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The December 1872 Washington State Earthquake

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Abstract The largest historical earthquake in eastern Washington occurred on 15 December 1872. We used Modified Mercalli intensity (MMI) assignments for 12 twentieth-century earthquakes to determine attenuation relations for different regions in the Pacific Northwest. MMI attenuation for propagation paths east and west of the Cascade Mountains differs significantly only for epicentral distances greater than about 225 km. We used these attenuation relations and the MMI assignments for the 15 December 1872 earthquake to conclude that its epicentral region was east of the Cascade Mountains near Lake Chelan, Washington, and most probably near the south end of Lake Chelan. The intensity magnitude, M_I, is 6.8 and moment magnitude, **M**, is 6.5–7.0 at the 95% confidence level.

Introduction

Seismic hazard in the Pacific Northwest (PNW) is dominated by earthquakes near the Juan de Fuca–North America plate boundary, but events in eastern Washington, such as the poorly understood large earthquake that occurred on 15 December 1872, are also important. The shaking from infrequent great earthquakes on the Cascadia subduction zone, such as the **M** 9 event in January 1700 (Atwater *et al.*, 1999), dominates seismic hazard along the Pacific coast (Frankel *et al.*, 1996). The **M** 7.3 earthquake on 23 November 1873 that occurred near the California–Oregon border may also have occurred within the Cascadia subduction zone (Bakun, 2000). Both intraslab and crustal earthquakes contribute to the seismic hazard west of the Cascade Mountains. The $M_0 = 1.5 \times 10^{26}$ dyne cm (**M** 6.8) earthquake on 13 April 1949 (Baker and Langston, 1987), the $M_0 = 1.4 \times 10^{26}$ dyne cm (**M** 6.7) earthquake on 29 April 1965 (Langston and Blum, 1977), and the **M** 6.8 Nisqually earthquake on 28 February 2001 were intraslab earthquakes in western Washington. The **M** 7 earthquake, which occurred in about 900 A.D. on the Seattle fault, was probably a shallow crustal event (Bucknam *et al.*, 1992) and may have been the source of a tsunami on Puget Sound about 1000 years ago (Atwater and Moore, 1992).

The largest historical PNW earthquake east of the Cascades in Washington occurred on 15 December 1872. This earthquake is critical in defining the seismic hazard east of the Cascade Range, but its location and magnitude are controversial. Although there are dramatic accounts of landslides and groundwater disturbances, there are only two reliable intensity assignments near the epicentral region. Different interpretations of the descriptions of damage, ground failures, and water effects, as well as different attenuation models for intensity, have resulted in proposed source locations in the north Cascades of southern British Columbia (Milne, 1956), near Ross Lake in the north Cascades of northern Washington (Malone and Bor, 1979), and east of the Cascades near Lake Chelan (Stover and Coffman, 1993). Malone and Bor (1979) obtained a magnitude of 7.4 from an analysis of the Washington Public Power Supply System (WPPSS) (1977) MMI assignments using a modification of Evernden's (1975) model of intensity data. (Note that we use the terms "magnitude" and "*M*" to refer to an unspecified magnitude scale.)

Bakun and Wentworth (1997) have developed an objective method for analyzing seismic intensity data that results in an intensity magnitude, M_I, that is calibrated to equal moment magnitude, **M** (Hanks and Kanamori, 1979). The method provides objective uncertainties, empirically tied to confidence levels, for **M** and for source location, and it works well with historical earthquakes for which only a small number of intensity observations are available. In this report we use this method to analyze the intensity data for 12 twentieth-century PNW earthquakes (see Fig. 1) as calibration. We then apply these results to determine permissible source locations and magnitudes for the 1872 earthquake from its MMI assignments.

Our source for the 1872 earthquake, a shallow **M** 6.8 event near Lake Chelan, does not agree with the conclusions of Malone and Bor (1979). In particular, Malone and Bor (1979, p. 546) assumed that the 1872 event was a deep source and concluded that its magnitude was 7.4 and that "a location to the east near Lake Chelan is definitely ruled out." We attempt to rationalize the contradictory conclusions of the two studies by examining the basis and effects of using different attenuation models east and west of the Cascades, a shallow versus a deep source, and different intensity assignments.

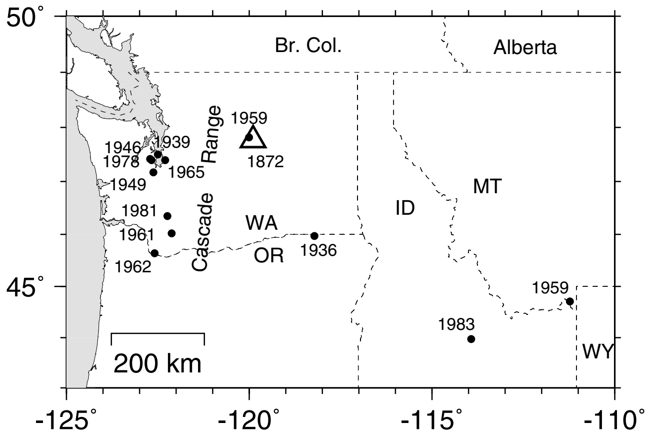

Figure 1. Map of the twentieth-century earthquakes (solid dots) used in this study and the intensity center (open triangle) of the 15 December 1872 earthquake.

Shallow Crustal Earthquakes East of the Cascades

As late as 1969 there were only three seismograph stations in Washington and three in western British Columbia (Noson *et al.*, 1988), so focal depths of nearly all PNW earthquakes before 1970 are unknown. Although earthquakes west of the Cascades occur throughout the crust and within the Juan de Fuca plate, all Washington earthquakes east of the crest of the Cascade Range since 1970 are located in the crust (Ludwin *et al.*, 1991), and there is no tectonic basis to suppose that large pre-1970 earthquakes might be deeper.

