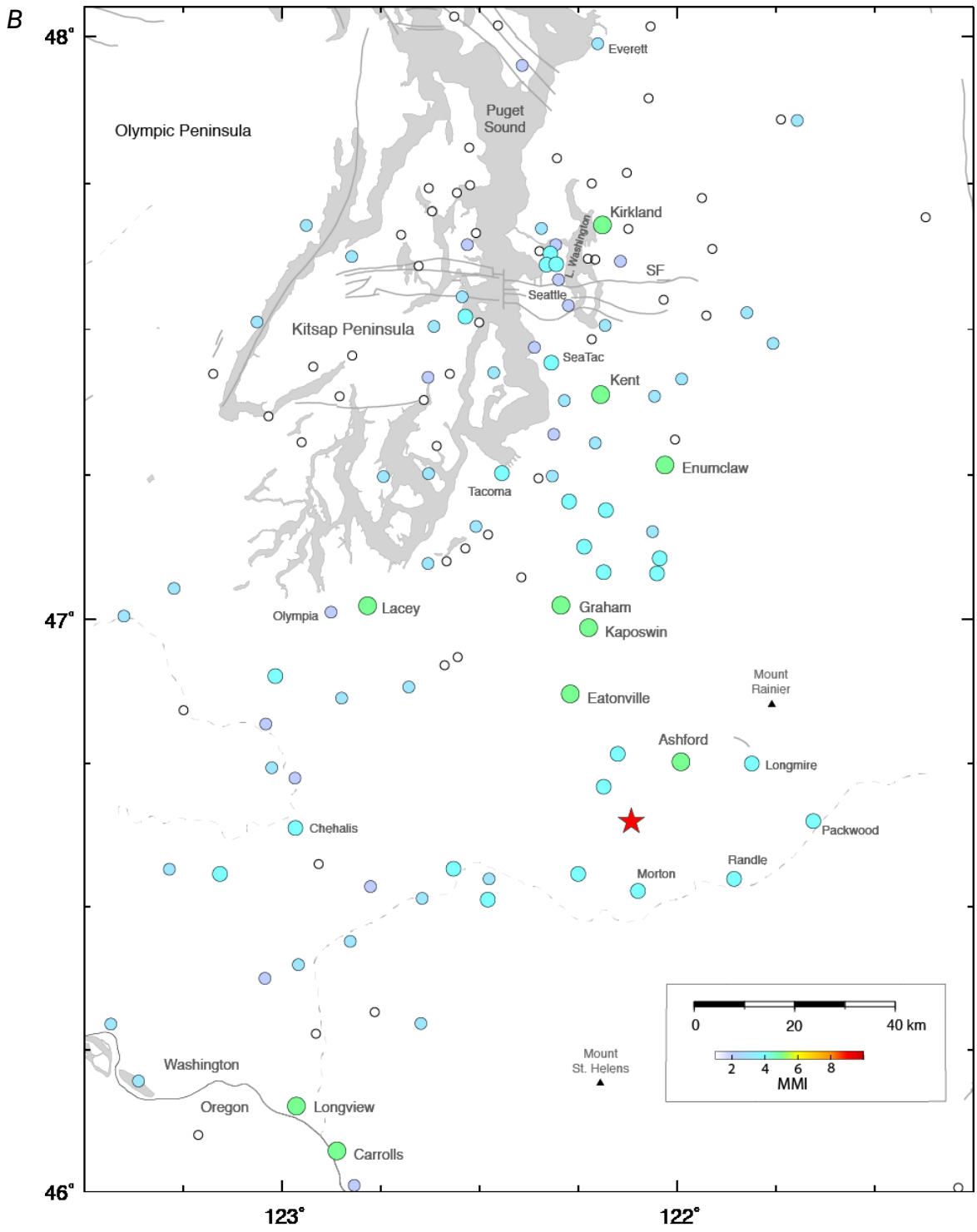


Figure 7.—Continued

Carrolls, Washington (88 km)—Felt by few (II), frightened few (II), windows, doors, dishes rattled slightly (III), building trembled slightly (III), a few small objects overturned (V), a few small objects fell (V), a few items thrown from store shelves (V), small cracks in sidewalks. No cracks in interior walls. Questions 8 and 9 on the returned questionnaire were answered by "No"; question 10 answered by "?".

Eatonville, Washington (32 km)—Felt by many (IV), windows, doors, dishes rattled slightly (III), building trembled slightly (III), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes broken (V), springs or well water muddied, no building damage within two city blocks.

Enumclaw, Washington (71 km)—Felt by few (II), awakened few (II), frightened no one, windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place (V), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes broken (V), a few items thrown from store shelves (V), no building damage within two city blocks or within zip code.

Graham, Washington (47 km)—Report 1: Felt by several (III), awakened a few (II), frightened a few (II), windows, doors, dishes rattled slightly (III), building trembled slightly (III), a few glassware/dishes broken (V), a few items thrown from store shelves (V), no building damage within two city blocks. Report 2: Felt by all (≥IV), awakened all (≥IV), frightened few (II), hairline cracks in interior dry walls (V), trees and bushes shaken slightly (IV).

Kapowsin, Washington (42 km)—Felt by many (IV), awakened several (III), frightened no one, windows, doors, dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place (V), a few small objects overturned (V), a few small objects fell (V), hanging pictures or doors swung slightly (III). Respondent's comment: "No reported damage."

Kent, Washington (84 km)—"Knocked pictures off the wall" (V) (Pacific Northwest Seismic Network, written commun., 1989). The PNSN also reported that the Kent police station "received great number of calls" (≥IV) and another observer reported "rattled mirror on the wall, wondered if it was an earthquake" (III).

Kirkland, Washington (115 km)—Felt strongly in an apartment building with a soft first story located in a wetlands area along Lake Washington. A window and two sliding doors were cracked and a crack was enlarged in the ceiling (V) (Pacific Northwest Seismic Network, written commun., 1989).

Lacey, Washington (68 km)—Felt by few (II), awakened no one, frightened no one, windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place (V), a few windows cracked (V), a few small objects overturned (>V), a few small objects fell? (V), a few glassware/dishes broken? (V), hanging objects or doors swung slightly (III), no building damage within two city blocks.

Longview, Washington (87 km)—A Carrolls, Washington, postal employee report: "Car motor sitting on floor at son's house in Longview, Washington tipped over." (V)

Intensity IV

We assigned intensity IV to 26 communities. Hypocentral distances for these communities ranged between 19 and 158 km, with a median hypocentral distance of 59 km.

Returned questionnaires indicate that the earthquake was felt (IV) in Washington at Carbonado, Chehalis, Cinebar, Curtis, Elbe, Glenoma, Greenwater, Littlerock, Longmire, Marysville, McMillin, Mineral, Morton, Mossyrock, Orting, Packwood, Puyallup (northeast) (98372), Randle, Seatac, South Colby, Sumner, Tacoma, and Wilkeson. In addition, the Pacific Northwest Seismic Network (written commun., 1989) reported observations indicative of intensity IV at Harmony (very loud report like a

rifle and the house moved left to right), Seattle (Capitol Hill, bed moved), Seattle (First Hill, "about threw me out of bed as I sat on the edge"), and Seattle (near the corner of Summit and Howell streets, "my plant jumped up in the air").

Intensity III

We assigned intensity III to 43 communities at hypocentral distances ranging from 34 to 198 km, with a median hypocentral distance of 91 km.

Felt (III) in Oregon at Gresham.

Returned questionnaires indicate that the earthquake was felt (III) in Washington at Amboy, Auburn, Brinnon, Buckley, Cathlamet, Cosmopolis, Darrington, Dupont, Elma, Everett, Fox Island, Galvin, Kent, Kent (Midway), Lakebay, Lakewood Center (east), Lilliwaup, Manchester, Maple Valley, McCleary, Milton, Mount Vernon, Pe Ell, Rainier, Ravensdale, Salkum, Seabeck, Silver Creek, Skamokawa, Snoqualmie, Tenino, Toledo, Toutle, Vader, and Vancouver (Evergreen Park). In addition, the Pacific Northwest Seismic Network (written commun., 1989) reported observations indicative of intensity III at Gold Bar (hanging objects swung slightly, duration estimated), North Bend (rattled furniture), Port Orchard (duration estimated), Renton (Kennydale, building shook), Seattle (Green Lake, house rumbled), and Vashon Island (woke resident).

Intensity II

We assigned intensity II to 15 communities. Hypocentral distances for these communities ranged between 55 and 147 km, with a median hypocentral distance of 95 km.

Felt (II) in Washington at Burley, Centralia, Clinton, Ethel, Kalama, Rochester, Ryderwood, Seahurst, and Seattle (98102).

Felt in Washington at Bainbridge Island, Bellevue, Federal Way, Olympia, Seattle (Leschi and Rainier Valley along west shore of Lake Washington), and all over Thurston County (Pacific Northwest Seismic Network, written commun., 1989).

Not Felt (I)

We assigned intensity I (not felt) to 150 communities. Hypocentral distances for these communities ranged between 49 and 256 km, with a median hypocentral distance of 128 km.

Reported not felt (I) in Oregon at Astoria, Beaver Creek, Beaverton, Boring, Canby, Cannon Beach, Cascade Locks, Clackamas, Clatskanie, Columbia City, Cornelius, Estacada, Forest Grove, Friend, Gaston, Gladstone, Hermiston, Hillsboro (south), Hood River, Lincoln City, Madras, Marylhurst, Molalla, Monmouth, Newberg, Odell, Oregon City, Portland (97208), Portland (International Airport) (97218), Salem (97302, 97310), Sandy, Scappoose, Seaside, Sherwood, Silverton, The Dalles, Tillamook, Troutdale, Vernonia, Warrenton, and Wilsonville.

Reported not felt (I) in Washington at Aberdeen, Allyn, American Lake (Tacoma), Anacortes, Battle Ground, Belfair, Bellevue (98004), Bellingham, Black Diamond, Bothell, Brush Prairie, Carnation, Carson, Cashmere, Castle Rock, Chelan, Cle Elum, Cowiche, Dockton, Duvall, Easton, Ellensburg, Ephrata, Fife, Forks, Fort Lewis, Freeland, Gig Harbor, Glenwood, Grandview, Granger, Granite Falls, Grapeview, Grays River, Harrah, Hoodsport, Hoquiam, Husum, Indianola, Issaquah, Kennewick, Keyport, Kingston, La Center, Lake Stevens, Langley, Leavenworth, Long Beach, Lynden, Mabton, McChord Air Force Base, McKenna, Medina, Menlo, Mountlake Terrace, Moxee City, Naches, Napavine, Oak Harbor, Oakville, Olalla, Pasco, Port Angeles, Poulsbo, Preston, Prosser, Quincy, Redmond, Renton, Richland, Ridgefield, Rollingbay, Ronald, Roslyn, Seattle (Queen Anne E),

Sedro Woolley, Selah, Sequim, Silverdale, Silverlake, Skykomish, Snohomish, South Cle Elum, Southworth, Spanaway, Stanwood, Stevenson, Sultan, Sunnyside, Suquamish, Tahuya, Thorp, Tieton, Toppenish, Tracyton, Trout Lake, Underwood, Union, Wapato, Wauna, Westport, White Salmon, White Swan, Woodinville, Yacolt, Yakima, Yelm, and Zillah.

There were no felt reports from Canada.

*M*5.0 1990 Deming Earthquake

UTC Date and Time: April 14, 1990 05:33:26 UTC
Local Date and Time: April 13, 1990 10:33:26 PM PDT
Epicenter: 48.845° N, 122.160° W
Depth: 11.9±0.2 km (7.4±0.1 miles)
Magnitude: 5.0 M_D(PNSN), 4.4 m_b(USGS)

Summary

The *M*5 1990 Deming earthquake occurred in northwest Washington between Bellingham and Mount Baker (fig. 1). The PNSN focal mechanism for the earthquake is oblique-reverse slip along a fault trending northeast (fig. 1). The south-dipping Macaulay Creek thrust fault is thought to have been the causative structure for the 1990 Deming earthquake and aftershocks (Qamar and Zollweg, 1990; Amadi, 1992; Dragovich and others, 1997; Haugerud and others, 2005). The earthquake was the largest of a swarm of earthquakes in the Deming area that produced four *M*4 to *M*5 events between April 2 and 14, 1990. In all, the swarm produced nearly 100 small to moderate shallow earthquakes in the vicinity of Nooksack Forks (Amadi, 1992; Cascadia Region Earthquake Workgroup, 2009).

The Deming earthquake was felt in the upper Puget Lowland, the San Juan Islands, Vancouver Island, and lower mainland of British Columbia and upper mainland of Washington. The largest reported intensity for the earthquake, intensity VII, was for Deming, Washington, where chimneys twisted, cracked, and fell, and many items were thrown from store shelves (fig. 8). The earthquake also caused the temporary closure of the U.S.-Canada border at Blaine, Washington (Cascadia Region Earthquake Workgroup, 2009). No injuries were reported.

There were 100 questionnaires mailed to a canvass radius of 175 km and 84 (84 percent) were returned (table 3).

Intensity VII

Deming, Washington (13 km)—Felt by all (≥IV), awakened many (IV), frightened many (IV), windows, doors, dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled strongly (≥IV), hanging pictures fell (V), some windows broken out (VI), many small objects overturned (≥V), many small objects fell (≥VI), many glassware/dishes broken (≥VI), light furniture or small appliances overturned and damaged seriously (VI), hanging objects or doors swung moderately (IV), many items thrown from store shelves (≥VI), hairline cracks in interior dry wall (V), standing vehicles rocked moderately (IV), chimneys cracked (VI), chimneys twisted (VII), chimneys fell (VII), foundation of a cinderblock building cracked (VI), spring or well water muddied, few (about 5 percent) buildings damaged within two city blocks and within zip code.

Intensity V

We assigned intensity V to four communities. Hypocentral distances for these communities ranged between 19 and 61 km, with a median hypocentral distance of 21 km.

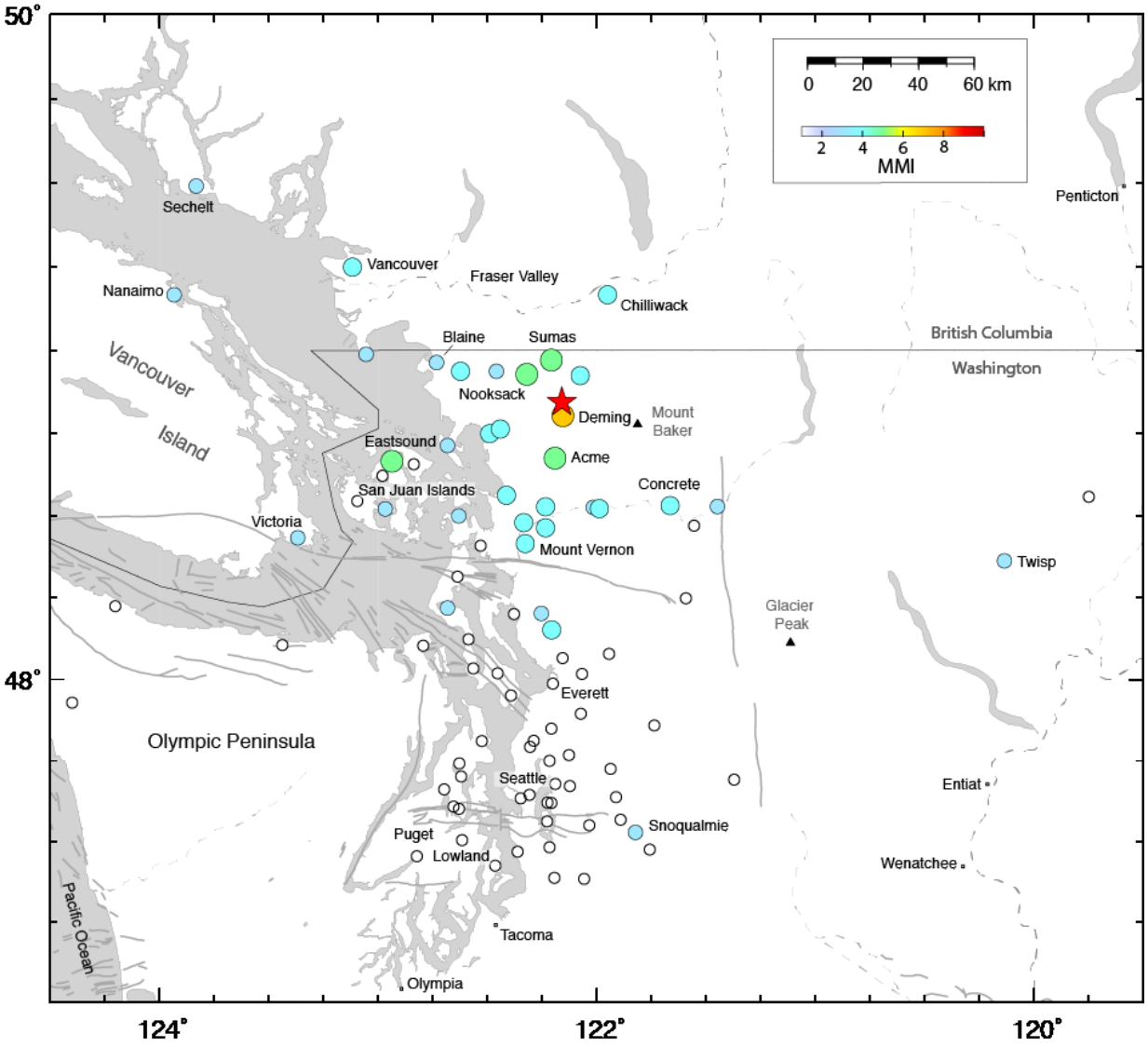


Figure 8. Modified Mercalli Intensities for the *M*5 1990 Deming earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which responses were received. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. Gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes.

Acme, Washington (22 km)—Felt by all (IV), awakened many (IV), frightened a few, windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung moderately (IV), no building damage within two city blocks.

Eastsound, Washington (61 km)—Felt by several (III), awakened few (II), frightened no one, windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), standing vehicles rocked slightly (III), no building damage within two city blocks or within zip code.

Nooksack, Washington (19 km)—Felt by many (IV), awakened many (IV), frightened many (IV), windows, doors, dishes rattled loudly (IV), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place (V), a few small objects overturned (V), no building damage within two city blocks or within zip code.

Sumas, Washington (19 km)—Felt by many (IV), awakened many (IV), frightened many (IV), windows, doors, dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), hairline cracks in interior plaster/stucco walls (V), no building damage within two city blocks.

Intensity IV

We assigned intensity IV to 15 communities. Hypocentral distances for these communities ranged between 13 and 84 km, with a median hypocentral distance of 40 km.

Felt (IV) in Washington at Bellingham (98225), Bellingham (northeast) (98226), Bow, Burlington, Clearlake, Concrete, Custer, Glacier, Hamilton, Lakewood, Maple Falls, Mount Vernon, and Sedro Woolley.

Felt throughout the lower mainland of British Columbia in the Upper, Central and Lower Fraser Valley from Chilliwack to Vancouver (maximum intensity IV) (Chilliwack Progress Staff, 1990; Drysdale and others, 1990).

Intensity III

We assigned intensity III to 15 communities. Hypocentral distances for these communities ranged between 27 and 159 km, with a median hypocentral distance of 70 km.

Felt (III) in Washington at Anacortes, Blaine, Coupeville, Lopez, Lummi Island, Lyman, Lynden, Marblemount, Point Roberts, Silvana, Snoqualmie, and Twisp.

Felt mildly (II-III) as far north as Sechelt, British Columbia (Drysdale and others, 1990).

Felt mildly (II-III) on southern Vancouver Island, British Columbia from Victoria to Nanaimo (Drysdale and others, 1990).

Intensity II

None reported.

Not Felt (I)

We assigned intensity I (not felt) to 54 communities. Hypocentral distances for these communities ranged between 55 and 195 km, with a median hypocentral distance of 127 km.

Reported not felt (I) in Washington at Belfair, Bellevue (Bellevue Square), Bothell, Bremerton (northeast), Carnation, Clallam Bay, Clinton, Conconully, Darrington, Deer Harbor, Duvall, Everett, Fall City, Forks, Freeland, Friday Harbor, Granite Falls, Greenbank, Issaquah, Kent, Keyport, Kingston, Kirkland, La Conner, Lake Stevens, Langley, Lynnwood, Maple Valley, Marysville, Medina, Mercer Island, Mill Creek, Mountlake Terrace, Seattle (98102), North Bend, Oak Harbor, Olga, Port Angeles, Port Orchard, Port Townsend, Poulsbo, Redmond, Renton, Rockport, Seahurst, Seattle (Queen Anne east) (98109), Silverdale, Skykomish, Snohomish, Stanwood, Sultan, Tracyton, Vashon, and Woodinville.