There is a general correlation between the occurrence of aftershocks and the depth of the mainshock (e.g., Mogi, 1963), and a convincing case can be made for such a correlation in and near the PNW. Grant *et al.* (1984) located more than 1000 aftershocks in the 24 months following the shallow **M** 5.5 Elk Lake event that occurred on 14 February 1981 in southwest Washington. The shallow 1983 **M** 7.0 Borah Peak, Idaho, earthquake was followed by four felt aftershocks (Stover, 1987) and hundreds of small aftershocks (Richins *et al.*, 1987). The shallow 1959 **M** 7.3 Hebgen Lake, Montana, earthquake was followed by a vigorous aftershock sequence (Stover and Coffman, 1993). In contrast, there were no aftershocks following the large intraslab events beneath Puget Sound in 1949 (magnitude 4.5 detection threshold) and 1965 (magnitude 2.5 detection threshold) (Ludwin *et al.*, 1991). Only four small aftershocks (coda-length magnitude 1.0 detection threshold) occurred after the 2001 **M** 6.8 intraslab Nisqually earthquake. Finally, only a few aftershocks followed the 1946 $M_0 = 2.5 \times 10^{27}$ dyne cm (**M** 7.6) lower-crust earthquake (focal depth near 30 km) that occurred above the subduction zone beneath Vancouver Island in British Columbia (Rogers and Hasegawa, 1978) and the $M_{\text{G-R}}$ 5.75 event in 1946 that occurred above the subduction zone beneath Puget Sound (Villasenor *et al.*, 2001). That is, shallow crustal events east and west of the Cascades have been followed by vigorous aftershock sequences, events above the subduction zone have been followed by a few aftershocks, and intraslab events have been followed by no more than a few small aftershocks.

Numerous aftershocks were felt following the $M_{\text{G-R}}$ 5.75 earthquake that occurred on 16 July 1936 near the Washington–Oregon border (Neumann, 1938) and three aftershocks were felt after the magnitude 5.0 earthquake that occurred on 5 August 1959 near Chelan, Washington (Eppley and Cloud, 1961). We consider both to be shallow events because they occurred east of the Cascades and were followed by aftershocks. Likewise, the 15 December 1872 earthquake was followed by a long, vigorous sequence of felt aftershocks (Milne, 1956), and we adopt Spence's (1989) conclusion that its source was shallow.

Intensity Data

Intensity observations have been obtained from sources that assign intensity values according to descriptions in the MMI scale proposed by Wood and Neumann (1931). MMI values for the twentieth-century earthquakes were obtained from issues of *United States Earthquakes*. The MMI assignments adopted for the 15 December 1872 earthquake are taken from Hopper *et al.* (2003). Those assignments of MMI, as well as those of WPPSS (1977) and Coombs *et al.* (1976) at Hopper *et al.*'s (2003) sites, are listed in Appendix A. We use only those MMI assignments that are not based solely on ground and water effects, because these effects can occur over several MMI levels (Hopper *et al.*, 2003). MMI I and MMI II values are not used. The number of MMI assignments for each MMI level and the source of the MMI assignments are listed in Table 1. The MMI assignments that we used to calibrate the attenuation of MMI with distance are shown in Figure 2.

Attenuation of MMI

Bakun and Wentworth (1997) fit median Δ for different MMI values for 11 **M** >5.5 California earthquakes to obtain the relation

$$\text{MMI} = f(\mathbf{M}) + g(\text{median } \Delta), \quad (1)$$

where $f(\mathbf{M}) = -3.29 + 1.68\mathbf{M}$, $g(\text{median } \Delta) = -0.0206 \times \text{median } \Delta$, and Δ is the epicentral distance in kilometers.

There are too few recent large earthquakes to determine $f(\mathbf{M})$ directly in the PNW, particularly if spatial variations in attenuation are considered. The $f(\mathbf{M})$ determined for California earthquakes is also appropriate for PNW earthquakes, however, since the same **M** and MMI scales are used in California and in the PNW.

We consider $g(\text{median } \Delta)$ of the form

$$g(\text{median } \Delta) = \text{MMI} - f(\mathbf{M}) = C_1 + C_2 \times \text{median } \Delta + C_3 \times \log(\text{median } \Delta), \quad (2)$$

Table 1
Earthquakes

			Instrumental Source Parameters				Intensity Data									Comparison of Source Parameters (Intensity Center, IC)							
No.	Date (UTC)	Locale	Lat (°N)*	Long (°W)*	Magni-tude	h (km)*	No. of MMI III	No. of MMI IV	No. of MMI V	No. of MMI VI	No. of MMI VII	No. of MMI VIII	No. of MMI IX	Total No. of MMI	Source	MMI Atten. Relation	M_I (at epicenter)	IC Lat (°N)	IC Long (°W)	M_I (at IC)	$M - M_I$ (epi)	$M - M_I$ (IC)	Δ (Epicenter − IC) (km)
1	15 Dec. 1872	Near Lake Chelan, WA (East of Cascades)					6	8	28	19	4	2		67	Hopper *et al.* (2003)	(4)		47.76	119.90	6.81			
2	16 July 1936	Near WA-OR Border (East of Cascades)	45.97	118.21	$5.75^{\dagger}$	5	62	59	18	4	3			146	Neumann (1938)	(4)	5.35	45.97	118.30	5.35	0.40	0.40	7.0
3	13 Nov. 1939	Puget Sound, WA (West of Cascades)	47.50	122.50	$5.75^{\dagger}$	—	36	131	83	54	7			311	Bodle (1941)	(3)	5.72	47.00	122.77	5.70	0.03	0.05	58.8
4	15 Feb. 1946	Puget Sound, WA (West of Cascades)	47.40	122.67	$5.75^{\dagger}$	18	20	67	43	29	3			162	Bodle and Murphy (1948)	(3)	5.85	47.40	122.71	5.84	−0.10	−0.09	3.1
5	13 April 1949	Puget Sound, WA (West of Cascades)	47.17	122.62	$6.8^{\ddagger}$	70	42	73	75	129	61	40		420	Murphy and Ulrich (1951)	(3)	7.02	46.67	122.57	6.92	−0.22	−0.12	55.2
6	5 Aug. 1959	Chelan, WA (East of Cascades)	47.82	120.00	$5.0^{\S}$	—	52	73	31	5				161	Eppley and Cloud (1961)	(4)	5.25	47.91	120.50	5.29	−0.25	−0.29	38.3
7	18 Aug. 1959	Hebgen Lake, MT (East of Cascades)	44.71	111.22	$7.3^{\|}$	5	64	239	359	179	9	22	3	875	Eppley and Cloud (1961)	(4),(5)	7.40	44.89	111.15	7.39	−0.12	−0.11	20.9
8	17 Sept. 1961	Near WA-OR Border (West of Cascades)	46.02	122.12	$5.1^{\#}$	7	19	27	14	4				64	Lander and Cloud (1963)	(3)	4.73	45.84	122.21	4.68	0.37	0.42	21.5
9	6 Nov. 1962	Near WA-OR Border (West of Cascades)	45.64	122.59	5.2**	16	22	77	86	42	1			228	Lander and Cloud (1964)	(3)	5.30	45.78	122.73	5.33	−0.10	−0.13	18.2
10	29 April 1965	Puget Sound, WA (West of Cascades)	47.4	122.3	$6.7^{\dagger\dagger}$	59	80	165	144	171	76	3		639	von Hake and Cloud (1967)	(3)	6.54	47.31	121.76	6.49	0.16	0.21	42.1
11	11 Mar. 1978	Puget Sound, WA (West of Cascades)	47.42	122.71	$4.8^{\ddagger\ddagger}$	25	15	51	22	4				92	Stover and von Hake (1980)	(3)	4.73	47.69	123.23	5.01	0.07	−0.21	49.4
12	14 Feb. 1981	Elk Lake, WA (West of Cascades)	46.35	122.24	$5.5^{\S\S}$	7	84	159	79	8				330	Stover (1984)	(3)	5.29	46.35	122.24	5.29	0.21	0.21	0.0
13	28 Oct. 1983	Borah Peak, ID (East of Cascades)	43.97	113.92	$7.0^{\|}$	14	132	156	211	56	6			561	Stover (1987)	(4),(5)	6.83	44.11	113.97	6.83	0.12	0.12	15.4

*Stover and Coffman (1993); $^{\dagger}M$ (Gutenberg and Richter, 1954); ‡**M** (Baker and Langston, 1987);
§Malone and Bor, (1979); ¶**M** (Doser, 1985); $^{\#}M_L$ (Grant and Weaver, 1986);
$\mathbf{M}$ (Yelin and Patton, 1991); ††M** (Langston and Blum, 1977); ‡‡(Ludwin *et al.*, 1991); §§**M** (Burger and Langston, 1985); $^{\|}$**M** (Ekstrom and Dziewonski, 1985)