*M*5.0 1995 Point Robinson Earthquake

UTC Date and Time: January 29, 1995 3:11:22 UTC
Local Date and Time: January 28, 1995 19:11:22 PST (7:11 PM local time)
Epicenter: 47.387° N, 122.364° W
Depth: 15.4±0.1 km (9.6±0.1 miles)
Magnitude: 5.0 M_D, 5.0 M_w(GCMT), 4.8 M_w(OSU), 5.1 m_b(USGS)

Summary

The *M*5.0 1995 Point Robinson earthquake occurred about midway between Seattle and Tacoma, Washington, along the eastern end of Puget Sound (fig. 1). The plotted focal mechanism for this crustal earthquake, based on P-wave first-motions, indicates east-trending reverse faulting, possibly on the south-dipping Seattle Fault (Dewberry and Crosson, 1996). The moment-tensor solutions determined by Oregon State University (Pacific Northwest Seismic Network, 1995a) also implies slip on an east-trending fault, and that of the Global Centroid Moment Tensor Project (2017) implies slip on a southeast-trending reverse fault.

This earthquake, which occurred at 7:11 PM local time on a Saturday evening, was widely felt in the Puget Lowland urban corridor (fig. 9*A*). The earthquake, centered on Puget Sound between SeaTac and Federal Way, Washington, produced the most pronounced shaking to the south in Tacoma and Auburn (fig. 9*B*), although “staffers at the Washington State Emergency Services unit, as well as local police, firefighters, and utility companies throughout the Puget Sound area, said there were no reports of significant damage or injuries” (Seattle Times Staff, 1995). Little building damage was noted in the postal employee responses or in press reports, apart from hairline cracks in walls. One woman fainted during the earthquake (Seattle Times Staff, 1995). There was one press report of this earthquake being felt at Salem, Oregon.

The earthquake caused travel delays. “As many as 600 passengers were stuck on four Amtrak trains in the Northwest for up to three hours while post-earthquake inspections were completed ... Four flights preparing to land at Sea-Tac International Airport were delayed for about 20 minutes, while the runways were checked for damage. None was reported” (Seattle Times Staff, 1995).

In comparison to other aftershock sequences associated with crustal earthquakes having similar magnitudes in the Pacific Northwest, the Point Robinson earthquake produced a relatively weak aftershock sequence (Dewberry and Crosson, 1996).

Intensity reports from British Columbia are summarized in Drysdale and Horner (1995). The British Columbia Provincial Emergency Program reported 36 calls from Greater Vancouver (including Delta, Richmond, and Vancouver), 37 calls from Fraser Valley, 15 calls from Vancouver Island, 2 calls from Kamloops, and 2 calls from Kootenay (Robert B. Horner, oral commun., 2016). Apart from Kamloops, Kootenay, and Greater Vancouver these calls are not represented on figure 9*A*.

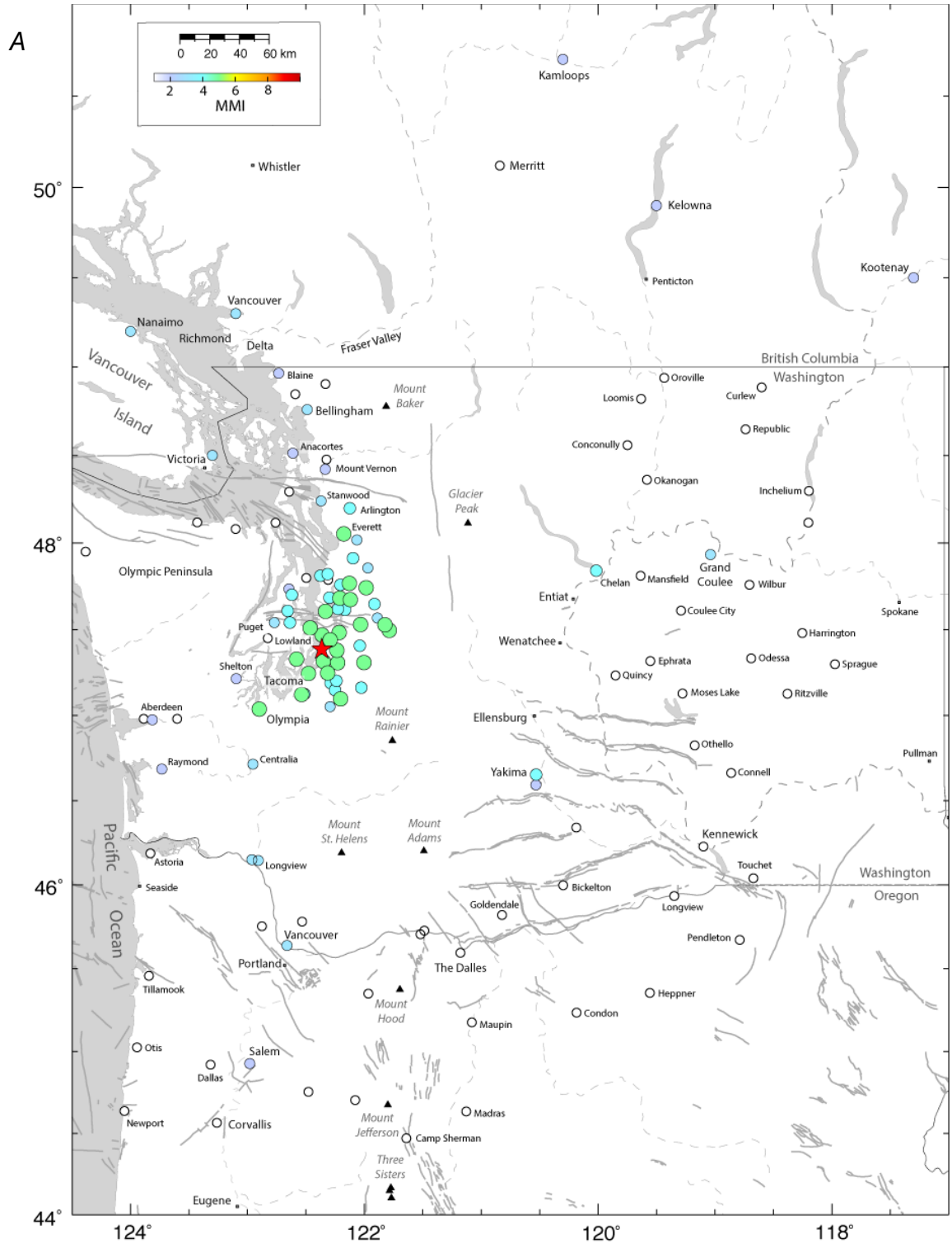


Figure 9. *A*. Modified Mercalli Intensities (MMI) for the *M*5.0 1995 Point Robinson earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which traditional intensities of II and higher were assigned. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. *B*. Expanded view of the Modified Mercalli Intensities for the *M*5.0 1995 Point Robinson earthquake. All communities that reported an MMI of V are identified. Dashed gray lines show contours of intensities reported by the Pacific Northwest Seismic Network (PNSN) based on internet and mailed

responses; small gray dots show locations of zip codes from which the PNSN obtained observations (Pacific Northwest Seismic Network, 1995b). Solid gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes. SWIF, Southern Whidbey Island Fault.

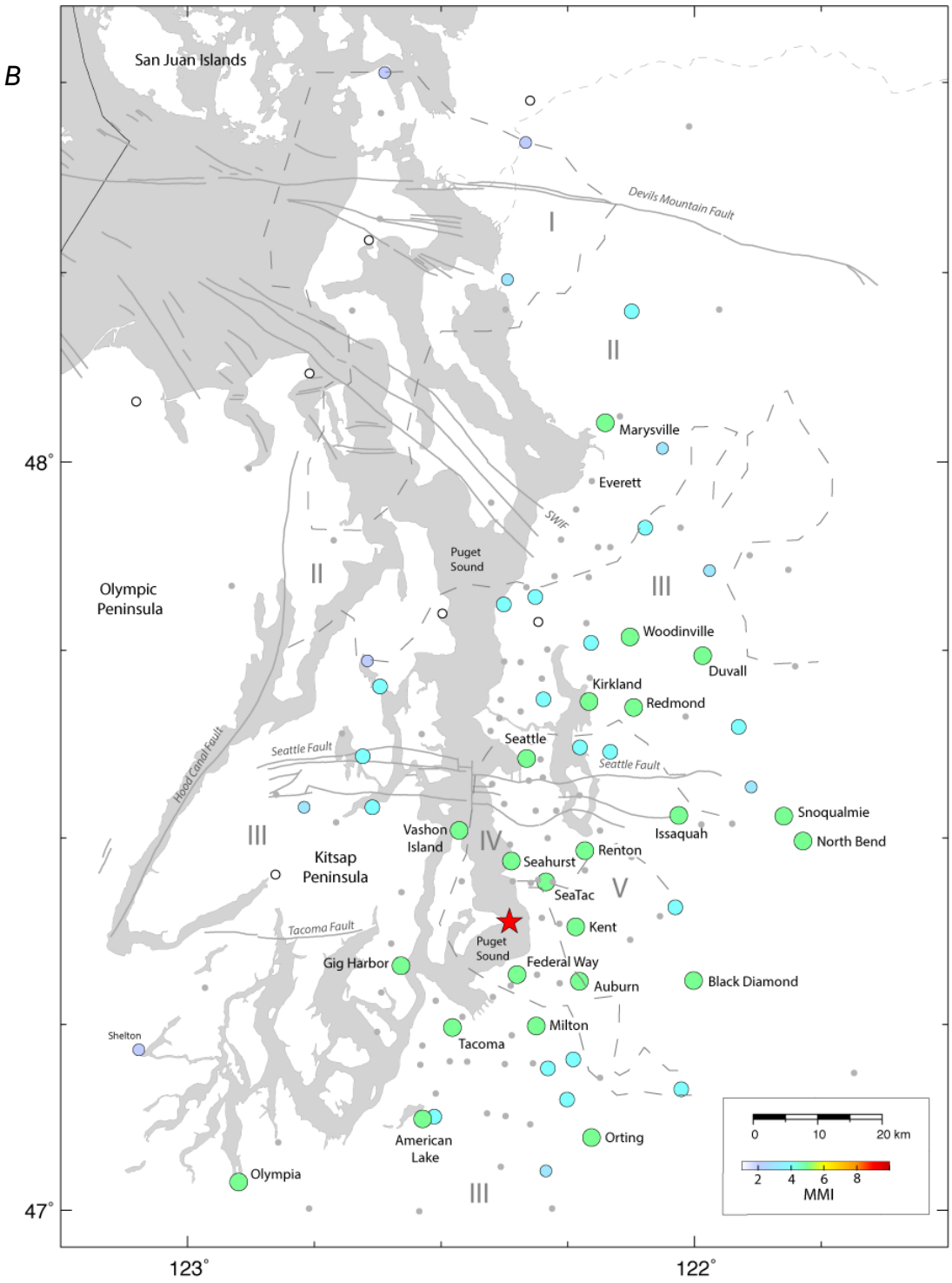


Figure 9.—Continued

The maximum traditional MMI that we assigned to the Point Robinson earthquake was V. As documented in the following, there were some reports, from communities to which we assigned intensity V, of effects that are typically associated with intensity VI. As discussed in the earlier section "Traditional USGS postal canvass and interpretation of MMI", reports of effects that are anomalously high with respect to other macroseismic observations from a community are not uncommon, and our assigned MMI is that which, in our judgment, best describes the set of observations as a whole. Similarly, there are a few press reports that describe possible intensity VI effects from imprecisely defined areas or from communities from which we do not have other observations; we report the effects below, but, lacking corroborative observations, we do not assign intensity VI to the communities from which they were reported. Finally, we note that M. Hopper and J. Dewey (the latter being the second author of the present report), in a preliminary map provided to the PNSN and viewable by way of the "traditional intensity map" link in PNSN (1995b), plotted an intensity VI for Auburn, Washington, to which we here assign V. This situation, where the same seismologist is associated with different intensities assigned from the same observations, is a manifestation of the lack of observational constraint, commonly arising with at least a few communities affected by a widely felt earthquake, that might cause different seismologists to assign different MMI from interpretation of the same observations.

Intensity V

We assigned intensity V to 23 communities. Hypocentral distances for these communities ranged between 17 and 77 km, with a median hypocentral distance of 33 km.

American Lake (Tacoma), Washington (36 km)—Felt by all (≥IV), frightened many (IV), awakened no one, windows, doors, and dishes rattled loudly (≥IV), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes/knickknacks broke (V), hanging objects/doors swung slightly (III), many items thrown from store shelves (≥VI), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), no water splashed, no buildings damaged within zip code.

Auburn, Washington (98001)—Olympia postal employee personal report: Felt while driving (car in motion) (V). Reported as a strong vibration (≥IV) of sudden duration (≥III). This observation is not represented in figure 9*B*.

Auburn, Washington (98002) (21 km)—Felt by and frightened many (IV), windows and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), several items thrown from shelves (V), a few ran out of buildings (V), felt moderately in stopped vehicles (IV), hairline cracks in interior plaster and drywall (V), a few (5 percent) buildings damaged within two city blocks and within zip code.

Auburn, Washington (98092)—Black Diamond postal employee personal report: Felt sitting inside home (II). Experienced difficulty standing up (≥V) and fright (≥IV), strong vibration (≥IV), of sudden, sharp duration (≥III). Auburn postal employee personal report: Experienced difficulty maintaining balance (V) while sitting inside first floor of home (II), moderate vibration (III), sudden, sharp duration (≥III). North Bend postal employee personal report: Experienced difficulty maintaining balance (V) while standing inside first floor of home (IV), frightened (IV), strong vibration (IV), short duration (≥III). This observation is not represented in figure 9*B*.

Auburn, Washington (press report)—The Seattle Times Staff (1995) reported that much of the minor damage reported (for the earthquake) was centered in the Auburn area, and that wine bottles

burst, light bulbs exploded, and several food items tumbled off the shelves in a supermarket in north Auburn. This observation is not represented in figure 9*B*.

Black Diamond, Washington (33 km)—Felt by and frightened all (≥IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked moderately (IV), a few small objects overturned (V), knickknacks broke (V), a few ran out of buildings (V), trees and bushes shaken moderately (V), felt slightly in moving vehicles (IV).

Duvall, Washington (51 km)—Felt by and frightened many (IV), awakened a few (II), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects/doors swung slightly (III), none ran out of buildings, trees and bushes shook slightly (IV), felt slightly in stopped and moving vehicles (III, IV), no water splashed, water muddied, no buildings damaged within two city blocks.

Federal Way, Washington (press reports) (17 km)—A resident "said that he fell down and pictures were knocked off the walls of his third-floor apartment" (V). Another resident estimated the duration of the shaking of his trailer as 30 to 40 seconds (Spokesman-Review Staff, 1995). "Minor damage had been reported by a fire station being renovated in Federal Way" (V) (New York Times Staff, 1995).

Gig Harbor, Washington (98335) (23 km)—Felt by many (IV), frightened a few (II), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects overturned (V), none ran out of buildings, trees and bushes slightly shaken (IV), felt slightly in stopped vehicles (III), hairline cracks in interior plaster walls (V), hairline cracks in exterior concrete block walls (V), no buildings damaged within zip code.

Issaquah, Washington (98027) (33 km)—Felt by and frightened many (IV), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), a few small objects overturned (V), a few small objects fell (V), hanging objects/doors swung slightly (III), a few items were thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shook slightly (IV), no water splashed, hairline cracks in interior dry walls (V), no buildings damaged within zip code.

Kent, Washington (18 km)—Felt by all (≥IV), frightened a few (II), awakened no one, windows rattled (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few items thrown from store shelves (V), a few ran out of buildings (V), hairline cracks in interior dry walls (V), no buildings damaged within zip code.

Kirkland, Washington (38 km)—Felt by many (IV), awakened and frightened a few (II), windows and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few dishes and knickknacks broke (V), light furniture/small appliances were displaced (V), a few items thrown from store shelves (V), none ran out of buildings, trees and bushes shook slightly (IV), no buildings damaged within zip code.

Marysville, Washington (77 km)—Felt by many (IV), frightened several (III), awakened no one, windows rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few knickknacks broke (V), hanging objects/doors swung moderately (IV), a few items thrown from store shelves (V), none ran out from buildings, trees and bushes shaken slightly (IV), felt moderately in stopped and moving vehicles (IV, V), no water splashed, no building damage within zip code.

Milton, Washington (22 km)—Felt by many (IV), frightened a few (II), awakened no one, dishes rattled slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects fell (V), hanging objects/doors swung slightly (III), a few ran out of buildings (V), no water splashed, hairline cracks in interior drywall (V), no buildings damaged within two city blocks.

North Bend, Washington (48 km)—Felt by and frightened many (IV), awakened no one, windows/doors/dishes rattled slightly (III), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), hanging objects/doors swung moderately (IV), a few items were thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), no water splashed, no buildings damaged within zip code. On the returned questionnaire for North Bend, sections 6 to 8 were answered as "No Knowledge".

Olympia, Washington (58 km)—Felt by all and frightened many (IV), awakened a few (II), windows, doors, and dishes rattled loudly (≥IV), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures out of place/tilted (V), some windows broken out (VI), several small objects overturned (V), several small objects fell (V), several glassware/dishes/knickknacks broken (V), hanging objects/doors swung moderately (IV), heavy furniture and heavy appliances displaced (VI), small furniture and small appliances displaced (V), several items thrown from store shelves (V), many ran out of buildings (V), trees and bushes shaken strongly (V), felt moderately in moving vehicles (V), no water splashed, masonry fences/retaining walls cracked (V), hairline cracks (V) and splits at seams (VI) in interior plaster, dry wall, and wallboard, hairline cracks in exterior walls (V), no buildings damaged within zip code. On the returned questionnaire for Olympia, sections 7 to 8 were answered as "None".

Orting, Washington (38 km)—Felt by many (IV), awakened and frightened a few (II), windows and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), several items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt moderately in stopped vehicles (IV), hairline cracks in interior plaster, drywalls, and wallboard (V), hairline cracks in exterior walls (V), very few (less than 5 percent) buildings damaged within two city blocks and within zip code.

Redmond, Washington (40 km)—Felt by many and frightened all (IV), awakened a few (II), rattled windows, doors, and dishes slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), trees and bushes shook slightly (IV), felt slightly in stopped vehicles (III), hairline cracks in interior and exterior walls, no buildings damaged within two city blocks.

Renton, Washington (22 km)—Felt by many (IV), frightened all (IV), windows/doors/dishes rattled slightly (III), walls creaked (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), hanging objects/doors swung slightly (III), felt slightly in stopped vehicles (III), hairline cracks in interior and exterior walls (V).

Seahurst, Washington (18 km)—Felt by and frightened all (≥IV), awakened no one, dishes rattled (III), walls creaked slightly (III), building trembled slightly (III), none ran out of buildings, trees and bushes shaken slightly (IV), hairline cracks in interior walls (V), no buildings damaged within two city blocks.

Seattle, Washington (98109) (29 km)—Felt by and frightened many (IV), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), hanging pictures out of

place/tilted (V), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), hanging objects/doors swung slightly (III), several items thrown from store shelves (V), a few ran out of buildings (V), felt slightly in stopped vehicles (III), no water splashed, no buildings damaged within zip code.

Seattle, Washington (98109) (press report) (29 km)—"Skyscrapers swayed in downtown Seattle and grocery stores across a wide area lost items off shelves" (Seattle Times Staff, 1995). This press report is not represented in figure 9*B* but agrees with the postal questionnaire response given for Seattle.

SeaTac, Washington (press report) (17 km)—A SeaTac resident stated that his house "all of a sudden went into this rolling motion. We all had to grab something just to remain standing" (V) (Connor, 1995).

Snoqualmie, Washington (46 km)—Felt by many (IV), frightened a few (II), windows and dishes rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few small objects overturned (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), none ran out of buildings, trees and bushes slightly shaken (IV), no buildings damaged within zip code.

Tacoma, Washington (98405) (24 km)—Felt by all (≥IV), awakened several (III), frightened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes/ knickknacks broke (V), hanging objects or doors swung slightly (III), none ran out of buildings, trees and bushes shaken slightly (IV), hairline cracks in interior wallboard (V), ground cracking in wet ground, few (5 percent) buildings damaged within two city blocks and within zip code.

Tacoma, Washington (press report)—"The quake caused minor damage at two aging Tacoma fire stations, prompting fire officials to park fire trucks outside throughout the city. New cracks zigzagged along the walls of the 1909 brick firehouse at South 43rd and L Streets. The largest extended from a window through the exterior wall and split the foundation to ground level. Dozens of hairline cracks appeared in the walls at another south end station at South 73rd and Park Avenue" (Robinson and Chavez, 1995). This observation is not represented in figure 9*B*. It is consistent with the intensity V assigned to Tacoma (98405).

Vashon Island, Washington (22 km) (press report)—"The Washington state ferry dock at Vashon Island in Puget Sound was reported to have been damaged." (Connor, 1995). This report is shown in figure 9*B* at the location of the Washington state ferry dock at Vashon Island, which is otherwise not labeled on the figure.

Woodinville, Washington (48 km) (press report)—"Frank Abe, spokesman for the King County Executive, Gary Locke, said a natural gas line had been ruptured in Woodinville" (≥V) (New York Times Staff, 1995).

Intensity IV

We assigned intensity IV to 20 communities. Hypocentral distances for these communities ranged between 27 and 184 km, with a median hypocentral distance of 38 km.

Arlington, Washington (94 km)—Felt by many (IV), none ran out of buildings, trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), no water splashed, no buildings damaged within zip code.

Bellevue, Washington (36 km)—Felt by and frightened many (IV), rattled windows/doors/dishes slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), none ran out of buildings, no buildings damaged within two city blocks.