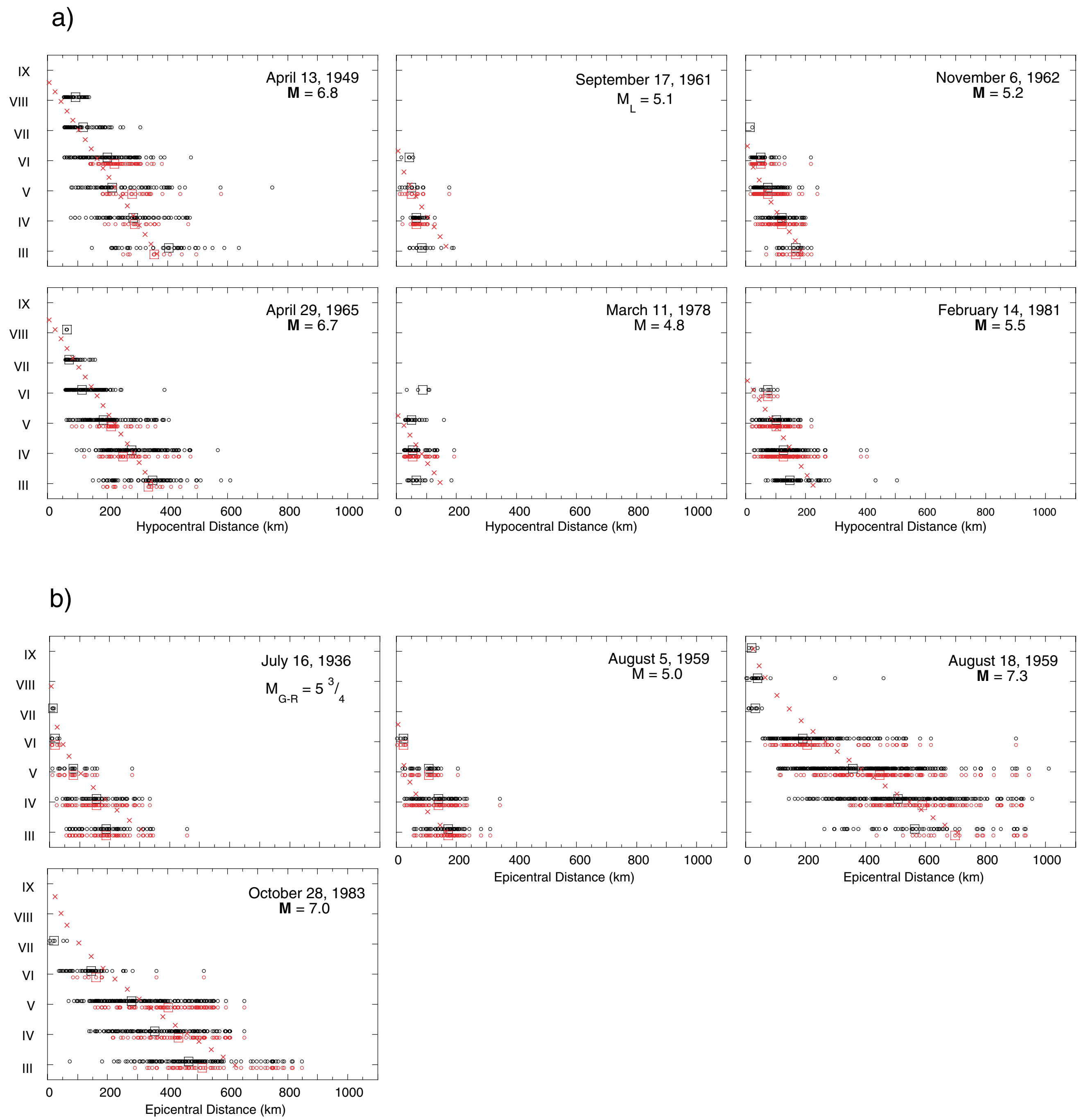

Figure 2. MMI values versus distance for PNW earthquakes (a) west and (b) east of the Cascade Range. Small open circles and large open squares are individual MMI values and the median distance for an MMI value, respectively. Black symbols show all the MMI values and median distances. Red symbols show those MMI and median distances used to obtain distance attenuation relation (3) in (a) and (4) in (b) (shown as red *X*s).

where C_1 might reflect a different average stress drop, C_2 can be associated with intrinsic attenuation and scattering, and C_3 with geometric spreading (e.g., Bakun and Joyner, 1984).

Malone and Bor (1979) argued that the attenuation of intensity with distance for propagation paths west of the crest of the Cascade Range is significantly greater than for paths to the east. MMI assignments for events west and east of the Cascades are shown in Figures 2a and 2b respectively. The depths h of earthquakes west of the Cascades can be significant so that Δ is not an appropriate measure of the length L of the propagation path. Rather, we use the slant distance $\Delta_h = [\Delta^2 + h^2]^{1/2}$ as the measure of L for propagation paths west of the Cascades.

We use the median distance of the sites assigned the same MMI value as a stable measure of the distance of that MMI value because local site effects can bias individual MMI values. The median distance can itself be biased, however, if based on only a few MMI, or if the distance range of MMI assignments is restricted by focal depth, political boundaries, coastlines, or other factors not related to wave propagation. In the following analysis, we estimate MMI attenuation from median Δ_h obtained using subsets of the MMI assignments specifically selected to minimize effects other than wave propagation.

Paths West of the Cascades

The MMI assignments for the large intraslab 1949 and 1965 events at sites east of the Cascades are not used to estimate Δ_h for paths west of the Cascades. The coastline to the west and the Canadian border to the north limit the possible range of distance of MMI assignments so that MMI sites west and north of the 1949 and 1965 epicenters are not used. Rather, we estimated median Δ_h for the 1949 and 1965 events from sites at azimuths of 150° to 210° from the epicenter. (All azimuths in this article are measured in degrees clockwise from north.) We do not estimate median Δ_h for MMI VII and VIII for the 1949 event and for MMI VI, VII, and VIII for the 1965 event since there are no MMI at $\Delta_h < h$. Similar arguments are used to obtain median Δ_h for MMI values for the 17 September 1961, 6 November 1962, 11 March 1978, and 14 February 1981 events (see red symbols in Fig. 2a). We do not use MMI for the 1939 or 1946 events in the attenuation calculations because the hypocenters are poorly determined and there are no instrumental estimates of **M**. A linear least-squares fit of the 17 $g(\text{median } \Delta_h)$ yields $C_1 = 1.53 \pm 3.14$, $C_2 = -0.0141 \pm 0.00543$, and $C_3 = -0.595 \pm 1.886$. Since C_3 is not significantly different from 0, we set $C_3 = 0$, and obtained $C_1 = 0.547 \pm 0.241$ and $C_2 = -0.0158 \pm 0.0012$. That is,

$$\text{MMI} = -2.74 + 1.68\mathbf{M} - 0.0158 \times \text{median } \Delta_h. \quad (3)$$

Equation (3) mingles the attenuation of the 1949 and 1965 intraslab events and the 1961, 1962, 1978, and 1981 shallow crustal events. Youngs *et al.* (1997) suggested, however, that attenuation from subduction zone events is lower than for shallow crustal events in active tectonic areas. To assess this possibility, we repeated the analysis for the four shallow crustal events only and for the two intraslab events only. $C_1 = 0.71 \pm 0.41$ and $C_2 = -0.0191 \pm 0.0042$ for the shallow events and $C_1 = 1.37 \pm 0.59$ and $C_2 = -0.0184 \pm 0.0022$ for the intraslab events. That is, for the shallow crustal events

$$\text{MMI} = -2.58 + 1.68 \times \mathbf{M} - 0.0191 \times \text{median } \Delta_h, \quad (3a)$$

and for the intraplate events

$$\text{MMI} = -1.92 + 1.68\mathbf{M} - 0.0184 \times \text{median } \Delta_h. \quad (3b)$$

The attenuation of damaging ground shaking with distance from interslab events and shallow crustal events in the Puget lowlands is the same (see Fig. 3).

Paths East of the Cascades

There are only a few significant PNW earthquakes east of the Cascades with instrumental locations and magnitude estimates. Although the 1959 Hebgen Lake and the 1983 Borah Peak earthquakes occurred hundreds of kilometers east of the Cascades (see Fig. 1), MMI assignments for many sites in eastern Washington are available for these events. While the effects of these earthquakes are evident at sites far to the northwest of these sources, the severity of the effects decreases rapidly with distance for sites to the southeast (Eppley and Cloud, 1961; Stover, 1987). A similar pattern is apparent in the isoseismals of the M_s 6.3 event on 23 November 1947 that occurred about 40 km west of the Hebgen Lake source (Stover and Coffman, 1993). Although Boatwright and Choy (1986) modeled this phenomenon as an effect of rupture toward the northwest for the Borah Peak event, there is no evidence for directivity toward the northwest during the Hebgen Lake event. While directivity toward the northwest may have contributed to the isoseismal pattern for the Borah Peak event, the similar isoseismal patterns for the Hebgen Lake, Borah Peak, and the 1947 events suggest that differential attenuation is more important. That is, the greater attenuation for propagation paths through Yellowstone and the Snake River Plain to the southeast should be accounted for in the analysis so we use only the MMI

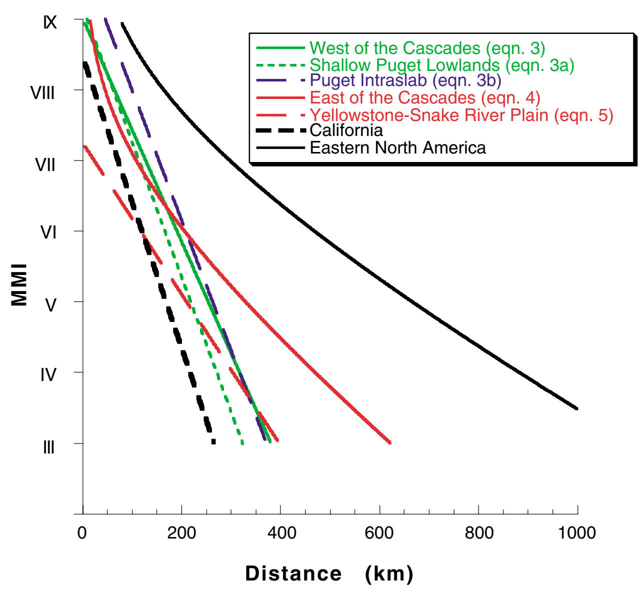

Figure 3. Attenuation of MMI with distance for **M** 7.0 earthquakes relative to California (Bakun and Wentworth, 1997) and eastern North America (Bakun *et al.*, 2003).

assignments at azimuths from 270° to 350° in the median Δ for the 1959 Hebgen Lake and the 1983 Borah Peak earthquakes. Propagation paths for the 16 July 1936 and the 5 August 1959 events (Table 1) are probably all primarily east of the Cascades. A linear least-squares fit of the 16 red g(median Δ) values in Figure 2b yields $C_1 = 2.76 \pm 1.47$, $C_2 = -0.00513 \pm 0.00182$, and $C_3 = -1.80 \pm 0.83$. That is,

$$\mathrm{MMI} = -0.54 + 1.68\mathbf{M} - 0.00513 \times \text{median } \Delta - 1.80\log(\text{median } \Delta). \quad (4)$$

Attenuation for propagation paths through Yellowstone and the Snake River Plain can be estimated using the MMI assignments at sites to the southeast of the Hebgen Lake and Borah Peak epicenters. Using MMI assignments at azimuths from 45° to 225°, a linear least-squares fit of 11 g(median Δ) values (MMI III–VIII for Hebgen Lake and MMI III–VII for Borah Peak) yields $C_1 = -1.22 \pm 0.26$, $C_2 = -0.0107 \pm 0.0010$ with C_3 set to 0. That is, for paths through the Yellowstone area and the Snake River Plain,

$$\mathrm{MMI} = -4.51 + 1.68\mathbf{M} - 0.0107 \times \text{median } \Delta. \quad (5)$$

Attenuation East of the Cascades and West of the Cascades

The MMI distance attenuation relations (3), (3a), (3b), and (4) predict comparable MMI for distances less than about 225 km for paths east and west of the Cascades and a more rapid decrease of MMI at distances greater than about 225 km for paths west of the Cascade Range than for paths to the east (Fig. 3). In contrast, Malone and Bor's (1979) attenuation model is characterized by significantly greater attenuation west of the Cascades at all distances. MMI decreases less with distance in the PNW than for comparably sized earthquakes in California, and MMI decreases more with distance than for comparable earthquakes in eastern North America.

Although attenuation of damaging ground motions from the 1961, 1962, 1978, and 1981 shallow crustal events in the Puget lowlands, equation (3a), and from the 1949 and 1965 intraslab events, equation (3b), are the same, the intraslab events apparently caused greater damage at all distances Δ_h than would comparable **M** shallow crustal events in the Puget lowlands (Fig. 3). Perhaps the **M** 6.8 and **M** 6.7 used for the 1949 and 1965 events, respectively, are too low, or the 1949 and 1965 events were sources with enhanced damaging high-frequency ground motions. Clearly the 1949 and 1965 sources generated much more damaging ground motions than did the anemic **M** 6.8 2001 Nisqually intraslab earthquake (Bakun and Ludwin, 2001). Intraslab events in other regions tend to generate more damaging ground motions than do nearby comparable **M** interplate events (Kirby, 2001). Anomalous high-frequency earthquake sources are not rare and can be rationalized by variations in source model parameters, such as unusual stress drop (Atkinson and Hanks, 1995). Perhaps intraslab events tend to cause more damage because they tend to be high stress drop sources rather than because of differences in attenuation from subduction zone events, as suggested by Youngs *et al.* (1997).

Attenuation model (5), obtained for propagation paths through Yellowstone and the Snake River Plain, is characterized by a rapid decrease of MMI with distance. Jackson and Boatwright (1987) found that peak ground accelerations for Borah Peak aftershocks at sites on the Snake River Plain were smaller and attenuated more rapidly with distance than predicted by Joyner and Boore's (1981) relations, which were developed mainly for earthquakes in California.