Bothell, Washington (47 km)—Felt by and frightened many (IV), windows and dishes rattled slightly (III), building trembled slightly (III), hanging pictures swung (III), hanging objects/doors swung slightly (III), a few small objects overturned (V). On the returned questionnaire for Bothell, section 6 was answered as "Unknown"; sections 6 to 9 were answered as "None".

Bremerton, Washington (35 km)—Gig Harbor postal employee personal report: Was frightened by earthquake (≥IV), moderate vibration (III) of sudden duration (≥III). Felt sitting inside at home on second floor (II).

Buckley, Washington (41 km)—Felt by many (IV), windows rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), none ran out of buildings, no buildings damaged within zip code. Postal employee personal report: Felt while standing (≥IV) inside on first floor of friend's house, frightened postal employee (≥IV), who had difficulty maintaining balance (≥V).

Carnation, Washington (49 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows and doors rattled (III), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures swung (III), hanging objects/doors swung slightly (III), none ran out of buildings, hairline cracks in exterior walls of wood frame construction (V), few (5 percent) buildings damaged within two city blocks and within zip code.

Chelan, Washington (184 km)—Felt by and frightened several (III), awakened no one, rattled windows and doors (III), walls creaked slightly (III), building trembled slightly (III), a few small objects fell (V), hanging objects/doors swung slightly (III), a few people ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), water splashed on banks of lakes.

Edmonds, Washington (51 km)—Felt by many (IV), awakened a few (II), dishes rattled slightly (III), none ran out of buildings, no buildings damaged within zip code. Postal employee personal report: Experienced difficulty maintaining balance (≥V), felt standing inside on first floor of home (≥IV), moderate vibration (III) of short duration (III).

Keyport, Washington (45 km)—Felt by many (IV), frightened a few (II), awakened no one, rattled windows slightly (III), none ran out of buildings, no buildings damaged within two city blocks. Postal employee personal report: Felt sitting on first floor of home (II), light vibration (II) of short duration (≥III).

Lynnwood, Washington (52 km)—Felt by many (IV), frightened several (III), awakened a few (II), building trembled moderately (IV), hanging pictures out of place/tilted (V), hanging objects/doors swung moderately (IV), none ran out of buildings, no buildings damaged within zip code.

Maple Valley, Washington (32 km)—Felt by and frightened many (IV), awakened no one, windows and dishes rattled loudly (IV), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures swung (III), hanging objects/doors swung moderately (IV), a few ran out of buildings (V), trees and bushes shaken moderately (V), felt slightly in stopped vehicles (III), no buildings damaged within zip code.

Medina, Washington (34 km)—Felt by several (III), rattled windows slightly (III), walls creaked slightly (III), building trembled slightly (III), a few ran out of buildings (V), hairline cracks in older plaster walls (V).

Port Orchard, Washington (33 km)—Vashon postal employee Community Report. Felt by many (IV), frightened all (≥IV), awakened no one, windows and dishes rattled slightly (III), walls creaked slightly (III), light furniture displaced (V), hanging objects/doors swung moderately (IV). On the returned questionnaire, sections 5 to 9 were answered as "N/A".

Puyallup, Washington (30 km)—Felt by many (IV), frightened several (III), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), none ran out of buildings, hairline cracks in plaster interior walls (V).

Seattle, Washington (98115) (39 km)—National Weather Service Forecast Office. The respondent used an earlier version of the postal questionnaire, form 42-R1700, than that of figure 2. Felt by and frightened many (IV), windows/doors/dishes rattled (III), walls creaked (III), building trembled slightly (III), hanging pictures swung (III), hanging objects/doors swung slightly (III), moderate vibration of sudden duration (III). On the returned questionnaire for Seattle, sections 6 to 10 (fig. 3*B*) were answered as "Unknown".

Selah, Washington (163 km)—Felt by many (IV), awakened a few (II), building trembled slightly (III), hanging pictures swung (III), none ran out of buildings. Postal employee personal report: felt sitting inside on first floor of home (≥II), moderate shock (III) of short duration (≥III).

Snohomish, Washington (65 km)—Felt by many (IV), frightened several (III), awakened no one, windows/doors/dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), none ran out of buildings, no water splashed, no buildings damaged within two city blocks.

Sumner, Washington (30 km)—Felt by and frightened many (IV), awakened none, rattled windows, doors, and dishes slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), no building damage within zip code.

Tacoma, Washington (98439) (37 km)—Doors rattled slightly (III), hanging pictures swung (III), hanging objects swung moderately (IV). Second page was not answered. Postal employee personal report: Felt sitting on first floor of home (II), difficulty maintaining balance (≥V), moderate vibration (III), short duration (≥III).

Tracyton, Washington (38 km)—Felt by several (III) and frightened a few (II), building trembled moderately (IV), hanging pictures out of place/tilted (V).

Intensity III

We assigned intensity III to 17 communities. Hypocentral distances for these communities ranged between 38 and 257 km, with a median hypocentral distance of 145 km.

Felt (III) in Washington at Bellingham (a few hanging objects swung, Spokesman-Review Staff, 1995), Bremerton (98312), Centralia, Electric City, Fall City, Graham, Kelso, Lake Stevens, Longview (long duration, Spokesman-Review Staff, 1995), Monroe, Stanwood, and Vancouver.

Felt (III) in British Columbia at Victoria.

Felt (II-III) in British Columbia in the Fraser Valley, Greater Vancouver (including Delta, Richmond and Vancouver), and Nanaimo.

Intensity II

We assigned intensity II to 12 communities. Hypocentral distances for these communities ranged between 47 and 441 km, with a median hypocentral distance of 131 km.

Felt (II) in Washington at Aberdeen, Anacortes, Blaine (calls received, press report, Spokesman-Review Staff, 1995), Mount Vernon, Poulsbo, Raymond, Shelton, and Yakima (press report, Spokesman-Review Staff, 1995).

Felt (II-III) in British Columbia at Kamloops, Kootenay, and Okanagan.

Felt (no intensity value assigned)

Felt in Oregon at Salem at a hypocentral distance of 279 km (Seattle Times Staff, 1995).

Not felt (I)

We assigned intensity I (not felt) to 66 communities. Hypocentral distances of the 60 communities for which observations were reported on both the "Personal Reports" and "Community Reports" sections of the postal questionnaires ranged between 39 and 334 km, with a median hypocentral distance of 239 km. These communities are represented by non-italic font in the following. Communities for which only personal reports are listed in italic-font in the following.

Reported not felt (I) in Oregon at Astoria, Camp Sherman, Condon, Corvallis, Dallas, *Eugene*, Heppner, Hood River, Idanha, Madras, Maupin, Mill City, Newport, *Oregon City*, Otis, Pendleton, *Prineville*, Scappose, The Dalles, Tillamook, and Wemme.

Reported not felt (I) in Washington at Battle Ground, Belfair, Bickleton, Burlington, Conconcully, Connell, Coulee City, Curlew, Ephrata, Everson, Ferndale, Forks, Goldendale, Granger, Harrington, Hoquiam, Hunters, Inchelium, Kingston, *Longview*, Loomis, *Lyle*, Mansfield, Montesano, Moses Lake, Mountlake Terrace, Oak Harbor, Odessa, Okanogan, Oroville, Othello, Pasco, Plymouth, Port Angeles, Port Townsend, Quincy, Republic, Ritzville, Sequim, *Snohomish*, Sprague, Touchet, White Salmon, and Wilbur.

Reported not felt (I) in British Columbia at Merritt (324 km).

Pacific Northwest Seismic Network Internet Intensity Responses for the 1995 Point Robinson Earthquake

The PNSN received 2,000 macroseismic reports through the internet (Pacific Northwest Seismic Network, 1995b; Qamar and others, 1995), calculated intensities from these reports, grouped and averaged the intensities by zip-code, and contoured the data. As noted earlier, for this earthquake intensity reports were submitted to PNSN in three ways: (1) questionnaires printed in newspapers, filled out and mailed in by respondents, and manually entered into the database at PNSN (about 7,000 responses), (2) email versions of the same questionnaire submitted by the respondents to PNSN by email (about 1,100 responses), and (3) a web-based form submitted directly by the respondent (about 600 responses). The PNSN map resembles our traditional MMI map (fig. 9*B*) in that the highest intensity (V) contour in the PNSN map corresponds to a concentration of highest intensity (also V) observations in our traditional MMI map. We view the broad-scale similarities as consistent with other evidence (for example, Wald and others, 2011) supporting the effectiveness of internet-based macroseismic intensities. In detail, there are differences in the maps within the region covered by both maps, even in populated areas having large numbers of communities with assigned intensities. For example, the PNSN map suggests that shaking was lower north of the Seattle Fault than south of the fault (fig. 9*B*), whereas the non-contoured plot of traditional MMI does not suggest a change of intensity near the latitude of the Seattle Fault. It is beyond the scope of the present paper to deconstruct the causes of the differences in detail. We view the differences as likely representing the kind of differences that might characterize any two independent sets of MMI or “calibrated-to-be-consistent-with-MMI” assignments for a region of moderate shaking.

*M*5.2 1996 Duvall Earthquake

UTC Date and Time: May 3, 1996 04:04:22 (UTC)
Local Date and Time: May 2, 1996 21:04:22 PDT (9:04 PM local time)
Epicenter: 47.761° N, 121.876° W

Depth: 3.8±2.1 km (2.4±1.4 miles)
Magnitude: 5.4 M_D, 5.2 M_w(OSU) (Pacific Northwest Seismic Network, 1996a), 5.2 m_b(USGS)

Summary

This crustal earthquake occurred about 35 km east-northeast of Seattle and 9 km northeast of Duvall, Washington (fig. 1), roughly midway between the Puget Sound and the Cascade Range (Malone and others, 1996). The earthquake occurred near a postulated southeast extension of the oblique-slip Southern Whidbey Island Fault (Blakely and others, 2011). The focal mechanism of the main shock shown in figure 1 is implied by the moment-tensor solution obtained at the University of Washington (Pacific Northwest Seismic Network, 1996b) and corresponds to predominantly reverse-slip on an approximately north-trending fault. A nearly identical mechanism is implied by the moment-tensor solution obtained at Oregon State University (Pacific Northwest Seismic Network, 1996a). Within the following 36 hours, the PNSN network recorded more than 80 aftershocks with the largest measuring *M*3.2 (Associated Press, 1996a). The distribution of the aftershocks (Ludwin, 1996) is elongated northwest-southeast or NNW-SSE, suggesting that the trend of the causative fault is somewhat west of north. A brief discussion of the range of the first magnitudes reported for the Duvall earthquake is provided by PNSN (1996c).

The earthquake occurred at 9:04 PM local time on a Thursday evening and was widely felt from Vancouver, British Columbia (194 km distant), to Vancouver, Washington (243 km), and from the Pacific Coast as far east as Davenport, Inchelium, and Yakima, Washington (167–278 km) and Castlegar and Nelson, British Columbia (352–388 km) (fig. 10*A*). It was felt most strongly in the Duvall-Monroe area of south Snohomish County, Washington (fig. 10*B*), where about 16,000 customers were reported to be without power for a few hours and the only reported injury occurred (Kremer and Gonzalez, 1996). However, in the next county south, King County, preliminary inspections of county bridges and dams reported no damage (Kremer and Gonzalez, 1996).

The earthquake was felt by most of the fans, frightening some of them, attending a Seattle Mariners professional baseball game in the Seattle Kingdome (Kremer and Gonzalez, 1996). To their disappointment the game was halted so that the Kingdome could be inspected for damage (fig. 10*B*). None was found during inspections by three different engineering firms on the following day (Egan, 1996; Associated Press, 1996b). In particular, no damage was reported to the partitions between the Kingdome's columns and beams (Foster and Reid, 1996).

Recorded accelerations at the Tolt River Dam at a hypocentral distance of 14.8 km (fig. 10*B*) were 24.6 percent of the acceleration due to gravity (*g*) on the north-component and 22.8 percent *g* on the east-component (Center for Engineering Strong Motion Data, 2016). Accelerations recorded in southern British Columbia at distances between 140 and 180 km varied between 0.5 and 1.5 percent *g*, but several closer accelerometers in Washington did not trigger at 1 percent *g* (Cassidy and others, 1997; Weichert and others, 1999).

The maximum traditional MMI that we assigned to the Duvall earthquake was VI, assigned to four communities in the epicentral area on the basis of reports that many objects fell from the shelves of some stores, that chimneys were damaged, that exterior walls bulged, or that heavy furniture or appliances were shifted.

Intensity data from British Columbia are from a variety of sources (for example, phone calls, emails, media reports, and Drysdale and Horner [1996]).

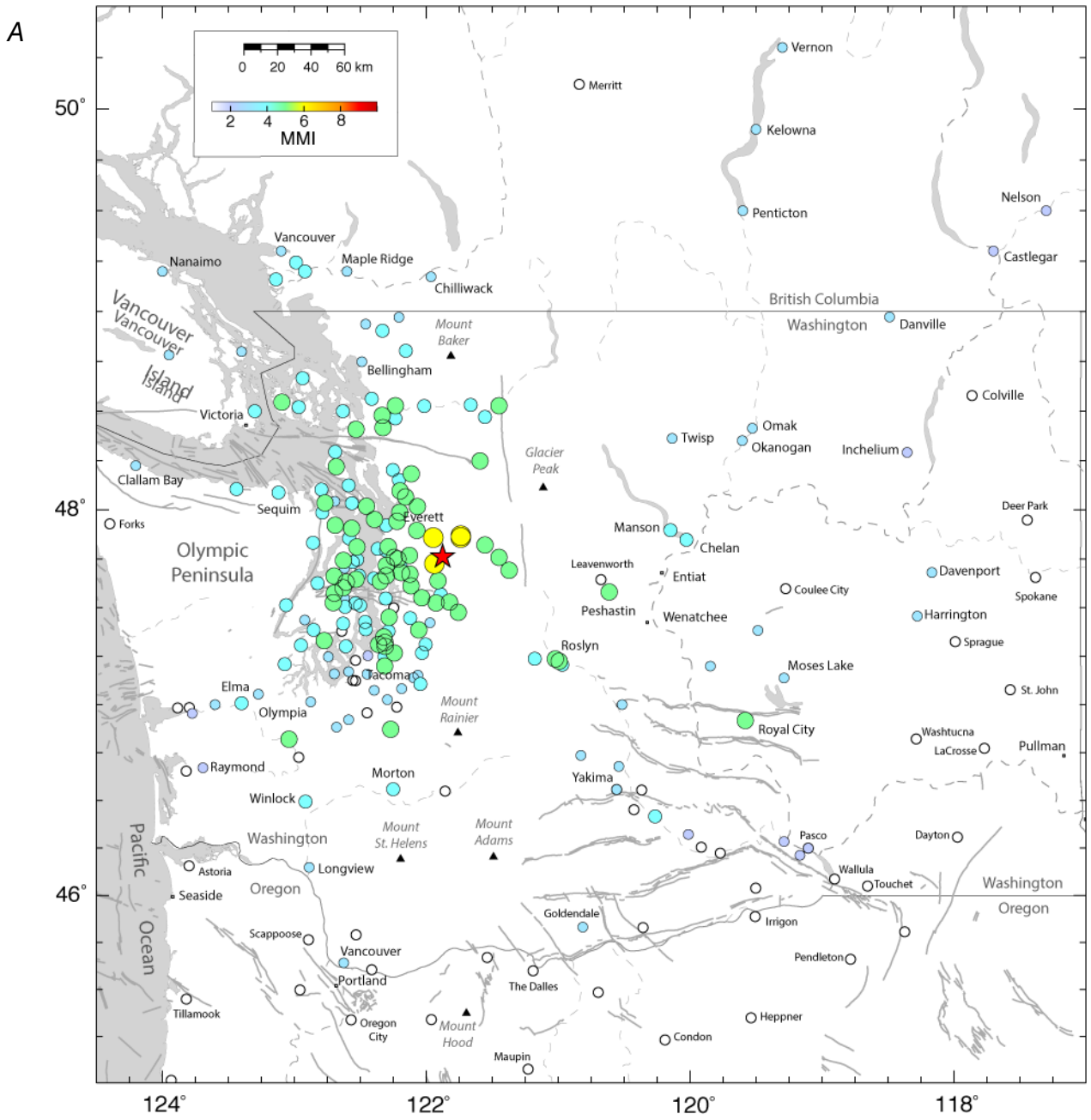


Figure 10. *A*. Modified Mercalli Intensities (MMI) for the *M*5.4 1996 Duvall earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which traditional intensities of II and higher were assigned. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. *B*. Expanded view of the Modified Mercalli Intensities for the *M*5.4 1996 Duvall earthquake (red star). All communities that reported an MMI of VI are identified. Dashed gray lines show intensity contours reported by the Pacific Northwest Seismic Network (PNSN) based on internet and mailed responses; small gray dots show locations of zip codes from which the PNSN (1996d) obtained observations. Solid gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes. DMF, Devils Mountain Fault; HCF, Hood Canal Fault; SWIF, Southern Whidbey Island Fault.

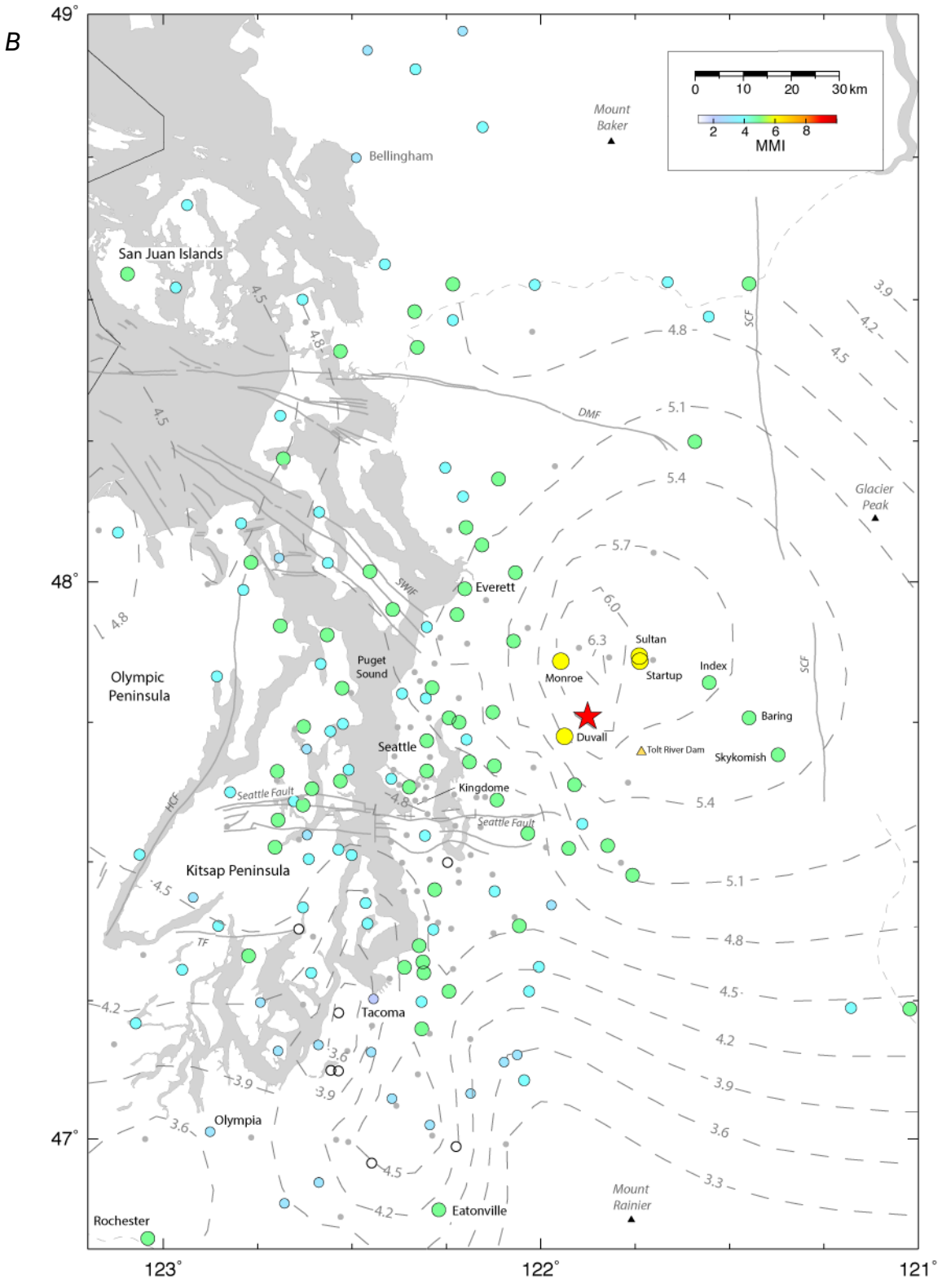


Figure 10.—Continued

Intensity VI

Intensity VI assignments were made to four communities. Hypocentral distances for these communities ranged between 7 and 16 km, with a median hypocentral distance of 14 km.