Analysis

We used the analysis of Bakun and Wentworth (1997) to estimate the location and magnitude of earthquakes from the individual MMI assignments with attenuation models (3) and (4) for sources west and east of the Cascades, respectively. We assume a grid of potential epicenters, and for each potential epicenter we calculate an intensity magnitude M_I.

$$M_\mathrm{I} = \text{mean } (M_\mathrm{i}), \quad (6)$$

where

$$M_\mathrm{i} = \{\mathrm{MMI_i} + 2.74 + 0.0158(\Delta_h)_\mathrm{i}\}/1.68, \quad (7a)$$

for paths west of the Cascades, and

$$M_\mathrm{i} = \{\mathrm{MMI_i} + 0.54 + 0.00513\Delta_\mathrm{i} + 1.80 \times \log(\Delta_\mathrm{i})\}/1.68, \quad (7b)$$

for paths east of the Cascades. $\mathrm{MMI_i}$, Δ_i, and $(\Delta_h)_\mathrm{i}$ are the MMI value, the epicentral distance (km), and the hypocentral distance (km) of site i. Site corrections are not used because there are too few recent large PNW earthquakes to calculate reliable site corrections.

The "fit" of the MMI is evaluated using

$$\mathrm{rms}\ [M_\mathrm{I}] = \mathrm{rms}\ (M_\mathrm{I} - M_\mathrm{i}) - \mathrm{rms}_0\ (M_\mathrm{I} - M_\mathrm{i}), \quad (8)$$

where rms is the root mean square, and $\mathrm{rms}_0\ (M_\mathrm{I} - M_\mathrm{i})$ is the minimum rms over the grid of assumed potential epicenters. We use the distance weighting function

$$\mathrm{W_i} = \begin{cases} 0.1 + \cos\ [(\Delta_\mathrm{i}/150) \times \pi/2] & \text{for } \Delta_\mathrm{i} < 150 \text{ km} \\ 0.1 & \text{for } \Delta_\mathrm{i} \geq 150 \text{ km.} \end{cases} \quad (9)$$

Bakun and Wentworth (1997) showed that the epicentral region is bounded by contours of rms $[M_\mathrm{I}]$ with levels of confidence appropriate for the number of MMI observations. Values for the contours for several levels of confidence and numbers of MMI observations are tabulated in the corrected table 5a of Bakun and Wentworth (1999). M_I at feasible source locations are the best estimates of **M** given the MMI data. The uncertainty in **M** for several levels of confidence and numbers of MMI observations is tabulated in the corrected table 5b of Bakun and Wentworth (1999). The intensity center, the source location for which rms [M_I] is minimum, is the point source of seismic energy that best satisfies the available intensity data (Bakun, 1999).

Twentieth-Century Earthquakes

We analyzed the MMI assignments for 12 twentieth-century PNW earthquakes with instrumental epicenters and magnitude estimates (Table 1). The results of our analysis are listed in Table 1 and displayed in Figure 4. We used attenuation model (3) for all sites for earthquakes west of the Cascades and model (4) for all sites for earthquakes in Washington or Oregon east of the Cascades. A combination of models (4) and (5) was used for the 1959 Hebgen Lake and the 1983 Borah Peak events.

16 July 1936

The 16 July 1936 Milton-Freewater, Umatilla County, Oregon $M_{G\text{-}R}$ 5.75 earthquake was located near the Washington–Oregon border east of the Cascades. There were no nearby seismic stations, so location and magnitude are poorly determined. The intensity center is located 7 km west of the epicenter (see Fig. 4a). M_I is 5.35 at the epicenter and at the intensity center, and **M** is 5.1–5.5 at the 95% confidence level.

13 November 1939

Damage caused by the 13 November 1939 $M_{G\text{-}R}$ 5.75 earthquake was centered in the southern Puget Sound region. The epicenter is poorly determined, and there are no instrumental estimates of focal depth. The occurrence of four small aftershocks (Stover and Coffman, 1993) is consistent with a shock in the lower crust, with depth comparable to that of the 1946 Vancouver Island earthquake. We assumed a focal depth of 30 km, the depth assigned to the 1946 source by Rogers and Hasegawa (1978). The intensity center for the 1939 event is located 59 km southwest of the epicenter (see Fig. 4b). M_I is 5.72 at the epicenter and 5.70 at the intensity center. **M** is 5.5 to 5.9 at the 95% confidence level.

15 February 1946

The 15 February 1946 $M_{G\text{-}R}$ 5.75 earthquake was followed by three small aftershocks (Stover and Coffman, 1993). Villasenor *et al.* (2001) concluded that a hypocenter shallower than the Juan de Fuca plate best fit the available teleseismic travel-time data. We used Stover and Coffman's (1993) focal depth of 18 km and obtain an intensity center located 3.1 km from the epicenter (see Fig. 4c). M_I is 5.85 at the epicenter and 5.84 at the intensity center, and **M** is 5.6–6.0 at the 95% confidence level.

13 April 1949

The 13 April 1949 event beneath Puget Sound was the largest earthquake in Washington in the twentieth century. We used Stover and Coffman's (1993) focal depth of 70 km in our analysis, but similar results were obtained with Baker and Langston's (1987) focal depth of 54 km. The intensity center is located 55 km south of the epicenter, consistent with the many MMI VII and VIII sites to the south of the epicenter (see Fig. 4d). M_I is 7.02 at the epicenter and 6.92 at the intensity center. **M** is 6.7 to 7.2 at the 95% confidence level. Baker and Langston's (1987) $M_0 = 1.5 \times 10^{26}$ dyne cm corresponds to **M** 6.8.

5 August 1959

The 5 August 1959 earthquake was located east of the central Cascades near Chelan, Washington (see Fig. 4e). The intensity center is located 38 km west of the poorly constrained epicenter. M_I is 5.25 at the epicenter and 5.29 at the intensity center, larger than the magnitude 5.0 listed by Malone and Bor (1979). **M** is 5.0–5.4 at the 95% confidence level.

18 August 1959

The 18 August 1959 Hebgen Lake, Montana, event is the largest historical earthquake in the intermountain region. The epicenter is located about 25 km south of the south-dipping fault scarps that formed northwest of Hebgen Lake (Witkind, 1964). However, epicenters for two subevents during the mainshock are located north of the south-dipping fault scarps (Doser, 1985), as are the epicenters for many of the aftershocks (Dewey *et al.*, 1973). We used attenuation model (4) to account for attenuation along propagation paths to the northwest (source-to-MMI site azimuths of 225° clockwise to 45°) and model (5) to account for attenuation along propagation paths to the southeast (45° clockwise to 22.5°). The intensity center is located 21 km north of the epicenter near the fault scarps formed during the earthquake. M_I is 7.40 at the epicenter and 7.38 at the intensity center (see Fig. 4f). **M** is 7.1–7.6 at the 95% confidence level.

17 September 1961

The M_L 5.1 event on 17 September 1961 occurred at shallow depth west of the Cascades near Portland, Oregon. The intensity center is located 21 km south of the epicenter (see Fig. 4g). M_I is 4.73 at the epicenter and 4.68 at the intensity center. **M** is 4.4–4.9 at the 95% confidence level.

6 November 1962

The **M** 5.2 event on 6 November 1962 occurred west of the Cascades near the Washington–Oregon border. The intensity center is located 18 km northwest of the epicenter (see Fig. 4h). M_I is 5.30 at the epicenter and 5.33 at the intensity center. **M** is 5.0–5.5 at the 95% confidence level.

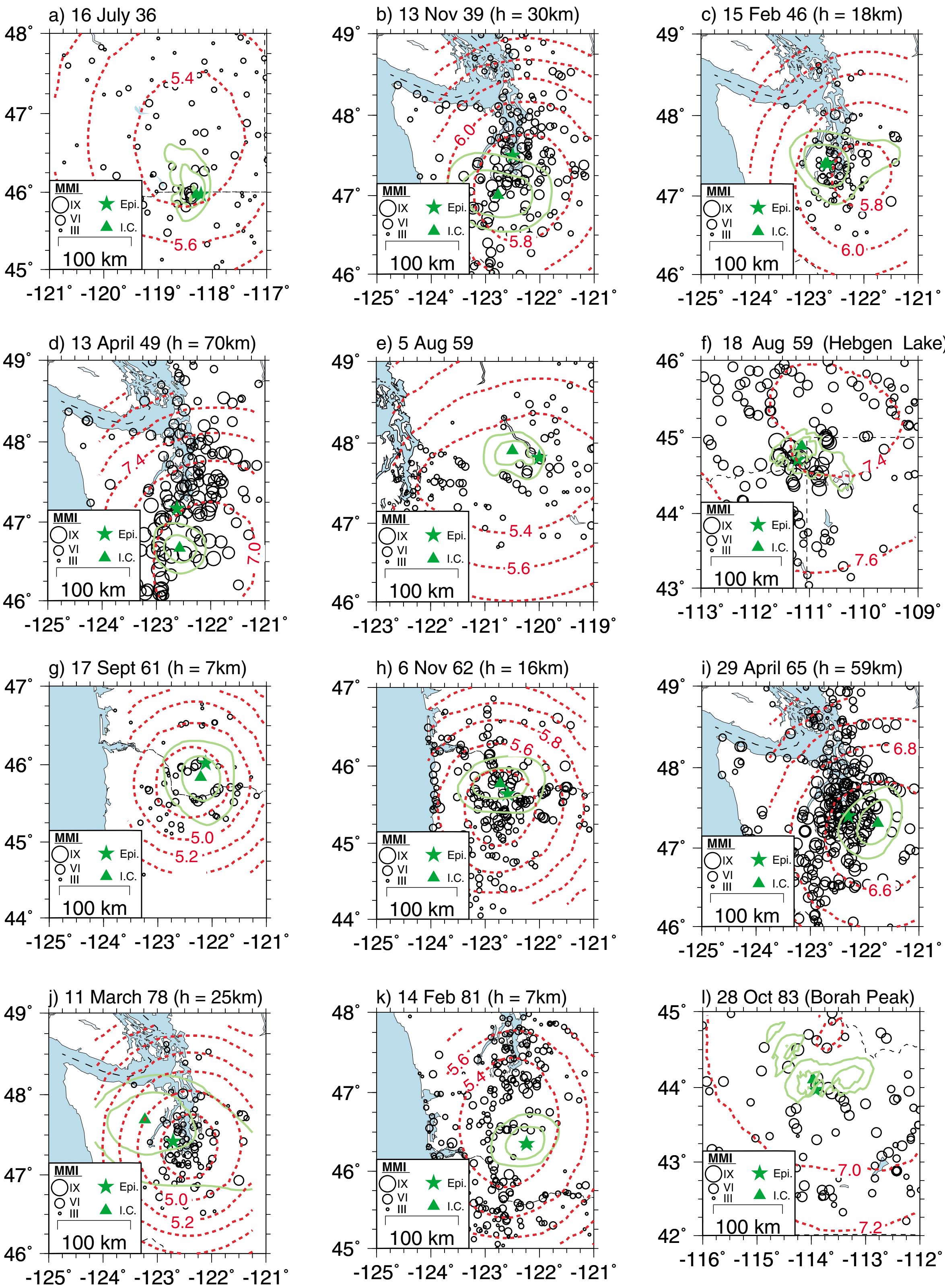

Figure 4. Maps of PNW earthquakes. Contours of M_I are dashed red lines. The rms $[M_I]$ contours corresponding to the 67%-(innermost contour) and 95%-confidence levels (outermost contour) for location from Bakun and Wentworth (1999) are shown as solid green lines. Some of the MMI sites used in our analysis are not shown.