Duvall, Washington (7 km)—Felt by all (≥IV), frightened many (IV), awakened a few (II), windows, doors, and dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled strongly (≥IV), hanging pictures fell (≥V), a few windows cracked (V), several small objects overturned (V), many small objects fell (≥VI), several glassware/dishes/ knickknacks broke (V), light furniture or small appliances displaced (V), heavy furniture or appliances were displaced (VI), hanging objects or doors swung violently (≥V), many items thrown from store shelves (≥VI), many ran out of buildings (≥V), trees and bushes shaken moderately (V), water splashed onto the banks of lakes, masonry fences/ retaining walls were cracked and partially fell (VI), hairline cracks in interior drywalls (V), drywall separated from ceiling or floor (V), large cracks in a foundation (VI), a few chimneys cracked and had bricks fallen (VI), small rock fall, wells disturbed, few (5 percent) buildings damaged within two city blocks.

Duvall, Washington (press reports)—Described as "a good jolt followed by a long roll". One woman bruised an arm when she fell during the quake while climbing some steps in her home (Bjorhus and others, 1996). A Duvall policeman reported no reports of significant damage although many items fell from store shelves and the owner of an antique store reported an 18-inch crack in a wall (Ang, 1996).

Monroe, Washington (13 km)—Felt by all (≥IV), awakened and frightened many (IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few windows cracked (V), a few small objects overturned (V), several small objects fell (V), several glassware, dishes, and knickknacks broken (V), hanging objects or doors swung moderately (IV), many items thrown from store shelves (≥VI), many people ran from buildings (≥V), trees and bushes shaken strongly (≥V), felt moderately in moving vehicles (V), interior dry wall fell (≥VI), a few bricks fell from chimneys (VI), few (5 percent) buildings damaged within zip code.

Monroe, Washington (press reports)—One injury was reported from falling objects within a house and another from a kick by a frightened animal. “About 16,000 customers of the Snohomish County Public Utility District were without electrical power in the Monroe, Clearview, Sultan and Everett areas as a result of the quake” (Bjorhus and others, 1996). A motorist crossing a bridge at Monroe reported that his car was “rocked up” by the earthquake (Ang, 1996).

Startup, Washington (16 km)—Felt by and frightened all (≥IV), awakened a few (II), windows/doors/dishes rattled loudly (≥IV), walls creaked moderately (IV), building trembled strongly (≥IV), hanging pictures fell (≥V), several small objects overturned (V), several small objects fell (V), many glassware, dishes, and knickknacks broke (≥VI), light furniture displaced (V), hanging objects or doors swung violently (V), many items were thrown from store shelves (≥VI), many ran from buildings (≥V), trees and bushes shaken strongly (≥V), felt slightly in moving vehicles (IV), underground pipes broken (≥VI), hairline cracks in interior dry wall (V), a few chimneys damaged (VI).

Sultan, Washington (16 km)—Felt by all (≥IV), windows and dishes rattled (III), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures fell (≥V), some windows broken out (VI), several small objects overturned (V), several small objects fell (V), several glassware, dishes, and knickknacks broke (V), small appliances displaced (V), heavy furniture or appliances displaced (VI), hanging objects or doors swung slightly (III), several items thrown from shelves (V), brick exterior walls bulged outward (VI), several chimneys were cracked, twisted, and had bricks fall (VII), few (5 percent) buildings damaged within zip code.

Intensity V

We assigned intensity V to 62 communities. Hypocentral distances for these communities ranged between 14 and 197 km, with a median hypocentral distance of 53 km.

Arlington, Washington (50 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows rattled slightly (III), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), none ran out of buildings, no buildings damaged within two city blocks.

Bainbridge Island-Winslow, Washington (51 km)—Felt by all (≥IV), awakened many (IV), frightened many (IV), rattled windows slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects overturned (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), felt slightly in stopped vehicles (III), water splashed on banks of lakes, no buildings damaged.

Baring, Washington (32 km)—Felt by all and frightened many (≥IV), windows, doors, and dishes rattled loudly (IV), hanging pictures swung (III), a few small objects overturned (V), a few knickknacks broke (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), a few ran out of buildings (V), no buildings damaged within two city blocks.

Bellevue (Lake Hills), Washington (25 km)—Felt by and frightened many (IV), awakened several (III), windows, doors, and dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), hanging objects or doors swung slightly (III), none ran from buildings, trees and bushes shaken slightly (IV), no water splashed, hairline cracks in interior plaster walls (V), no buildings damaged in zip code.

Bothell, Washington (26 km)—Felt by all (≥IV), frightened many (IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), knickknacks broken (V), felt moderately in moving vehicles (V), no buildings damaged within two city blocks.

Bremerton (northeast), Washington (59 km)—Felt by many (IV), awakened and frightened no one, windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging objects or doors swung slightly (III), trees and bushes shaken slightly (IV), a few large cracks in interior dry wall (VI).

Bremerton (west), Washington (65 km)—Felt by and frightened many (IV), awakened several (III), rattled windows and dishes slightly (IV), building shook slightly to moderately (IV), hanging pictures swung (III), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), hairline cracks in plaster walls (V), hairline cracks in cement foundation (V). On the returned questionnaire from Bremerton, sections 7 to 9 were answered by "this information not known/reported."

Burlington, Washington (87 km)—Felt by and frightened all (≥IV), awakened many IV), windows rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung out of place/tilted (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), no buildings damaged in zip code.

Carnation, Washington (15 km)—Felt by all (≥IV) and awakened and frightened many (IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled strongly (≥IV), hanging pictures fell (V), several small objects overturned (V), several small objects fell (V), a few glassware/dishes/knickknacks broke (V), light furniture displaced (V), hanging objects or doors swung moderately (IV), a few items thrown from store shelves (V), a few ran out of buildings (≥V),

trees and bushes shook moderately (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), 5 percent or less buildings damaged in zip code, "no real damage", "no damage to bridges or dams".

Carnation, Washington (press report)—No damage was noted by Department of Transportation inspectors to the Tolt River Bridge near Carnation (Bjorhus and others, 1996).

Clinton, Washington (44 km)—Windows, doors, and dishes rattled (III), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures out of place/tilted (V), no damage to windows, a few small objects overturned (V), hanging objects or doors swung moderately (IV), no buildings damaged within two city blocks. On the returned questionnaire for Clinton, sections 6 to 8 were answered as "none."

Coupeville, Washington (79 km)—Felt by and frightened many (IV), awakened a few (II), windows, doors, and dishes rattled loudly (IV), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few small objects fell (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), none ran out of buildings, not felt in moving vehicles, no water splashed, no buildings damaged within zip code.

Darrington, Washington (58 km)—Felt by many (IV), awaked several (III), frightened a few (II), windows, doors, dishes rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), none ran out of buildings.

East Bremerton, Washington (57 km)—Felt by many (IV), awakened and frightened no one, windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging objects or doors swung slightly (III), trees and bushes shaken slightly (IV), a few large cracks in interior dry wall (VI).

Eatonville, Washington (103 km)—Felt by all (≥ IV), awakened and frightened a few (III), windows and doors rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt moderately in stopped vehicles (IV), no splashing of water, no buildings damaged within zip code.

Everett, Washington (35 km)—Felt by, awakened, and frightened many (IV), rattled doors and dishes slightly (III), walls creaked slightly (III), building shook moderately (IV), hanging pictures swung out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), interior wallboard damaged (V).

Everett, Washington (press report)—Power was out in Everett for about 30 minutes (Kremer and Gonzalez, 1996).

Everett (Beverly Park), Washington (33 km)—Felt by and frightened many (IV), dishes rattled loudly (IV), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), none ran out of buildings, no buildings damaged within zip code.

Federal Way, Washington (59 km)—Felt by and frightened many (IV), awakened several (III), rattled windows and dishes slightly (III), walls creaked moderately (IV), building shook moderately (IV), hanging pictures swung out of place/tilted (V), a few knickknacks broke (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), no buildings damaged within zip code.

Federal Way (west), Washington (62 km)—Felt by and frightened many (IV), awakened several (III), rattled windows and dishes slightly (III), walls creaked moderately (IV), building shook moderately (IV), hanging pictures swung out of place/tilted (V), a few knickknacks broke (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), no buildings damaged within zip code.

Friday Harbor, Washington (126 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows rattled (III), several small objects fell (V), a few glassware/dishes/ knickknacks broke (V), hanging objects or doors swung slightly (III), several items thrown from store shelves (V), none ran from buildings, trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), slight damage to dams, no buildings damaged in zip code.

Gorst, Washington (67 km)—Felt by and frightened many (IV), awakened several (III), rattled windows and dishes slightly (IV), building shook slightly to moderately (IV), hanging pictures swung (III), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), hairline cracks in plaster walls (V), hairline cracks in cement foundation (V). On the returned questionnaire from Gorst, sections 7 to 9 were answered by "this information not known/reported."

Hadlock, Washington (73 km)—Felt by many (IV), awakened and frightened several (III), windows, doors, and dishes rattled (III), walls creaked slightly (III), building trembled strongly (IV), hanging pictures fell (V), hanging objects or doors swung slightly (III), none ran out of buildings, no buildings damaged within two city blocks.

Hansville, Washington (54 km)—Felt by many (IV), awakened and frightened none, rattled windows (III), walls creaked slightly (III), building trembled slightly (III), hanging objects or doors swung moderately (IV), a few ran out of buildings (V), hairline cracks in interior drywall (V), no buildings damaged within two city blocks.

Index, Washington (25 km)—Felt by many (IV), windows and dishes rattled loudly (V), walls creaked slightly (III), buildings trembled moderately (IV), hanging pictures out of place/tilted (V), several small objects overturned (V), a few small objects fell (V), light furniture displaced (V), hanging objects or doors swung slightly (IV), trees and bushes shaken slightly (IV), no buildings damaged within two city blocks.

Issaquah, Washington (27 km)—Felt by many (IV), windows and dishes rattled loudly (V), walls creaked slightly (III), buildings trembled moderately (IV), hanging pictures out of place/tilted (V), several small objects overturned (V), a few small objects fell (V), light furniture displaced (V), hanging objects or doors swung slightly (IV), trees and bushes shaken slightly (IV), no buildings damaged within two city blocks. Snoqualmie postal employee personal report: Frightened by earthquake (IV) while sitting on lower floor of home, difficulty in walking (≥V), moderate vibration (III) of short duration (≥III).

Kenmore, Washington (28 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), a few glassware, dishes, knickknacks broke (V), hanging objects or doors swung slightly (III), a few objects thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in moving vehicles (IV), no water splashed, no buildings damaged within two city blocks.

Kingston, Washington (49 km)—Felt by, awakened, and frightened many (IV), rattled windows/doors/ dishes slightly (III), walls creaked slightly (III), building shook slightly (III), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small

objects fell (V), hanging objects or doors swung slightly (III), none ran out of buildings, trees and bushes shaken slightly (IV), felt slightly in moving vehicles (IV), no water splashed.

Kirkland, Washington (26 km)—Felt by all (≥IV), awakened and frightened many (IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled strongly (≥IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes broke (V), hanging objects or doors swung moderately (IV), several items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shook moderately (IV), felt strongly in stopped vehicles (IV), felt moderately in moving vehicles (V), water splashed on banks of lakes and ponds, hairline cracks in interior plaster and wallboard (V), hairline cracks in exterior walls (V), chimneys cracked (V), no buildings damaged within two city blocks.

La Conner, Washington (87 km)—Felt by many (IV), awakened and frightened a few (III), windows and dishes rattled slightly (III), building trembled slightly (III), hanging pictures swung out of place/tilted (V), a few small objects fell (V), none ran out of buildings, felt slightly in stopped vehicles (III), no water splashed, no buildings damaged within zip code. On the returned questionnaire from La Conner, sections 6 to 8 were crossed out.

Lake Stevens, Washington (32 km)—Felt by all (≥IV) and awakened many (IV), frightened several (III), windows, doors, and dishes rattled (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes/knickknacks broke (V), light furniture or small appliances were displaced (V), heavy furniture or heavy appliances were displaced (VI), hanging objects or doors swung slightly (III), many ran out of buildings (V), trees and bushes shaken moderately (V), felt slightly in moving vehicles (IV), water splashed onto sides of swimming pools, exterior wall bulged outward (VI), no buildings damaged within two city blocks.

Langley, Washington (52 km)—Felt by and awakened many (IV), frightened several (III), a few small objects fell (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), many people ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), no buildings damaged within zip code.

Lynnwood, Washington (32 km)—Felt by and frightened many (IV), awakened a few (II), windows rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), a few small objects overturned (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), trees and bushes shaken slightly (IV), hairline cracks in interior wallboard (V).

Maple Valley, Washington (44 km)—Felt by all (≥IV), awakened and frightened many (IV), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects fell (V), glassware and knickknacks broke (V), hanging objects or doors swung slightly (III), water splashed onto the sides of swimming pools.

Marblemount, Washington (91 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows, doors, and dishes rattled loudly (≥IV), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung slightly (III), trees and bushes shaken moderately (V), underground pipes cracked, no buildings damaged within two city blocks.

Marysville, Washington (40 km)—Felt by all (≥IV), awakened and frightened many (IV), windows and dishes rattled loudly (≥IV), walls creaked moderately (IV), building trembled strongly (≥IV), hanging pictures out of place/tilted (V), a few windows cracked (V), several small objects overturned (V), several small objects fell (V), several glassware, dishes, and knickknacks broke (V), light furniture displaced (V), a few items thrown from store shelves (V), many ran out of buildings

(≥V), trees and bushes shaken moderately (V), felt moderately in moving vehicles (V), no water splashed, no buildings damaged in zip code.

Marysville (northwest), Washington (45 km)—Felt by all and awakened and frightened many (IV), windows and dishes rattled loudly (≥ IV), walls creaked moderately (IV), building trembled strongly (≥ IV), hanging pictures out of place/tilted (V), a few windows cracked (V), several small objects overturned (V), several small objects fell (V), several glassware, dishes, and knickknacks broke (V), light furniture displaced (V), a few items thrown from store shelves (V), many ran out of buildings (≥ V), trees and bushes shaken moderately (V), felt moderately in moving vehicles (V), no water splashed, no buildings damaged in zip code.

Mount Vernon, Washington (80 km)—Felt by many (IV), rattled dishes slightly (III), hanging pictures swung out of place/tilted (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), none ran out of buildings, no buildings damaged within two city blocks.

North Bend, Washington (33 km)—Felt by many (IV), frightened a few (III), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few glassware broken (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), none ran from buildings, trees and bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), hairline cracks in interior dry wall (V), a few chimneys cracked (V), no buildings damaged in zip code.

Pacific, Washington (62 km)—Felt by many (IV), awakened and frightened several (III), windows and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects fell (V), a few knickknacks broke (V), a few items thrown from store shelves (V), none ran out of buildings, no buildings damaged within two city blocks.

Peshastin, Washington (97 km)—Felt by many (IV), frightened a few (II), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging objects or doors swung out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), light furniture displaced (V), hanging objects or doors swung slightly (III), none ran out of buildings, trees and bushes shaken slightly (IV), no water splashed, no buildings damaged within zip code.

Port Ludlow, Washington (64 km)—Felt by many (IV), rattled windows, doors, and dishes (III), building trembled strongly (≥IV), hanging pictures fell (≥V), several small objects overturned (V), a few small objects fell (V), a few glassware/dishes/knickknacks broke (V), light furniture/small appliances displaced (V), hanging objects or doors swung moderately (IV), a few large cracks in interior walls (VI), no buildings damaged within two city blocks.

Poulsbo, Washington (56 km)—Felt by many (IV), awakened and frightened a few (II), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung moderately (IV), a few ran out of buildings (V), trees and bushes shook slightly (IV).

Preston, Washington (27 km)—Felt by and frightened many (IV), awakened a few (II), rattled windows slightly (III), walls creaked slightly (III), building shook moderately (IV), hanging pictures swung (III), a few small objects overturned (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), trees and bushes shook slightly (IV), no water splashed.

Puyallup (west), Washington (71 km)—Felt by many (IV), awakened several (III), and frightened all (≥ IV), rattled windows, doors, and dishes slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects fell (V), glassware broke (V), hanging objects or doors swung moderately (IV), a few ran out of buildings (V), trees and

bushes shaken slightly (IV), felt slightly in stopped and moving vehicles (III, IV), a few tombstones cracked (VI), masonry fences/retaining walls were cracked (V), hairline cracks in interior wallboard (V), no buildings damaged within two city blocks of location.

Redmond, Washington (21 km)—Felt by all (≥IV) and frightened many (IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked loudly (≥IV), building trembled strongly (≥IV), hanging pictures swung out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung moderately (IV), a few items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shaken moderately (V), water tanks on stands fell, hairline cracks in interior dry wall (V). On the returned questionnaire from Redmond, sections 7 to 9 were answered by "I do not know."

Redondo, Washington (57 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung out of place/tilted (V), a few small objects overturned (V), heavy appliances displaced (VI), a few items thrown from store shelves (V), hairline cracks in interior dry wall (V), no buildings damaged within zip code.

Rochester, Washington (137 km)—Felt by many (IV), awakened and frightened a few (II), windows rattled (III), walls creaked slightly (III), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung moderately (IV). On the returned questionnaire from Rochester, page 2 was answered as "unknown".

Ronald, Washington (87 km)—Felt by many (IV), dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung out of place/tilted (V), a few small objects overturned (V), none ran from buildings, trees and bushes shook slightly (IV).

Roslyn, Washington (89 km)—Felt by many (IV), awakened and frightened several (III), windows, doors, and dishes rattled loudly (≥IV), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few glassware broke (V), hanging objects or doors swung slightly (III).

Royal City, Washington (197 km)—Felt by many (IV), building trembled slightly (III), hanging pictures swung out of place/tilted (V), heavy furniture or appliances displaced (VI), hanging objects or doors swung slightly (III), none ran out of buildings, no buildings damaged within zip code.

Seattle (Lake City), Washington (33 km)—Felt by and frightened all (≥IV), awakened no one, windows, doors, and dishes rattled slightly (III), walls creaked moderately (IV), building trembled strongly (IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), hanging objects or doors swung slightly (III), trees and bushes shaken moderately (V), no buildings damaged within 2 city blocks.

Seattle (Laurelhurst), Washington (34 km)—Felt by all (≥IV), frightened several (III), awakened a few (II), windows, doors, and dishes rattled (III), walls creaked moderately (IV), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), hanging objects or doors swung moderately (IV), a few items thrown from store shelves (V), a few ran out of buildings (V), trees and bushes shook moderately (V), felt slightly in stopped vehicles (III), no buildings damaged within zip code.

Seattle (Queen Anne east), Washington (38 km)—Felt by many (IV), windows and dishes rattled slightly (III), building trembled moderately (IV), a few glassware/dishes/knickknacks broken (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), trees and bushes shaken moderately (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), no buildings damaged within two city blocks.

Seattle, Washington (press report)—"The earthquake left about eight floor-to-ceiling cracks in the walls of the detention center at King County Department of Youth Services in Seattle. The cracks, considered superficial by a county building inspector, ran along the mortar in the masonry joints of the gym and corridor walls. The masonry joints are designed to help the building flex." (Bjorhus and others, 1996) This observation is not represented in figure 10*B* but is consistent with reports of intensity V effects for some Seattle zip codes. Life-sized marble statues in a downtown art gallery on S. Jackson Street near Pioneer Square wobbled and rocked during the earthquake but did not topple over (Kremer and Gonzalez, 1996).

Sedro Woolley, Washington (89 km)—Felt by and frightened all (≥IV), awakened many (IV), rattled windows, doors, and dishes (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in moving vehicles (IV), no water splashed, no buildings damaged within two city blocks.

Silverdale, Washington (63 km)—Felt by many (IV), awakened and frightened a few (II), dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung out of place/tilted (V), a few small objects overturned (V), hanging objects or doors swung slightly (III), none ran out of buildings, trees and bushes shaken slightly (IV), no buildings damaged within zip code.

Skykomish, Washington (39 km)—Felt by and awakened all (≥IV), frightened many (IV), windows, doors, and dishes rattled slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), no water splashed, no buildings damaged within two city blocks.

Snohomish, Washington (21 km)—Windows rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), glassware and knickknacks broke (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), none ran out of buildings, trees and bushes shaken slightly (IV).

Snoqualmie, Washington (26 km)—Windows rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), glassware and knickknacks broke (V), hanging objects or doors swung slightly (III), a few items thrown from store shelves (V), none ran out of buildings, trees and bushes shaken slightly (IV).

Stanwood (Camano Island), Washington (61 km)—Silvana postal employee personal report. Felt while driving car in motion (V), difficulty in steering (≥V), experienced as a light vibration (II) of short duration (≥III).

Tacoma, Washington (61 km)—Felt by many (IV), windows/doors/dishes rattled slightly (III), building trembled moderately (IV), hanging objects or doors swung slightly (III), none ran out of buildings, felt slightly in stopped and moving vehicles (III, IV), no water splashed, hairline cracks in plaster interior walls (V), hairline cracks in brick exterior walls (V), few (5 percent) buildings damaged within zip code.

Tacoma, Washington (press report)—Audio tapes fell off a shelf in a Tacoma residence near the Pierce-King county line (Kremer and Gonzalez, 1996). Tacoma hospitals, including Tacoma General, Allenmore, and Mary Bridge hospitals, reported no damage or interruptions due to the earthquake (Kremer and Gonzalez, 1996).

Tukwila, Washington (46 km)—Felt by all (≥IV), frightened a few (II), rattled windows and dishes slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung

(III), a few small objects fell (V), a few ran out of buildings (V), no buildings damaged within two city blocks.

Vaughn, Washington (83 km)—Felt by many (IV), frightened several (III), awakened no one, windows and doors rattled slightly (III), walls creaked moderately (IV), building trembled slightly (III), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few glassware broke (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), no buildings damaged within zip code.

Woodinville, Washington (19 km)—Felt by all (≥IV), frightened many (IV), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few windows cracked (V), a few small objects overturned (V), a few small objects fell (V), a few glassware and dishes broke (V), hanging objects or doors swung moderately (IV), a few ran out of buildings (V), trees and bushes shaken moderately (V), felt moderately in stopped vehicles (IV), hairline cracks in interior plaster walls (V), no buildings damaged within zip code.

Intensity IV

We assigned intensity IV to 68 communities. Hypocentral distances of the 59 communities for which observations were reported on both the "Personal Reports" and "Community Reports" sections of the postal questionnaires ranged between 22 and 193 km, with a median hypocentral distance of 75 km. These communities are represented by non-italic font in the following. Communities for which only personal reports are listed in italic-font in the following.

Felt (IV) at Allyn, Anacortes, Auburn, Black Diamond, Bow, Burley, Burton, Chelan, Chimacum, Cle Elum, Clearlake, Concrete, Deming, Easton, Eastsound, Edmonds, Elma, Enumclaw, Everson, Fall City, Freeland, Gig Harbor, Grapeview, Greenbank, *Hadlock*, Indianola, Kent (Midway), Kirkland (N), Lakewood, Lilliwaup, Lopez Island, Lyman, Manson, *Mill Creek*, Milton, Morton, Mountlake Terrace, Mukilteo, *Olalla*, *Pateros*, Port Angeles, Port Gamble, Port Orchard, Port Townsend, Quilcene, Ravensdale, Renton (Cascade), Rockport, Rollingbay (Bainbridge Island), Seabeck, Seattle (Georgetown), Seattle (Magnolia Bluffs), Sequim, Shelton, Silvana, South Colby, Southworth, Suquamish, Tracyton, Vashon, Whidbey Island Naval Air Station, Wilkeson, Winlock, and Zillah.

Felt (IV) in British Columbia at Burnaby, where is was felt by most, frightened some, and a few people ran outside; at New Westminster, where it was felt by most, frightened some, windows and other objects rattled, buildings trembled and shook, hanging objects swung noticeably, and a few people ran outside; at Richmond, where is was felt by all, shook the entire house, hanging objects swung, and a few people ran outside; and (III-IV) at Victoria, where cutlery shook, and lamps wobbled.

Intensity III

We assigned intensity III to 63 communities. Hypocentral distances of the 45 communities for which observations were reported on both the "Personal Reports" and "Community Reports" sections of the postal questionnaires ranged between 39 and 339 km, with a median hypocentral distance of 142 km. These communities are represented by non-italic font in the following. Communities for which only personal reports are listed in italic-font in the following.

Felt (III) in Washington at Anderson Island, *Belfair*, *Bellevue (Bellevue Square)*, Bellingham, Buckley, *Buena*, Clallam Bay, *Connell*, Danville, Davenport, Ellensburg, *Ephrata*, *Ferndale*, Goldendale, Graham, Harrington, Hobart, *Hunters*, Kelso, *Kent*, Keyport, Lakebay, *Lakewood Center (west)*, *Lilliwaup*, *Longview*, Lynden, McCleary, Montesano, Moses Lake, Naches, Nordland,

Okanogan, Olympia, Omak, Orting, Parkland, Quincy, Rainier (Olympian Staff, 1996), Ravensdale, *Redmond (east)*, Retsil, *Seattle (Wallingford)*, *Seattle (Youngstown)*, Selah, Soap Lake, South Prairie, Spanaway, Steilacoom, Sumas, *Tacoma (98465)*, *Tacoma (Franklin Park-98405)*, Tahuya, Twisp, Vancouver (Evergreen Park), Yakima, and Yelm.

Press reports—Although buildings at the State capital campus in Olympia perceptibly swayed, no building damage there was reported (Ang, 1996). A post-earthquake inspection of the Fourth Avenue Bridge in Olympia revealed hairline cracks in the bridge's support column, but city engineers could not be certain that the earthquake had caused the cracks in the deteriorating 70-year old bridge (Dodge, 1996). In Olympia, "the earthquake produced mild rattling and a low rumble for about 10 seconds" (Kremer and Gonzalez, 1996).

Felt (III) in British Columbia at Chilliwack, Salt Spring Island, and Skutz Falls (23 km west of Duncan on Vancouver Island).

Felt (II-III) in British Columbia at Kelowna, Maple Ridge, Nanaimo, Penticton, Vancouver, and Vernon.

Intensity II

We assigned intensity II to eight communities. Hypocentral distances for these communities ranged between 71 and 388 km, with a median hypocentral distance of 262 km. The earthquake was felt in five other communities in Idaho, Oregon, and Washington.

Felt (II) in Washington at Cosmopolis, Inchelium, Port Angeles, Raymond, Sunnyside, and Tacoma (98413).

Felt (II) in British Columbia at Castlegar and Nelson.

Felt in Idaho at Coeur d'Alene (Bjorhus and others, 1996).

Felt in Oregon at Portland (Olympian Staff, 1996).

Felt in Washington at Kennewick, Pasco, and Richland (Olympian Staff, 1996).

Not Felt (I)

We assigned intensity I (not felt) to 54 communities. Hypocentral distances for these communities ranged between 40 and 344 km, with a median hypocentral distance of 254 km.

Reported not felt (I) in Oregon at Astoria, Condon, Dallas, Fossil, Heppner, Hillsboro (S), Hood River, Idanha, Irrigon, Maupin, Moro, Oregon City, Otis, Pendleton, Scappoose, The Dalles, Tillamook, Wemme, and Weston.

Reported not felt (I) in Washington at Aberdeen, American Lake (Tacoma), Battle Ground, Camas, Centralia, Colville, Coulee City, Dayton, Deer Park, Fircrest, Forks, Grandview, Greenwood, Hoquiam, Kapowsin, La Crosse, Leavenworth, Lyle, Moxee City, Plymouth, Prosser, Randle, Roosevelt, Roy, Saint John, Seattle (Skyway), South Bend, Spokane (E. Downtown), Sprague, Sumner, Tillicum, Touchet, Union Gap, Wallula, Wapato, Washtucna, and Wauna.

Reported not felt (I) in British Columbia at Merritt (273 km distance).

Pacific Northwest Seismic Network Internet Intensity Responses for the 1996 Duvall Earthquake

By the end of May 1996, the Pacific Northwest Seismic Network received 845 unique responses to an internet based felt-report form (Malone and others, 1996; Pacific Northwest Seismic Network, 1996d). Figure 10*B* shows the felt intensities estimated from these responses and averaged over zip codes. For most of the mapped region, these contours are quite consistent with those of our traditional MMI map (fig. 10*B*), when the PNSN decimal intensities are rounded off to the nearest integer. Both

maps have intensity VI (between 5.5 and 6.3 in the decimal representation used in the PNSN map) in the epicentral region, extending a little farther to the north than to the south. The distributions of the traditional MMI and the PNSN intensity contours both may be interpreted as showing a slightly elevated intensity along the north side of the Seattle Fault in Seattle, Washington, where increased intensities were reported in the 1949, 1965, and 2001 Nisqually-type and other smaller earthquakes, including aftershocks of the 1996 Duvall earthquake (Frankel and others, 1999, 2009; Booth and others, 2004; Stephenson and others, 2006). We have noted in discussion of the 1995 Point Robinson earthquake (above) that, for that event, the PNSN map of internet intensities showed lower intensities north of the Seattle Fault than south of the fault, an effect not obvious in the traditional MMI for that earthquake.

*M*4.9 1997 Bremerton Earthquake

UTC Date and Time: June 23, 1997 19:13:27 UTC
Local Date and Time: June 23, 1997 12:13:27 PM PDT
Epicenter: 47.598° N, 122.570° W
Depth: 13.4±0.1 km (8.3±0.1 miles)
Magnitude: 4.9 M_D(PNSN), 4.5 M_w(OSU) (Pacific Northwest Seismic Network, 1997a), 5.0 m_b(USGS)

Summary

The *M*4.9 1997 Bremerton earthquake was widely felt throughout the Puget Lowland as far north as Mount Vernon to Orting in the south (fig. 11*A*). The strongest intensities, VI, were reported in the Bremerton region where hairline cracks were observed in interior and exterior walls and in the Silverdale area where a mobile home slid off its foundation (fig. 11*B*). Elsewhere, damage was slight (Dunagan, 1997).

"Some residents of the region felt just a few seconds of shaking yesterday. Some didn't feel it at all. The quake was accompanied by four rapid-fire aftershocks and followed by at least nine other aftershocks" (Henderson and Kokmen, 1997). Many people felt the earthquake in Kitsap County, where "77 people called Cencom within less than an hour" (Dunagan, 1997).

The earthquake epicenter lies along strands of the Seattle fault zone (fig. 11*B*). Both the PNSN focal-mechanism based on first-motions (Pacific Northwest Seismic Network, 1997b) and the Oregon State University moment-tensor solution (Pacific Northwest Seismic Network, 1997a; represented in our fig. 1) are consistent with faulting in response to an approximately north-south compressive stress, such as would also have produced the Seattle fault zone.

The largest recorded accelerations were about 1 percent *g* at station GNW (Green Mountain) located about 19 km west of the epicenter (fig. 11*B*; Pacific Northwest Seismic Network, 1997c).

Intensity contours prepared from the 402 entries to the PNSN community intensity response website (Pacific Northwest Seismic Network, 1997d) agree favorably with the intensities assigned to the postal questionnaires (fig. 11*B*). The maximum intensity reported by PNSN (1997d), 5.63, is close to the maximum intensity, VI, reported here. A notable difference is that the PNSN (1997d) received reports implying intensities of about 4.5 in the Everett area, whereas the several postal questionnaires returned from the same region indicated that the earthquake was not felt there (fig. 11*B*).

There were 255 postal questionnaires mailed to a canvass radius of 300 km and 190 (75 percent) were returned (table 3).

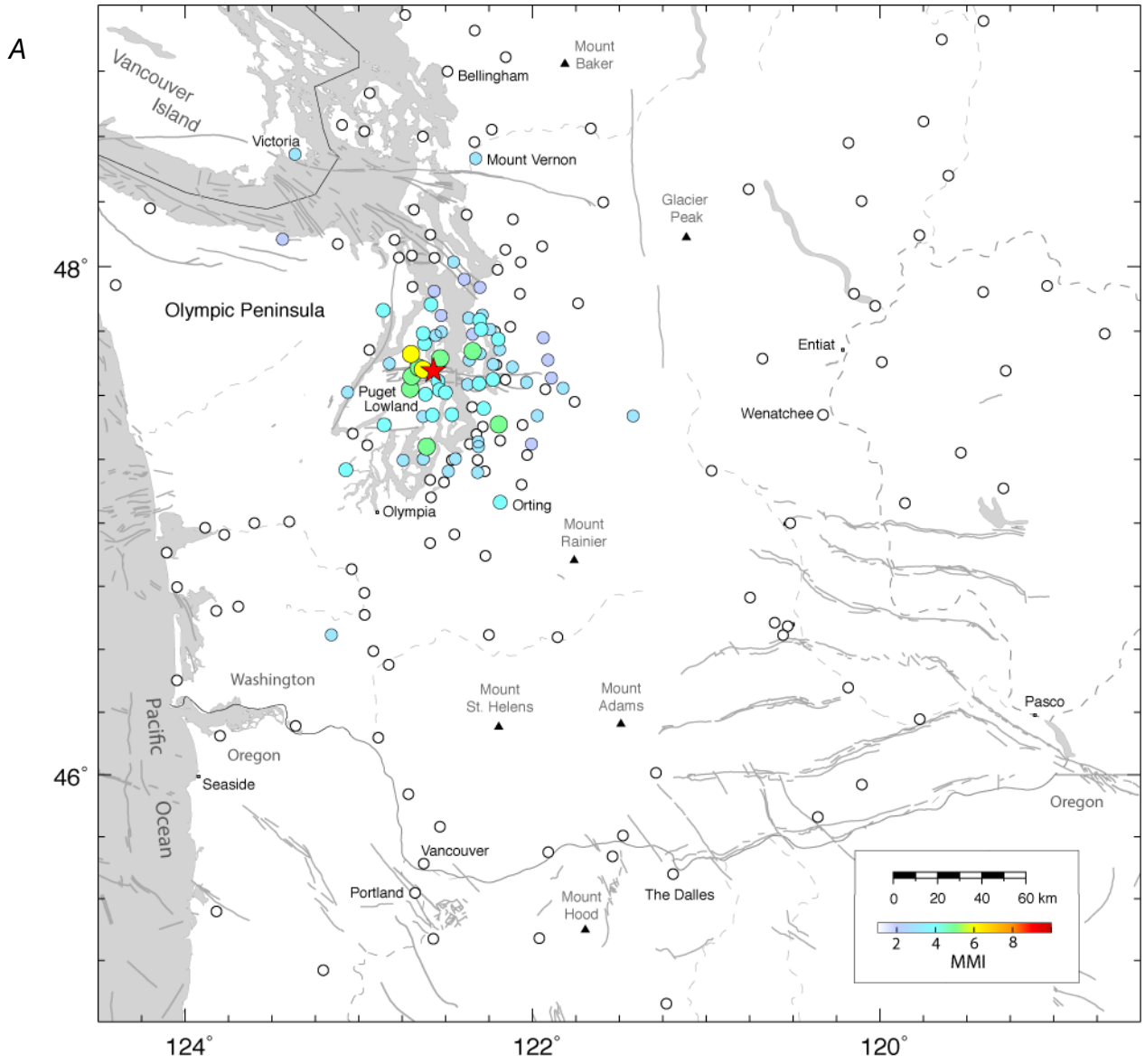


Figure 11. *A*. Modified Mercalli Intensities for the *M*4.9 1997 Bremerton earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which responses were received. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. *B*. Expanded view of the Modified Mercalli Intensities for the *M*4.9 1997 Bremerton earthquake (red star). Labeled dashed gray lines show intensity contours reported by the Pacific Northwest Seismic Network (PNSN) based on internet intensity responses; small gray dots show locations of zip codes from which the PNSN (1997d) obtained observations. Solid gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes. DMF, Devils Mountain Fault; SF, Seattle Fault; TF, Tacoma Fault; BI, Bainbridge Island; Bre, Bremerton; GNW, Green Mountain; and VI, Vashon Island.

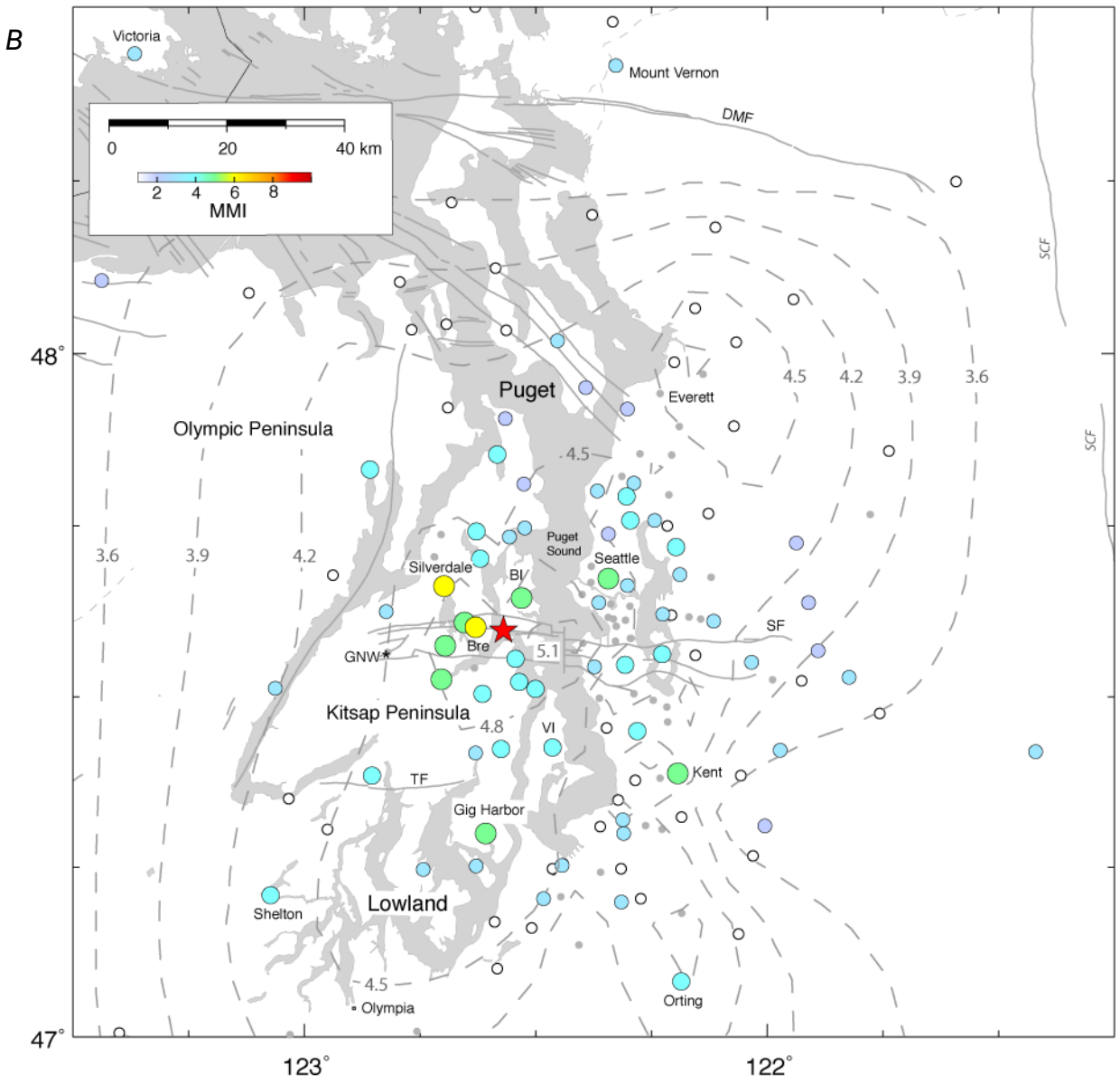


Figure 11.—Continued

Intensity VI

Intensity VI assignments were made to two communities. Hypocentral distances for these communities ranged between 14 and 18 km, with a median hypocentral distance of 16 km.

Bremerton (northeast), Washington (14 km)—Felt by many (IV), awakened none, frightened many (IV), windows, doors, and windows rattled loudly (≥IV), walls creaked moderately (IV), building trembled strongly ≥ (IV), hanging pictures out of place/tilted (V), many small objects overturned (≥V), several small objects fell (V), heavy furniture or heavy appliances were displaced (VI), hanging objects or doors swung moderately (IV), several objects thrown from store shelves (V), a few people ran out of buildings (V), trees and bushes shaken moderately (V), water splashed onto the banks of lakes, hairline cracks in interior dry wall (V), interior dry wall split at seams (VI), hairline cracks to exterior concrete block walls (V), few (about 5 percent) building damage within zip code. On the returned questionnaire from Bremerton, questions 7 and 8 answered by "UNK" meaning unknown.

Bremerton, Washington (press report)—A Bremerton resident noticed violent shaking “when he heard a loud ‘pop’ within the structure.” A city building inspector later “reported that one of the 2-inch-by-6-inch beams had cracked, weakening the house.” An employee at an antique store in Bremerton reported that “all the stuff moved back and forth on the shelves. The telephone poles and wires moved back and forth” (Dunagan, 1997).

Bremerton, Washington (press report)—At the Puget Sound Naval Shipyard on the north shore of Sinclair Inlet in Bremerton, “minor wall and ceiling cracks were found in Building 290, which houses offices and a gyro shop, and Building 980, which houses offices and engineering spaces.” No significant structural damage was found to several buildings and the six dry docks there (Dunagan, 1997).

Bremerton, Washington (press report)—“In Bremerton, a records clerk for the Bremerton Police Department, was trying to start her car when it started shaking. "I thought it was something wrong with my car," she said. "But then I thought, wait a minute!"” (Henderson and Kokmen, 1997).

Silverdale, Washington (~18 km) (press report)—“Reports of residential damage included a mobile home that slid partially off its foundation in Silverdale (VI)” (Dunagan, 1997).

Intensity V

We assigned intensity V to seven communities. Hypocentral distances for these communities ranged between 15 and 39 km, with a median hypocentral distance of 18 km.

Bainbridge Island, Washington (15 km) (press report)—An employee of “the Bainbridge Island School District, said it happened so fast a colleague thought a truck had hit the building. ‘This one was quick and to the point,’ she said.” At the Bainbridge Island Thriftway, little grass huts suspended from the ceiling as part of the store's Hawaiian Days celebration began to sway. Customers gasped and a few screamed. Cans fell from shelves and a few jars broke (V). “We were really rolling,” said Manager Rich Petersen (Henderson and Kokmen, 1997).

Bremerton (Gorst), Washington (18 km)—Felt by many (IV), frightened several (III), windows, doors, and dishes rattled loudly (≥IV), building trembled strongly (≥IV), hanging pictures fell (V), many small objects overturned (≥V), many small objects fell (≥VI), several glassware and knickknacks broken (V), hanging objects or doors swung moderately (IV), several items thrown from store shelves (V), many people ran out of buildings (≥V), trees and bushes shaken moderately (V), felt moderately in moving vehicles (V), a few masonry fences/retaining walls were cracked (V), a few chimneys were cracked (V).

Bremerton (west), Washington (17 km)—Felt by many (IV), awakened many (IV), frightened many (IV), windows and dishes rattled (III), walls creaked slightly (III), building trembled slightly (III),

a few small objects overturned (V), a few small objects fell (V), a few glassware/dishes/knickknacks broke (V), a few people ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), felt slightly in moving vehicles (IV), hairline cracks in interior walls (V), hairline cracks in exterior walls (V), no building damage within 2 city blocks and few (about 5 percent) buildings damaged within zip code.

West Bremerton (press report)—"Reports of residential damage included … minor cracks in a West Bremerton basement" (Dunagan, 1997).

Gig Harbor, Washington (36 km)—Felt by many (IV), awakened a few (II), frightened several (III), windows, doors, and windows rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few small objects overturned (V), a few small objects fell (V), none ran out of buildings, trees and bushes shaken slightly (IV), hairline cracks in interior plaster wall (V), hairline cracks to exterior concrete block walls (V), no building damage within two city blocks or within zip code.

Kent, Washington (39 km)—Ravensdale postal employee personal report (V): Frightened by earthquake (IV), experienced difficulty maintaining balance (V) while standing (IV) on concrete floor. Short duration (III). Community report for Kent by Ravensdale postal employee (III): Felt by several (III), frightened a few (II), windows rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), hanging objects or doors swung slightly (III).

Seattle (Wallingford), Washington (23 km)—Felt by many (IV), frightened many (IV), dishes rattled slightly (III), walls creaked moderately (IV), building trembled strongly (IV), a few small objects overturned (V), hanging objects or doors swung moderately (IV), a few items thrown from store shelves (V), a few people ran out of buildings (V), trees and bushes shaken slightly (IV), no building damage within two city blocks or within zip code.

Tracyton, Washington (15 km)—Felt by all (IV), windows, doors, and dishes rattled loudly (IV), walls creaked loudly (≥IV), building trembled strongly (≥IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), hanging objects or doors swung moderately (IV), a few people ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), hairline cracks in interior plaster walls (V).

Intensity IV

We assigned intensity IV to 19 communities. Hypocentral distances for these communities ranged between 14 and 66 km, with a median hypocentral distance of 29 km.

Felt (IV) in Washington at Allyn, Bainbridge Island-Winslow, Keyport, Kirkland (north), Manchester, Mercer Island, Mountlake Terrace, Olalla, Orting, Port Gamble, Port Orchard, Poulsbo, Quilcene, Seatac-Des Moines, Seattle (Forest Park) (98155), Seattle (Downtown, 98101; Lake Union, 98105; Georgetown, 98108; University of Washington, 98195), Shelton, South Coulby, Southworth, Vashon Island.

Port Orchard, Washington (press report)—"In Port Orchard a couple of glass vases fell and shattered, but most items were just shifted a bit." The earthquake was felt at Port Orchard by County Commissioner Chris Endresen during lunch at Tweten's restaurant. At the Kitsap County Courthouse in Port Orchard members of the county canvassing board dropped, covered, and held on to a table (Dunagan, 1997).

Seattle, Washington (98101) (press report)—"It was a shaker, not a roller," said a worker on the 40th floor of the Rainier Tower. "We felt the ground moving, and my computer was jumping. You could feel the floor really rumble." Thirteen floors down, at the Scandinavian Airlines System office, a

sales coordinator whose office faces Elliott Bay, said the quake "felt pretty scary" (Henderson and Kokmen, 1997).

Seattle, Washington (98101) (press report)—The 44-story U.S. Bank Center building shook "like a bowl full of Jell-O"—just like it was supposed to, said its architect. "There's this quick slop! and then it keeps vibrating for a moment before it stops. I'd say this one was a very quick shake" (Henderson and Kokmen, 1997).

Seattle, Washington (98101) (press report)—At Elliott's on the Seattle waterfront, a visitor from the Midwest, "thought a boat had hit the restaurant. We were like, gosh, what was that? But we kind of looked around and everyone was doing their own thing, so we said, whatever" (Henderson and Kokmen, 1997).

Seattle, Washington (98105) (press report)—It was reported that “at Benjamin's on (south) Lake Union (the) liquor bottles started slipping and sliding, and the TV swayed” (Henderson and Kokmen, 1997).

Seattle, Washington (98195) (press report)—At the University of Washington, Mark Ghiorso, chairman of the Department of Earth and Space Sciences, called it a "sudden jolt” (Henderson and Kokmen, 1997).

Intensity III

We assigned intensity III to 29 communities. Hypocentral distances for these communities ranged between 20 and 125 km, with a median hypocentral distance of 40 km.

Felt (III) in Washington at Bellevue (Lake Hills) (98008), Burley, Curtis, Edmonds, Federal Way, Fox Island, Hobart, Indianola, Issaquah, Kenmore, Kirkland, Lakebay, Langley, Lilliwaup, Lynnwood (Alderwood Manor), Medina, Mount Vernon, Puyallup (west), Seabeck, Seattle (Laurelhurst) (98105), Seattle (Queen Anne west) (98119), Seattle (Youngstown) (98125), Snoqualmie, Snoqualmie Pass, Suquamish, Tacoma (98411, 98413), and Tacoma (south) (98409).

Seattle, Washington (press report)—It was reported that “the Kingdome was inspected shortly after the earthquake. No damage was found.” “First Lady Hillary Rodham Clinton, who was attending a reception in downtown Seattle [at the Rainier Club, 98104], gave no indication of having felt the quake” (Dunagan, 1997).

Felt mildly (II-III) in Victoria, British Columbia.

Intensity II

We assigned intensity II to 10 communities. Hypocentral distances for these communities ranged between 27 and 87 km, with a median hypocentral distance of 47 km.

Felt (II) in Washington at Black Diamond, Carnation, Clinton, Duvall, Fall City, Hansville, Kingston, Mukilteo, Port Angeles, and Seattle (Haller Lake) (98133).

Not Felt (I)

We assigned intensity I (not felt) to 122 communities. Hypocentral distances for these communities ranged from 27 to 299 km, with a median hypocentral distance of 125 km.

Reported not felt (I) in Oregon at Astoria, Hood River, Maupin, McMinnville, Oregon City, Portland, The Dalles, Tillamook, and Wemme.

Reported not felt (I) in Washington at Anacortes, Arlington, Auburn (northeast), Battle Ground, Bellevue (Bellevue Square), Bellingham, Bickleton, Blaine, Bothell, Brewster, Brinnon, Buckley, Burlington, Carlton, Cathlamet, Centralia, Chehalis, Chelan, Clallam Bay, Cle Elum, Clearview,

Conconully, Concrete, Cosmopolis, Coulee City, Coupeville, Darrington, Eastsound, Eatonville, Electric City, Ellensburg, Elma, Enumclaw, Ephrata, Everett, Everson, Federal Way (west), Forks, Fort Lewis, Freeland, Friday Harbor, George, Glacier, Glenwood, Granger, Granite Falls, Grapeview, Greenbank, Hoquiam, Kelso, Kent (Midway), Lake Stevens, Lakewood Center (east), Leavenworth, Long Beach, Loomis, Lopez Island, Mansfield, Marysville, Milton, Montesano, Morton, Moses Lake, Newport Hills, Nordland, Normandy Park, North Bend, Okanogan, Oroville, Oso, Port Hadlock, Port Ludlow, Port Townsend, Preston, Prosser, Puyallup (northeast), Randle, Raymond, Redondo, Rochester, Roosevelt, Roy, Sedro Woolley, Sequim, Snohomish, South Bend, Stanwood, Stehekin, Steilacoom, Stevenson, Sultan, Tacoma (Downtown), Tacoma (Franklin Park), Tieton, Tokeland, Toledo, Union, Vancouver (Evergreen Park), Waterville, Wenatchee, Westport, White Salmon, Wide Hollow, Wilbur, Winlock, Winthrop, Woodinville, Woodland, Yakima, Yakima (southwest), and Yelm.

*M*4.6 1997 Okanogan Earthquake

UTC Date and Time: June 24, 1997 14:23:13 (UTC)
Local Date and Time: June 24, 1997 7:23:13 AM PDT
Epicenter: 48.364° N, 119.888° W
Depth: 10.2±0.1 km (6.3±0.1 miles)
Magnitude: 4.6 M_D(PNSN), 4.1 M_w(OSU) (Pacific Northwest Seismic Network, 1997e), 3.9 m_b(USGS)

Summary

The *M*4.6 1997 Okanogan earthquake struck in north-central Washington approximately 20 km north of the 1989 Okanogan earthquake reported above (fig. 1). An *M*3.6 aftershock struck 13 minutes later. The focal-mechanism of the earthquake that is implied by the Oregon State University moment tensor solution (Pacific Northwest Seismic Network, 1997e; our fig. 1) corresponds to reverse slip on an east-west-trending reverse fault. The focal-mechanism reported on PNSN (2017) implies that the earthquake occurred as oblique-slip on a vertical, north-northwest-trending fault, or as strike-slip on an east-northeast-trending, southwest-dipping, fault. The two different mechanisms would have different tectonic implications, if the deformation implied by either mechanism were taken as representative of deformation throughout the Okanogan region. The PNSN (2017) mechanism, not plotted in figure 1, is similar to the mechanism of the 1989 Okanogan earthquake that is shown in figure 1. The moment-tensor solution for the 1997 earthquake that is plotted in figure 1 is similar to the moment-tensor focal-mechanism reported by the U.S. Geological Survey (2017) for an *M*4.6 earthquake that occurred nearby on November 18, 2011. We have selected the Oregon State University moment-tensor solution for plotting in figure 1 so as to convey, by comparison with the mechanism of the 1989 earthquake, that various published focal-mechanisms for the Okanogan region are inconsistent in terms of their implications for regional tectonics.

The highest recorded ground motions were about 0.45 percent *g* at station LTY (Liberty Mine), at an epicentral distance of 136 km (fig. 12; Pacific Northwest Seismic Network, 1997f).

Press reports indicate that the 1997 Okanogan earthquake “was felt across north-central Washington and in the Spokane area, and as far north as Kelowna and Vernon in British Columbia, Canada” (Associated Press, 1997). There was little significant damage or injury. “A dispatcher for the Okanogan County Sheriff's Office said it received no reports or calls this morning of major injuries or damage” (Henderson and Kokmen, 1997).

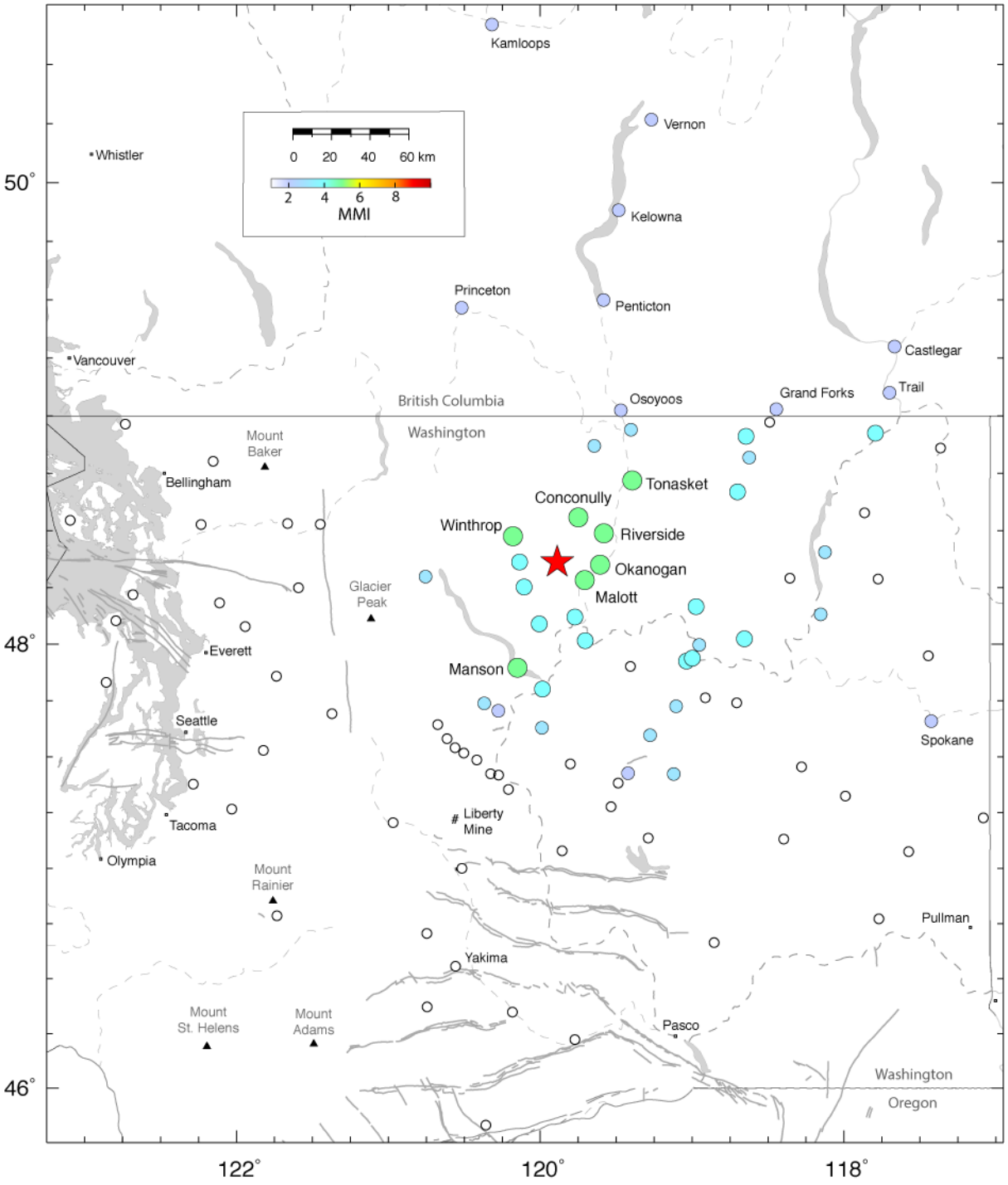


Figure 12. Modified Mercalli Intensities for the *M*4.6 1997 Okanogan earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which responses were received. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. Solid gray lines, Quaternary faults and folds from Barrie and Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes; # provides location of Liberty Mine.

The largest reported intensities, V, were from communities that experienced small objects falling and/or breaking and hairline cracks in walls (fig. 12). The distribution of intensity for the 1989 and 1997 Okanogan earthquakes was generally similar, with the primary difference being that the 1997 earthquake was felt well into lower British Columbia, as far north as Kamloops, whereas there are no felt reports from Canada for the 1989 event (figs. 6 and 12).

There were too few (21) entries to the PNSN community intensity response website to prepare a contour map (Pacific Northwest Seismic Network, 1997g). Nonetheless, the maximum intensity determined from these responses, 5.28, agrees well with the maximum intensities assigned to the postal questionnaires (V). Entries to the online community intensity response website reported minor building damage, including minor chimney cracks, as well as pictures left askew and furniture moved (Pacific Northwest Seismic Network, 1997g).

There were 112 questionnaires mailed to a canvass radius of 250 km and 95 (85 percent) were returned (table 3).

Intensity V

We assigned intensity V to seven communities. Hypocentral distances for these communities ranged between 19 and 56 km, with a median hypocentral distance of 27 km.

Conconully, Washington (26 km)—Felt by all (≥IV), awakened many (IV), frightened many (IV), windows and dishes rattled slightly (III), building trembled moderately (IV), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), none ran out of buildings, no building damage within two city blocks or within the zip code.

Malott, Washington (19 km)—Felt by all (≥IV), awakened a few (II), frightened several (III), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), a few small objects fell (V), hanging objects or doors swung slightly (III), a few items were thrown from store shelves (V), felt moderately in stopped vehicles (IV), hairline cracks in exterior walls (V), no building damage within two city blocks.

Manson, Washington (56 km)—Felt by several (III), awakened a few (II), frightened a few (II), windows and dishes rattled (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), none ran out of buildings, no building damage within two city blocks or within zip code.

Okanogan, Washington (23 km)—Felt by many (IV), awakened many (IV), frightened many (IV), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), a few small objects fell (V), a few glassware/dishes/knickknacks broke (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), felt slightly in stopped vehicles (III), felt slightly in moving vehicles (IV), hairline cracks in interior plaster walls (V), few buildings (about 5 percent) damaged within two city blocks.

Okanogan, Washington (press report)—We provide the entire quote: “In Eastern Washington, Katie Quill, a dispatcher for the Colville Tribal Police, said she felt quite a jolt and was surprised no one called after the quake. ‘It really shook the building,’ she said. ‘It felt like a horse shaking.’” (Henderson and Kokmen, 1997).

Riverside, Washington (28 km)—Felt by all (IV), awakened several (III), frightened several (III), windows and dishes rattled slightly (III), building trembled moderately (IV), hanging pictures fell (V), several small objects overturned (V), several small objects fell (V), hanging objects or doors swung moderately (IV), felt moderately in stopped vehicles (IV), no building damage within two city blocks or within zip code.

Tonasket, Washington (55 km)—Felt by many (IV), awakened several (III), frightened several (III), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), building trembled slightly (III), hanging pictures swung (III), a few windows cracked (V), hanging objects or doors swung slightly (III), a few items were thrown from store shelves (V), none ran out of buildings, no building damage within two city blocks or within zip code.

Winthrop, Washington (27 km)—Felt by many (IV), awakened several (III), frightened a few (II), windows, doors, and dishes rattled (III), walls creaked slightly (III), building trembled moderately (IV), hanging pictures swung (III), several small objects overturned (V), several small objects fell (V), knickknacks broke (V), hanging objects or doors swung slightly (III), a few ran out of buildings (V), trees and bushes shaken slightly (IV), felt slightly in stopped vehicles (III), hairline cracks in interior dry walls (V), small rocks falls, water muddied, no building damage within two city blocks or within zip code.

Intensity IV

We assigned intensity IV to 14 communities. Hypocentral distances for these communities ranged between 23 and 166 km, with a median hypocentral distance of 68 km.

Felt (IV) in Washington at Brewster, Bridgeport, Carlton, Chelan Falls, Curlew, Electric City, Grand Coulee, Keller, Methow, Nespelem, Northport, Republic, and Twisp.

Grand Coulee Dam, Washington (press report)—"Because of its size and location, though, (the) quake did trigger inspections at the Grand Coulee Dam. Inspectors found no damage. 'It felt like a large truck driving by,' said dam spokesman Greg Sprankle" (Henderson and Kokmen, 1997).

Intensity III

We assigned intensity III to 13 communities. Hypocentral distances for these communities ranged between 60 and 131 km, with a median hypocentral distance of 83 km.

Felt (III) in Washington at Ardenvoir, Coulee City, Elmer City, Hartline, Hunters, Loomis, Malo, Oroville, Rice, Stehekin, Waterville, and Wilson Creek.

Intensity II

We assigned intensity II to 12 communities. Hypocentral distances for these communities ranged between 79 and 258 km, with a median hypocentral distance of 152 km.

Felt (II) in Washington at Entiat, Spokane area (Associated Press, 1997), and Stratford.

Felt in British Columbia, Canada at Castlegar, Grand Forks, Kamloops, Kelowna (Associated Press, 1997), Osoyoos, Penticton, Princeton, Trail, and Vernon (Associated Press, 1997).

Not Felt (I)

We assigned intensity I (not felt) to 56 communities. Hypocentral distances for these communities ranged between 63 and 284 km, with a median hypocentral distance of 157 km.

Reported not felt (I) in Washington at Almira, Arlington, Blaine, Cashmere, Chewelah, Cle Elum, Colville, Concrete, Connell, Coupville, Danville, Darrington, Deer Park, Dryden, East Wenatchee, Ellensburg, Enumclaw, Ephrata, Friday Harbor, George, Glacier, Granger, Granite Falls, Harrington, Inchelium, Kent (Midway), La Crosse, Leavenworth, Malaga, Mansfield, Marblemount, Metaline Falls, Monitor, Moses Lake, Palisades, Peshastin, Port Townsend, Prosser, Quilcene, Ritzville, Roosevelt, Saint John, Sedro Woolley, Skykomish, Snoqualmie, Soap Lake, Sprague, Sultan, Tekoa, Tieton, Wenatchee, White Swan, Wilbur, and Yakima (southwest).

*M*5.8 1999 Satsop Earthquake

UTC Date and Time: July 3, 1999 01:43:54 (UTC)
Local Date and Time: July 2, 1999 18:43:54 PDT (6:43 PM local time)
Epicenter: 47.074° N, 123.464° W
Depth: 40.0±0.1 km (24.8±0.1 miles)
Magnitude: 5.8 M_D, 5.8 M_w(GCMT), 5.7 M_w(OSU), 5.4 m_b(USGS)

Summary

The *M*5.8 1999 Satsop earthquake occurred within the subducting Juan de Fuca slab at a depth of 40 km beneath Elma and Satsop, Washington, located between Olympia, Washington, and the Pacific Ocean (fig. 1). The focal mechanism of the earthquake is consistent with normal faulting along either a north- or northeast-trending fault, resulting from down-dip tension in the subducting slab (Pacific Northwest Seismic Network, 2017). Focal mechanisms implied by P-wave first-motions, the OSU moment tensor solution (both at Pacific Northwest Seismic Network, 1999a), and Global Centroid Moment Tensor Project Project (2017) moment-tensor solution are all similar. As is typical for inslab earthquakes, this earthquake produced very few (and very small) aftershocks. About a week following this earthquake there were three small (*M*2.5 or less) aftershocks with hypocenters nearly identical to the main shock (Pacific Northwest Seismic Network, 1999a).

This earthquake occurred at 6:43 PM local time on Friday, July 2. It was felt widely west of the Cascade Range from southwestern British Columbia to northwestern Oregon (fig. 13*A*). Shaking and related damage was strongest in the vicinity of Aberdeen, Brady, Hoquiam, Montesano, and Satsop, Washington (fig. 13*B*), where seven people were injured. One person was also injured in Olympia (Washington Department of Natural Resources, 1999; Grays Harbor County Emergency Management, 2014). The earthquake caused over $8.1 million in damage in western Washington (EQE International, 1999).

Recorded accelerations for the earthquake were reported by the Pacific Northwest Seismic Network (1999a). They show a north-south trending elongation of the accelerations in the orientation of the focal plane. The largest recorded peak ground accelerations were 8 percent *g* at Wynoochee Dam (fig. 13*B*), at a hypocentral distance of 55 km. Recorded accelerations in the Tacoma-Seattle-Edmonds urban corridor ranged between 0.5 to 1 percent *g* whereas those recorded near Portland varied between 0.2 and 0.5 percent *g*. According to the PNSN website created for the earthquake, calculated accelerations near the epicenter reached 15 percent *g* based on an unspecific ground motion prediction equation (Pacific Northwest Seismic Network, 1999a).

The maximum traditional MMI that we assigned to the Satsop earthquake was VII, assigned to several communities in the epicentral area on the basis of damage to buildings and chimneys. These communities are all located to the west of the epicenter within the flood plain of the Chehalis River and its tributaries (fig. 13*B*).

Intensity data for British Columbia are from a variety of sources, including a web-based felt intensity questionnaire and Drysdale and Horner (1999).

Intensity VII

We assigned intensity VII to four communities. Hypocentral distances for these communities ranged between 41 and 49 km, with a median hypocentral distance of 42 km.

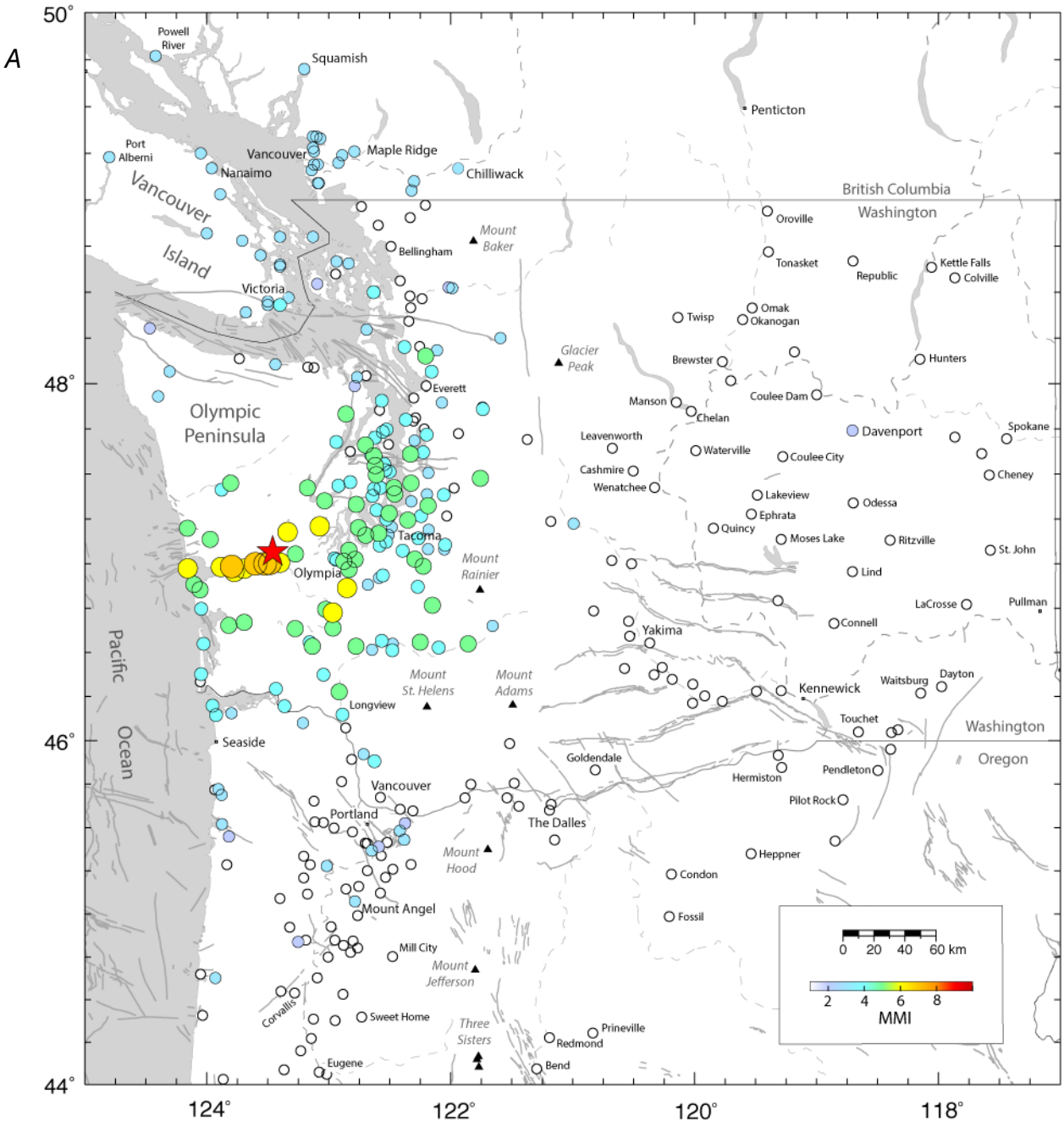


Figure 13. *A*. Modified Mercalli Intensities (MMI) for the *M*5.8 1999 Satsop earthquake (red star). Intensities are plotted as colored dots using the ShakeMap and Did You Feel It? color palette (U.S. Geological Survey, 2016d). The map encompasses all communities for which traditional intensities of II and higher were assigned. Communities that reported that the earthquake was not felt are shown as smaller white circles. Communities plotted as squares are shown for purposes of geographic referencing, but we have no intensity data for these communities for this earthquake. *B*. Expanded view of the Modified Mercalli Intensities for the *M*5.8 1999 Satsop earthquake (red star). All communities that reported an MMI of VI or VII are identified. Labeled dashed gray lines show intensity contours reported by the Pacific Northwest Seismic Network (PNSN) based on internet and mailed responses; small gray dots show locations of zip codes from which the PNSN (1999b) obtained observations. The location of the intensity IV contour is uncertain in places because of the small number of felt responses in outlying areas (Pacific Northwest Seismic Network, 1999b). Solid gray lines, Quaternary faults and folds from Barrie and

Greene (2015), the U.S. Geological Survey Quaternary fault and fold database (U.S. Geological Survey, 2015), and Morell and others (2017). Dashed lines show larger rivers. Triangles, Holocene volcanoes. DMF, Devils Mountain Fault; HCF, Hood Canal Fault; LRF, Leech River Fault; SCF, Straight Creek Fault; SWIF, Southern Whidbey Island Fault; TF, Tacoma Fault.

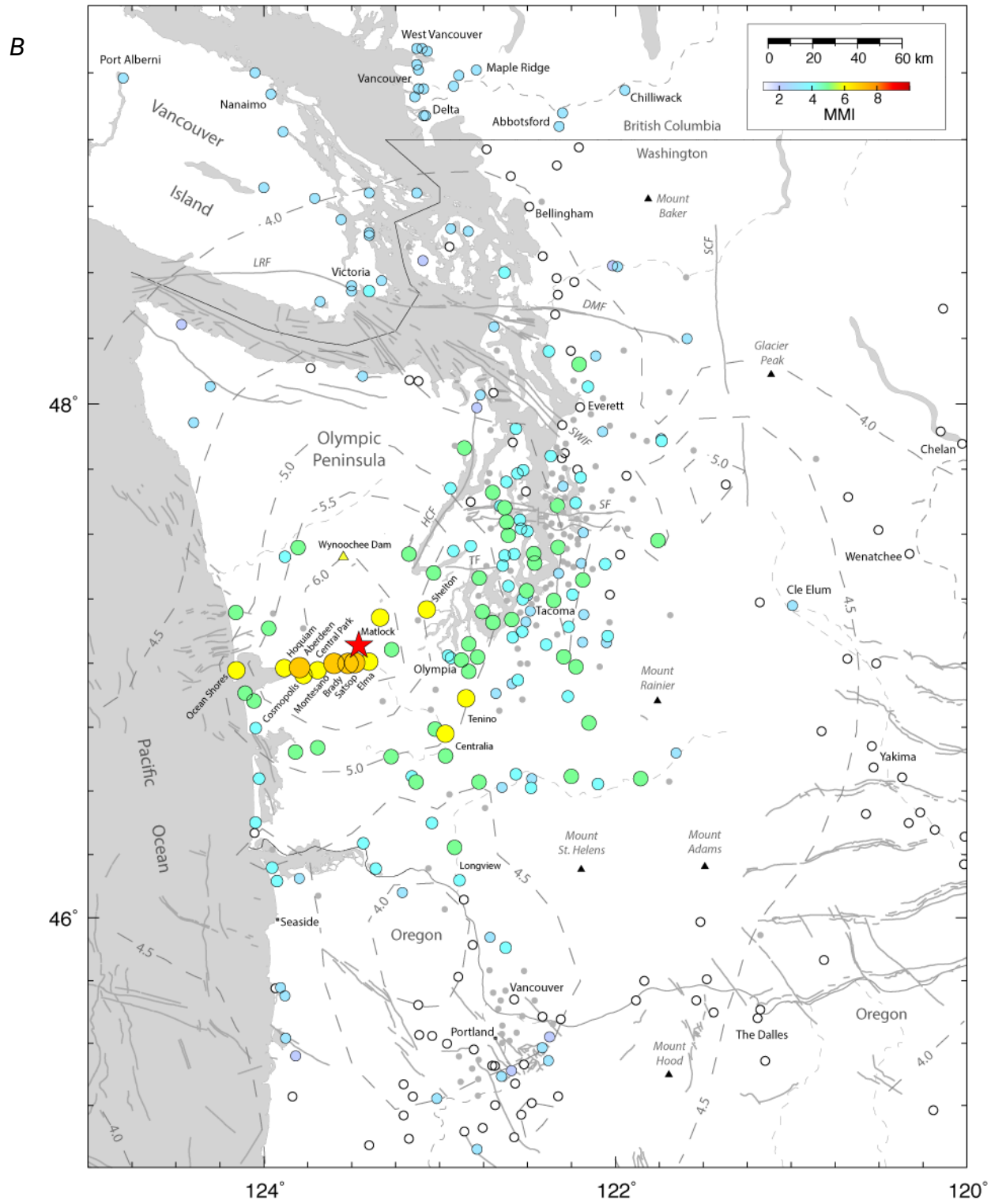


Figure 13.—Continued

Aberdeen, Washington (49 km)—Earthquake was felt by all (≥IV), greatly frightened many (IV), awakened none, windows and dishes rattled loudly (≥IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), many small objects overturned (V), many small objects fell (VI), many dishes or knickknacks broke (VI), many items thrown from store shelves (VI), appliances shifted (V), large furniture shifted (VI), heavy appliances shifted by inches (VI), a few ran out of buildings (IV), felt strongly in stopped vehicles and moderately in moving vehicles (V), several tombstones cracked (VII), masonry fences and retaining walls cracked (V), some windows broke out (VI), many large cracks in interior plaster and drywalls (VI), hairline cracks in exterior wood walls (VI), hairline cracks in exterior brick veneer, solid brick, stucco, and concrete walls (V), several old chimneys cracked (VI), several old chimneys twisted/leaning (VII), several old chimneys lost bricks (VII), a few old chimneys fell (VII), old wooden and brick buildings distorted/off foundation (VIII), large cracks in columns of old reinforced concrete buildings (VIII), a few pipes developed leaks, large cracks in sidewalks, streets, highways (VI), electric power was out in some areas for more than one hour, small landslides and rock falls, slumping of river banks, ground cracks in wet ground, few (about 5 percent) buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Aberdeen, Washington (press report, Daily World Staff, 1999)—A decorative wall collapsed onto the roof of a store, smashing through the ceiling and causing an estimated $250,000 in damage; heavy damage was reported to the main Public Utility Department (PUD) substation in Aberdeen; there were several reports of ruptured gas and water lines and reports of several downed power lines; Aberdeen's two fire stations were reported to have received minor structural damage.

Aberdeen, Washington (EQE International, 1999)—Other older brick and concrete buildings in the city center suffered significant structural damage, including the Goldberg Building. The Chehalis Bridge in downtown Aberdeen suffered several cracks in the north approach abutments. The main fire station in Aberdeen, built in 1966, suffered minor structural damage to concrete beams (EQE International, 1999).

Brady, Washington (41 km)—Hoquiam postal employee Community Report for Brady, 2 miles west of Satsop. Felt by all (≥IV), dishes rattled loudly (≥IV), walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (≥IV), hanging objects and doors swung moderately (IV), hanging pictures left out of place/tilted (IV), many small objects overturned (V), many small objects fell (VI), a few dishes or knickknacks broke (V), several items thrown from store shelves (V), appliances shifted (V), heavy appliances shifted (VI), a few ran out of buildings (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), trees and bushes shook strongly (V), partial collapse of roof (VII).

Montesano, Washington (43 km)—Felt by all (≥IV), frightened several (III), windows and dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures fell (≥V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), several items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), a few ran out of buildings (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), trees and bushes shook (IV), a few tombstones displaced (VI), a few large cracks in interior walls (VI), hairline cracks in exterior walls (brick veneer, solid brick, and stucco) (V), a few old chimneys cracked (VII), a few old chimneys twisted/leaning (VI), a few old chimneys lost bricks (VI), a few old chimneys fell (VII), old other structures distorted (VIII), few (5 percent) buildings within two city blocks, few (5 percent) buildings within zip code.

Montesano, Washington (observations from other sources than postal questionnaires)—The historic county courthouse, built in 1910, sustained substantial damage. Other county buildings had minor damage, including dislodged tiles, cracked plaster, and toppled office equipment (Zappala, 1999). The City of Montesano fire station, a concrete masonry block structure with a timber roof built in 1979, suffered some spalling of masonry beneath roof girders (EQE International, 1999).

Satsop, Washington (41 km)—Felt by all (≥IV), frightened many (IV), windows, doors, and dishes rattled loudly (≥IV), walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (≥IV), hanging objects or doors swung moderately (IV), hanging pictures fell (V), many small objects overturned (≥V), several small objects fell (V), several dishes or knickknacks broke (V), many items thrown from store shelves (VI), appliances shifted (V), a few ran out of buildings (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), trees and bushes shook moderately (V), masonry fences and retaining walls cracked (V), some windows broke out (VI), hairline cracks in interior plaster walls (V), a few old chimneys lost bricks (VI), modern wooden building distorted/off foundation (VIII), no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Intensity VI

We assigned intensity VI to eight communities. Hypocentral distances for these communities ranged between 41 and 67 km, with a median hypocentral distance of 50 km.

Central Park, Washington (press report) (45 km)—A 78-year-old house was damaged, with bowed walls (VI), ceiling cracks (VI), and significant chimney damage (≥VII) (Hong, 1999).

Centralia, Washington (68 km)—Adna postal employee Community Report. Felt by all (≥IV), frightened several (III), windows, doors, and dishes rattled slightly (III), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), several small objects overturned (V), several small objects fell (V), several dishes or knickknacks broke (V), several items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), large appliances shifted by inches (VI), many ran out of buildings (≥V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), trees and bushes shook moderately (V), several tombstones displaced (VI), masonry fences and retaining walls cracked (V), hairline cracks in interior plaster walls (V), hairline cracks in exterior wood, brick veneer, stucco, and concrete block walls (V), partial collapse of solid brick exterior wall (VII), a few old chimneys cracked (V), many old chimneys lost bricks (VII), no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Cosmopolis, Washington (49 km)—Felt by and frightened many (IV), awakened several (III), windows/doors/dishes rattled loudly (IV), walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (≥IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), several small objects overturned (V), several small objects fell (V), a few dishes or knickknacks broke (V), a few ran out of buildings (V), felt slightly in stopped and moving vehicles (III, IV), some windows broke out (VI), a few large cracks in interior walls (VI), a few old chimneys were cracked (V), a few old chimneys were twisted/leaning and a few lost bricks (VI), a few old chimneys fell (VII), many buildings damaged within two city blocks, many buildings damaged within zip code.

Elma, Washington (42 km)—Felt by many (IV), frightened several (III), and awakened no one, windows and dishes rattled loudly (≥IV), walls creaked moderately (IV), buildings trembled, shook, or rocked slightly (III), hanging objects and doors swung moderately (IV), hanging pictures fell (≥V), a few small objects overturned (V), several small objects fell (V), several dishes or knickknacks broke (V), a few items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), a

few ran out of buildings (V), felt slightly in stopped and moving vehicles (III, IV), bushes and trees shook lightly (IV), hairline cracks in interior drywall (V), hairline cracks in exterior concrete block walls (V), a few old chimneys cracked (V), regular telephone service was out for more than one hour, no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Matlock, Washington (43 km)—Felt by many (IV), frightened several (III), awakened no one, windows/doors/dishes rattled loudly (≥IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), large furniture shifted (VI), a few ran out of buildings (V), hairline cracks in interior drywall (V), a few chimneys cracked (V), a few mobile homes off foundation (VI).

Ocean Shores, Washington (67 km)—Taholah postal employee Community Report. Felt by all (≥IV), frightened many (IV), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects and doors swung moderately (IV), hanging pictures left out of place/tilted (V), many ran out of buildings (V). Many items fell from the shelves of a grocery store on Chance a la Mer (press report, Daily World Staff, 1999).

Shelton, Washington (52 km)—Felt by and awakened all (≥IV), frightened many (IV), windows, doors, and dishes rattled loudly (IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures fell (≥V), several small objects overturned (V), many small objects fell (VI), several dishes or knickknacks broke (V), several items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), heavy appliances shifted by inches (VI), many ran out of buildings (≥V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), trees and bushes shook moderately (V), a few tombstones cracked (VII), masonry fences and retaining walls cracked (V), water splashed on the banks of lakes (V), a few windows cracked (V), hairline cracks in interior plaster and drywalls (V), hairline cracks in exterior brick veneer walls (V), hairline cracks in exterior concrete block walls (V), a few old chimneys cracked (V), a few old chimneys lost bricks (VI), well muddied, no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code. A local grocery store reported cracked walls and merchandise knocked off the shelves (Arne, 2010).

Tenino, Washington (66 km)—Felt by many (IV), frightened several (III), windows and doors rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), a few small objects overturned (V), a few small objects fell (V), a few ran out of buildings (V), felt slightly in stopped vehicles (III), trees and bushes shook lightly (IV), a few large cracks in interior walls (VI), few (5 percent or less) buildings damaged within two city blocks, few (5 percent or less, with an annotation of mostly cracking reported) buildings damaged within zip code.

Intensity V

We assigned intensity V to 42 communities. Hypocentral distances for these communities ranged between 43 and 142 km, with a median hypocentral distance of 77 km.

Anderson Island, Washington (71 km)—Felt by many (IV), frightened several (III), awakened no one, dishes rattled slightly (III), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), appliances shifted (V), a few ran out of buildings (V), felt moderately in stopped vehicles (IV). Annotation at bottom of the returned questionnaire: "No damage".

Auburn (northeast), Washington (108 km)—Felt by all (≥ IV), awakened and frightened a few (II), windows, doors, dishes rattled slightly (III), buildings trembled, shook, or rocked slightly (III),

hanging objects or door swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), felt slightly in stopped and moving vehicles (III, IV), none ran out of buildings, no buildings damaged within two city blocks.

Boisfort, Washington (77 km)—Lebam postal employee Community Report. Felt by many (IV), frightened a few (II), awakened no one, walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (≥IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few ran from buildings (V), bushes and trees shook moderately (V), hairline cracks in interior drywall (V), telephone service unusable for less than one hour, no buildings damaged within two city blocks.

Bremerton (northeast), Washington (95 km)—Belfair postal employee Community Report. Felt by many (IV), frightened several (III), awakened no one, windows/doors/dishes rattled slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects and doors swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), felt in stopped vehicles (III), trees and bushes shook lightly (IV), none ran out of buildings, no buildings damaged within zip code.

Burien, Washington (103 km)—Kent (Midway) postal employee Community Report. Felt by many (IV), awakened a few (II), frightened no one, windows/door/dishes rattled slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), felt slightly in stopped vehicles (III), retaining walls cracked (V), hairline cracks in interior plaster walls (V), no building damage within zip code.

Burton, Washington (93 km)—Felt by all (≥IV), greatly frightened many (IV), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (≥IV), hanging objects and doors swung moderately (IV), a few small objects overturned (V), a few small objects fell (V), a few ran out of buildings (V), felt moderately in stopped and moving vehicles (IV, V), bushes and trees shook strongly (≥V), water splashed onto the sides/banks of ponds and swimming pools (V), hairline cracks in interior drywall (V), hairline cracks in exterior walls (V), ground slump in land fill, no buildings damaged within zip code.

Castle Rock, Washington (106 km)—Felt by and awakened many (IV), frightened several (III), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects and doors swung slightly (III), a few small objects overturned (V), a few small objects fell (V), none ran out of buildings. Sections were 5–10 of the questionnaire were annotated by "N/A".

Chehalis, Washington (74 km)—Winlock postal employee Community Report. Felt by many (IV), frightened several (III), awakened a few (II), windows, doors, and dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), none ran out of buildings, felt slightly in stopped vehicles (III), bushes and trees shook strongly (≥V), few (about 5 percent) buildings damaged within two city blocks.

Doty, Washington (65 km)—Felt by many (IV), frightened a few (II), awakened no one, windows and dishes rattled slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or door swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), felt slightly in stopped and moving vehicles (III, IV), none ran out of buildings, no

buildings damaged within zip code. Section 6 of the questionnaire was answered "None"; section 7 was answered "Vibration Only".

East Olympia, Washington (64 km)—Felt by many (IV), frightened several (III), awakened a few (II), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes and knickknacks broke (V), several items thrown from store shelves (V), bushes and trees shook moderately (V), water splashed on sides of swimming pools (V), none ran out of buildings, no buildings damaged within zip code. Sections 6–9 of the questionnaire were answered by "None".

Elbe, Washington (113 km)—Felt by many (IV), frightened several (III), awakened no one, dishes rattled (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), hanging pictures fell (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), none ran out of buildings, no buildings damaged within zip code.

Ethel, Washington (89 km)—Felt by several (III), awakened and frightened a few (II), windows, doors, dishes rattled slightly (III), walls creaked slightly (III), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few objects overturned (V), a few objects fell (V), a few dishes or knickknacks broke (V), hanging pictures were left out of place/tilted (V), a few people ran out of buildings (V), trees and bushes shook lightly (IV), a few underground pipes developed leaks (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Fife, Washington (95 km)—Felt by many (IV), frightened several (III), windows, doors, dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), several objects overturned (V), several objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), appliances shifted (V), heavy appliances shifted by inches (VI), many people ran out of buildings (≥V), felt slightly in stopped vehicles (III), not felt in moving vehicles, trees and bushes shook lightly (IV), no buildings damaged within two city blocks, no buildings damaged within zip code. Section 6 of the questionnaire was answered as "None".

Galvin, Washington (64 km)—Felt by all (≥IV) and frightened several (III), windows, doors, and dishes rattled loudly (IV), walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (≥IV), hanging objects or doors swung moderately (IV), a few objects overturned (V), a few objects fell (V), a few dishes or knickknacks broke (V), many people ran outside (≥V), felt slightly in stopped and moving vehicles (III, IV), a few windows cracked (V), hairline cracks in interior plaster and drywalls (V), a few leaks in underground pipes (V), no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Graham, Washington (98 km)—Felt by many (IV), awakened and frightened a few (II), buildings trembled, shook, or rocked slightly (III), appliance (microwave) shifted (V), hairline cracks in exterior concrete block walls (V), few (about 5 percent) buildings damaged within two city blocks, no buildings damaged within zip code.

Grayland, Washington (66 km)—Felt by all (IV), frightened several (III), awakened no one, windows and dishes rattled loudly (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects and doors swung moderately (IV), several small objects overturned (V), several small objects fell (V), several dishes or knickknacks broke (V), several items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), a few ran out of buildings (V), felt slightly in

stopped and moving vehicles (III, IV), trees and bushes shook moderately (IV), no buildings damaged within two city blocks, no buildings damaged within zip code.

Hoodsport, Washington (60 km)—Felt by all (≥IV), frightened several (III), awakened no one, dishes rattled slightly (III), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), a few objects overturned (V), appliances shifted (V), a few ran out of buildings (V), felt slightly in stopped and moving vehicles (III, IV), trees and bushes shook lightly (IV), small rock falls, no buildings damaged within two city blocks, no buildings damaged within zip code.

Humptulips, Washington (56 km)—Felt by many (IV), frightened several (III), awakened no one, windows, doors, and dishes rattled loudly (IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few objects overturned (V), a few objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), heavy appliances shifted by inches (VI), a few ran out of buildings (V), felt slightly in stopped vehicles (III), trees and bushes shook moderately (V), water in ponds splashed onto banks/sides, electric power in some areas was out for more than one hour, no buildings damaged within two city blocks.

Kapowsin, Washington (103 km)—Felt by several (III), frightened a few (II), awakened no one, windows, doors, dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), no one ran out of buildings, hairline cracks in interior drywall (V).

Lacey, Washington (66 km)—Bremerton postal employee Community Report. Felt by all (≥IV), awakened and frightened a few (II), dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects and doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), large appliances shifted by inches (VI), none ran out of buildings, felt slightly in stopped and moving vehicles (III, IV), trees and bushes shook slightly (IV), no buildings damaged within two city blocks, no buildings damaged within zip code.

Longbranch, Washington (69 km)—Felt by many (IV), frightened a few (II), awakened no one, windows, doors, dishes rattled loudly (IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes and knickknacks broke (V), a few ran out of buildings, trees and bushes shook lightly (IV), water splashed on the banks of Puget Sound.

McCleary, Washington (43 km)—Felt by all (≥IV), greatly frightened many (IV), windows and dishes rattled slightly (III), walls creaked moderately (IV), hanging objects and doors swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects fell (V), a few dishes or knickknacks broke (V), several items were thrown from store shelves (V), felt slightly in moving vehicles (IV), bushes and trees shook lightly (IV).

Morton, Washington (116 km)—Mineral postal employee Community Report. Felt by many (IV), awakened and frightened a few (II), windows, doors, and dishes rattled loudly (IV), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves

(V), none ran out of buildings, trees and bushes shook lightly (IV), hairline cracks in interior drywalls (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

North Bend, Washington (142 km)—Felt by several (III), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), none ran out of buildings, felt slightly in stopped and moving vehicles (III, IV), no buildings damaged within two city blocks, no buildings damaged within zip code. Answer to Section 6 of the questionnaire was "No damage"; sections 7 to 9 were answered "None".

Olympia, Washington (61 km)—Felt by many (IV), frightened a few (II), awakened no one, windows, doors, and dishes rattled slightly (III), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few old chimneys cracked (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Pacific Beach, Washington (68 km)—Felt by many (IV), awakened several (III), frightened a few (II), windows and dishes rattled loudly (IV), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few ran out of buildings (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), hairline cracks in interior drywall (V), a few old chimneys cracked (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Port Orchard (south), Washington (89 km)—Bremerton postal employee Community Report. Felt by all (≥IV), frightened few (II), awakened no one, dishes rattled (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects and doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), appliances shifted (V), a few ran out of buildings (V), felt slightly in stopped and moving vehicles (III, IV), trees and bushes shook lightly (IV), hairline cracks in interior walls (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Quilcene, Washington (104 km)—Felt by many (IV), windows and doors rattled loudly (≥IV), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), large furniture shifted (VI), a few ran out of buildings (V), trees and bushes shook lightly (IV), large cracks in old cement foundations (VI). Sections 7–10 of the questionnaire were answered by "NA".

Quinault, Washington (64 km)—Felt by many (IV), awakened and frightened a few (II), windows/doors/dishes rattled loudly (≥IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), many ran out of buildings (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), trees and bushes shook lightly (IV), a few hairline cracks in interior plaster walls (V), no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Randle, Washington (142 km)—Felt by many (IV), frightened a few (III), awakened no one, windows/doors/dishes rattled (III), walls creaked moderately (IV), buildings trembled, shook, or rocked strongly (IV), hanging objects or doors swung moderately (IV), a few small objects fell (V), a few dishes or knickknacks broke (V), no buildings damaged within two city blocks, no buildings damaged within zip code. Randle postal employee personal report: experienced some fright (IV), had difficulty

maintaining balance (≥V). Experienced as a strong vibration (IV) of short duration (≥III). Felt standing (IV) inside Randle Fire Hall.

Raymond, Washington (63 km)—Felt by many (IV), awakened or frightened no one, windows and dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few small objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), a few ran out of buildings (V), felt slightly in stopped vehicles (III), bushes and trees shook lightly (IV), no buildings damaged within two city blocks, few (about 5 percent) buildings damaged within zip code.

Retsil, Washington (92 km)—Felt by many (IV), frightened several (III), awakened none, windows and doors rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung moderately (IV), a few people ran out of doors (V), felt slightly in stopped vehicles (III), hairline cracks in interior walls (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Sheridan Park, Washington (95 km)—Felt by and frightened many (IV), awakened no one, dishes rattled loudly (IV), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung slightly (III), a few objects overturned (V), a few objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), felt slightly in stopped vehicles (III), hairline cracks in interior walls (V). Sections 7 to 10 of the questionnaire were answered by "NA".

Silverdale, Washington (96 km)—Felt by many (IV), awakened a few (II), frightened no one, windows, doors, dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung slightly (III), none ran out of buildings, felt slightly in stopped vehicles (III), water splashed on the bank/sides of ponds and swimming pools, hairline cracks in interior drywalls (V), hairline cracks in exterior stucco walls (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

South Bend, Washington (68 km)—Felt by many (IV), frightened several (III), awakened no one, windows rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures fell (≥V), a few small objects overturned (V), several small objects fell (V), a few dishes or knickknacks broke (V), a few items were thrown from store shelves (V), appliances shifted (V), large furniture shifted (VI), heavy appliances shifted by inches (VI), none ran out of buildings, felt slightly in stopped and moving vehicles (III, IV), trees and bushes shook lightly (IV), hairline cracks in interior walls (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Steilacoom, Washington (78 km)—Felt by, awakened, and frightened many (IV), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), a few people ran out of doors (V), felt moderately in stopped vehicles (IV), felt slightly in moving vehicles (IV), retaining walls cracked (V), no buildings damaged within two city blocks.

Tacoma (Point Defiance Park), Washington (86 km)—Felt by many (IV), awakened and frightened a few (II), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few small objects overturned (V), a few ran out of buildings (V), felt slightly in stopped vehicles (III), no buildings damaged within two city blocks, no buildings damaged within zip code.

Tumwater, Washington (61 km)—Felt by all (≥IV), frightened a few (II), awakened no one, doors rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung slightly (III), many ran from buildings (V), felt strongly in parked vehicles (V), felt moderately in moving vehicles (V), bushes and trees shook moderately (V), no buildings damaged within zip code.

Union, Washington (60 km)—Felt by all (≥IV), frightened several (III), dishes rattled slightly (III), hanging pictures fell (V), a few small objects fell (V), a few ran out of buildings (V), felt strongly in stopped vehicles (V), felt moderately in moving vehicles (V), water splashed on the sides of swimming pools (V), no buildings damaged within zip code.

Vashon, Washington (94 km)—Felt by and awakened many (IV), frightened a few (II), dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked moderately (IV), hanging objects or door swung slightly (III), hanging pictures left out of place/tilted (V), a few ran out of buildings (V), felt slightly in stopped and moving vehicles (III, IV), trees and bushes shook lightly (IV), no buildings damaged within two city blocks, no buildings damaged within zip code.

Vaughn, Washington (72 km)—Felt by several (III), dishes rattled slightly (III), walls creaked moderately (IV), buildings trembled, shook, or rocked moderately (IV), hanging objects or doors swung moderately (IV), hanging pictures left out of place/tilted (V), a few objects overturned (V), a few objects fell (V), a few ran out of buildings (V), felt slightly in stopped vehicles (III), trees and bushes shaken slightly (IV), hairline cracks in interior walls (V), no buildings damaged within two city blocks, no buildings damaged within zip code.

Westport, Washington (67 km)—Felt by all (≥IV), frightened several (III), windows/doors/dishes rattled slightly (III), walls creaked slightly (III), buildings trembled, shook, or rocked slightly (III), hanging objects or doors swung slightly (III), hanging pictures left out of place/tilted (V), a few objects overturned (V), a few objects fell (V), a few dishes or knickknacks broke (V), a few items thrown from store shelves (V), a few ran out of buildings (V), felt slightly in stopped vehicles (III), trees and bushes shook lightly (IV), no buildings damaged within two city blocks.

Intensity IV

We assigned intensity IV to 58 communities. Hypocentral distances of the 51 communities for which observations were reported on both the "Personal Reports" and "Community Reports" sections of the postal questionnaires ranged between 57 and 175 km, with a median hypocentral distance of 97 km. These communities are represented by non-italic font in the following. Communities for which only personal reports are listed in italic-font in the following.

Felt (IV) in Washington at Anacortes, *Belfair*, *Bellevue (Midlakes)*, Brinnon, Burley, Cathlamet, Cinebar, Curtis, Eatonville, Edmonds, Fort Lewis, Gig Harbor, Glenoma, Hansville, Indianola, Kelso, Keyport, Kirkland (north), La Center, Lakewood Center (south), *Lebam*, Long Beach, Manchester, Maple Valley, Marysville, McKenna, Medina, Mossyrock, Neilton, Ocean City, Olalla, Olympia (west), *Onalaska*, Oysterville, Pacific, *Port Orchard (98366)*, Puyallup (southeast), Ryderwood, Skamokawa, South Colby, Southworth, Spanaway, Stanwood, Sultan, Suquamish, Tacoma (98465), Tahuya, Tokeland, Tracyton, Tumwater (west), *Tumwater*, Wauna, and Wilkeson.

Felt (IV) in Oregon at Hammond, Seaside, Warren, and Warrenton.

Felt (IV) in British Columbia at Victoria, at a hypocentral distance of 156 km.

Intensity III

We assigned intensity III to 77 communities. Hypocentral distances of the 67 communities for which observations were reported on both the "Personal Reports" and "Community Reports" sections of

the postal questionnaires ranged between 75 and 311 km, with a median hypocentral distance of 180 km. These communities are represented by non-italic font in the following. Communities for which only personal reports are listed in italic-font in the following.

Felt (III) in Washington at Beaver, *Bremerton (west)*, Carbonado, Darrington, Eastsound, Forks, *Freeland*, Hamilton, *Ilwaco*, *Issaquah*, Kent, *Kingston*, Lakewood Center (east), *Mukilteo*, Olga, Orting, Oso, Packwood, *Pe Ell*, Port Angeles, Port Hadlock, Rainier, *Redmond*, Redondo, Renton, *Renton (Highlands)*, Roslyn, Salkum, Seattle (Wedgwood), Silver Creek, Snohomish, Startup, Summer (Bonney Lake), Tacoma (Jefferson Park), Tacoma (South), Whidbey Island Naval Air Station, Woodland, and Yelm.

Felt (III) in Oregon at Astoria, Bay City, Boring, Clatskanie, Dundee, Gresham, Mount Angel, Nehalem, *Rockaway*, Toledo, West Linn, and Wheeler.

Felt (III) in British Columbia at Abbotsford, Chilliwack, Cobble Hill, Coquitlam, Cowichan Lake, Delta, Duncan, Ladner, Ladysmith, Langford, Metchosin, Mission, Nanaimo, New Westminster, North Vancouver, Port Alberni, Port Coquitlam, Powell River, Richmond, Salt Spring Island, Saturna Island, Sidney, Sooke, Squamish, Vancouver, Victoria, and West Vancouver.

Intensity II

We assigned intensity II to 12 communities. Hypocentral distances for these communities ranged between 120 and 412 km, with a median hypocentral distance of 197 km.

Felt (II) in Washington at Chimacum, Friday Harbor, Lyman, Sekiu, and Wilbur.

Felt (II) in Oregon at Gladstone, Monmouth, Oakridge, Seaside (press report, Corda, 1999), Sutherlin, Tillamook, and Troutdale.

Not Felt (I)

We assigned intensity I (not felt) to 179 communities. Hypocentral distances of the 177 communities for which observations were reported on both the "Personal Reports" and "Community Reports" sections of the postal questionnaires ranged between 88 and 460 km, with a median hypocentral distance of 258 km. These communities are represented by non-italic font in the following. Communities for which only personal reports are listed in italic-font in the following.

Reported not felt (I) in Washington at Alderwood Manor, Arlington, Bellingham, Benton City, Bingen, Blaine, Bothell, Bow, Brewster, Bridgeport, Burlington, Camas, Carlsborg, Carrolls, Carson, Cashmere, Chelan, Cheney, Clearlake, College Place, Colville, Connell, Conway, Coulee City, Coulee Dam, Dayton, Duvall, Easton, Ellensburg, Enumclaw, Ephrata, Everett, Everson, Fairchild Air Force Base, Ferndale, Goldendale, Grand Coulee, Grandview, Granger, Harrah, Hobart, Hunters, Joyce, Kettle Falls, La Crosse, Leavenworth, Lind, Lynnwood, Mabton, Manson, Moses Lake, Mount Vernon, Mountlake Terrace, Moxee City, Mukilteo, Naches, Nordland, Odessa, Okanogan, Omak, Orcas, Orchards (Vancouver), Oroville, Othello, Port Gamble, Prosser, Quincy, Reardan, Republic, Richland, Ritzville, Rollingbay, Saint John, Seabeck, Seaview, Selah, Sequim, Silvana, Skykomish, Soap Lake, *South Prairie*, Spokane (Audubon Park), Sumas, Sunnyside, Thorp, Tonasket, Toppenish, Touchet, Trout Lake, Twisp, Waitsburg, Walla Walla, Washougal, Waterville, Wenatchee, White Salmon, Yakima, and Zillah.

Reported not felt (I) in Oregon at Albany, Amity, Athena, Aumsville, Banks, Beaver Creek, Beaverton, Bend, Brownsville, Canby, Carlton, Cascade Locks, Clackamas, Cloverdale, Columbia City, Condon, Coos Bay, Coquille, Cornelius, Corvallis, Cottage Grove, Dallas, Dillard, Drain, Elmira, Estacada, Eugene, Florence, Forest Grove, Fossil, Friend, Halsey, Harrisburg, Heppner, Hermiston, Hillsboro (south), Hood River, Hubbard, Independence, Jefferson, Junction City, La Pine, Lake

Oswego, Lakeside, Lebanon, Lyons, Manzanita, Mapleton, Marylhurst, McMinnville, Mill City, Milton-Freewater, Molalla, Mulino, Myrtle Point, Newport, North Bend, Odell, Oregon City, Pendleton, Philomath, Pilot Rock, Prineville, Redmond, Reedsport, *Saint Helens*, Salem, Scappoose, Sheridan, Silverton, Springfield (west), Stayton, Sublimity, Sweet Home, The Dalles, Turner, Umatilla, Waldport, Winston, Woodburn, and Yamhill.

Pacific Northwest Seismic Network Internet Intensity Responses for the 1999 Satsop Earthquake

By 3 PM on July 3, 1999, about 20 hours after the earthquake, PNSN received 738 responses to its intensity report form website (Pacific Northwest Seismic Network, 1999b). The PNSN intensity map is similar to the traditional MMI map in that both maps show a zone of higher intensity (PNSN intensity ≥5.8, traditional MMI≥VI) in the lower valley of the Chehalis River (fig. 13*B*). We assigned traditional MMI of VII to several locations (fig. 13*B*). Contours on the PNSN map do not define a region of average PNSN as high as 6.5 (the lower bound of decimal numbers that would be represented by VII in integer Roman numeral notation), but individual PNSN values were as high as 6.68 (follow the "Summary of the Responses" link at PNSN [1999b]).

A notable difference between the PNSN internet-based intensities and the traditional MMI intensities is that the PNSN intensity 4 contour extends well to the east and south of the region within which postal questionnaires from most communities even reported the earthquake as having been felt (fig. 13*B*). The tendency of PNSN internet intensities to be larger than traditional USGS MMI may reflect in part a positive bias of internet intensities for regions near the margins of the felt area associated with an earthquake: this bias may result from the higher likelihood of individuals to contribute a report of an earthquake that they felt than a report of an earthquake that they did not feel (Dewey and others, 2002; Boatwright and Phillips, 2017). It is also likely that, that for some communities, postal employees who returned USGS questionnaires with "not felt" responses were simply not aware that the earthquake had in fact been felt in their zip-codes. We note that development of the procedure used for the USGS "Did You Feel It?" intensities (Wald and others, 1999) modified previously developed formulas so as to make CII/DYFI consistent with traditional USGS MMI in regions of light shaking (see fig. 1 and associated text in Wald and others, 1999). Several studies that have compared traditional USGS MMI with CII/DYFI do not show a tendency for CII/DYFI to be larger than traditional USGS MMI in regions of light shaking (for example, Dewey and others, 2002).

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