29 April 1965

The 29 April 1965 event occurred in the Juan de Fuca plate beneath Puget Sound. Assuming Stover and Coffman's (1993) focal depth of 59 km, we obtain an intensity center located 42 km east of the epicenter (see Fig. 4i). M_I is 6.54 at the epicenter and 6.49 at the intensity center. Similar results were obtained with Langston and Blum's (1977) focal depth of 63 km. **M** is 6.3–6.7 at the 95% confidence level. Langston and Blum's (1977) M_0 of 1.4 × 10^{26} dyne cm corresponds to **M** 6.7.

11 March 1978

The 11 March 1978 M_L 4.8 event occurred at midcrustal depth in the Puget Sound area. The intensity center is located 49 km northwest of the epicenter (see Fig. 4j). The location is poorly constrained to the west because there are few MMI assignments at sites on the Olympic Peninsula west of the epicenter. M_I is 4.73 at the epicenter and 5.01 at the intensity center. **M** is 4.5–4.9 at the 95% confidence level.

14 February 1981

The **M** 5.5 Elk Lake earthquake occurred on 14 February 1981 at shallow depth west of the Cascades. The intensity center is located at the epicenter and M_I is 5.29 (see Fig. 4k). **M** is 5.0–5.5 at the 95% confidence level.

28 October 1983

The Borah Peak earthquake on 28 October 1983 is the largest historical earthquake in Idaho. The earthquake caused a 36-km-long northwest-trending zone of surface faulting near the southwest edge of the Lost River Range (Crone *et al.*, 1987). Aftershocks in the 24 hours after the mainshock occurred southwest of the surface rupture all along the surface rupture (Richins *et al.*, 1987). The location of the epicenter near the southeast end of the surface rupture suggests rupture to the northwest (Richins *et al.*, 1987). We used models (4) and (5) to account for attenuation as described above for the 18 August 1959 Hebgen Lake event. The intensity center is located 15 km north of the epicenter (see Fig. 4l) near the southeast end of the zone of aftershocks. M_I is 6.83 at the epicenter and at the intensity center. **M** is 6.6–7.0 at the 95% confidence level. While we used Ekstrom and Dziewonski's (1985) **M** 7.0 in our calibration calculations, the U.S. Geological Survey Preliminary Determination of Epicenters and Doser and Smith (1985) obtained **M** 6.9 and 6.85, respectively, for this event. Our estimate, M_I 6.83, is most consistent with Doser and Smith's (1985) estimate of **M**.

Earthquakes East of the Cascades

The location and **M** estimated from intensity data are in good agreement with the instrumental values for the four events located east of the Cascades. The epicenters of three of the four events are located within the 67% confidence contour for location and all four epicenters are located within the 95% contour. **M** is not available for the 1936 and 1959 Chelan events, but the instrumental **M** for the 1959 Hebgen Lake and 1983 Borah Peak events are within the 95% confidence interval for **M** obtained from the intensity data.

Earthquakes West of the Cascades

The location and **M** estimated from intensity data for the three events located south of the Puget Sound region are in good agreement with the instrumental values. The epicenters are all located within the 67% confidence contour for location, and the instrumental **M** for the 1962 and 1981 events are within the 95% confidence interval for **M** obtained from the intensity data (an independent estimate of **M** for the 1961 event is not available.)

Mixed results are obtained for the three crustal events and two intraslab events located beneath the Puget Sound region. The magnitudes for all five events are within the 95% confidence interval for **M** obtained from the intensity data, but the epicenters for the 1939 and 1949 events are not within the 95% confidence contour for location. Although the epicenter for the 1939 event is poorly located and near the contour, the epicenter for the 1949 event is significantly north of the probable locations inferred from the intensity data (see Fig. 4d). Apparently, the simple slant-distance propagation path assumed here for the attenuation correction does not satisfactorily represent energy propagation beneath Puget Sound. The use of site corrections, as suggested by Malone and Bor (1979), may be important in accounting for significant near-surface variations in geology in the Puget Sound region.

The 15 December 1872 Earthquake

The 15 December 1872 earthquake is important in quantifing the seismic hazard in eastern Washington because it is the largest historical earthquake in Washington east of the crest of the Cascade Range. Several assignments of MMI from the descriptions of the effects of the earthquake were prepared as part of the evaluation of proposals for nuclear power plants in Washington in the 1970s. Malone and Bor (1979) used WPPSS (1977) in their study of the 1872 earthquake, and Coombs *et al.* (1976) is a consensus opinion of a panel of experts assembled by public power utilities in the PNW. We use Hopper *et al.*'s (2003) assignments of MMI because they represent a broader consensus, with 10 independent sets of MMI assignments, including those of Coombs *et al.* (1976), Scott (1976), Weston Geophysical Research, Inc. (1976), and WPPSS (1977). Hopper *et al.* (2003) noted that there were substantial disagreements among the 10 independent assignments of intensity at some MMI sites. The Hopper *et al.* (2003), WPPSS (1977), and Coombs *et al.* (1976) MMI assignments are generally consistent, however, with a maximum difference of 2 MMI units at a few sites (see Appendix A). The different assignments at Entiat, Wenatchee, and Snoqualmie are particularly important because, as described subsequently, the location of the intensity center is sensitive to the MMI assignments at these sites, largely because of the distance-weighting function.

The 1872 earthquake was a shallow source located east of the crest of the Cascade Range (Spence, 1989). We used (4) to account for attenuation and geometrical spreading to all MMI sites because there is little difference between models (3) and (4) for distances to sites in the Puget Sound region ($\Delta \approx 200$ km), Our analysis constrains the epicentral area to the Lake Chelan region (Fig. 5), and the intensity center is located near the southeast end of the lake. M_I is 6.8 at the intensity center and over most of the area enclosed by the 95% confidence level contour for location. **M** is 6.5–7.0 at the 95% confidence level.

The MMI VIII at Entiat and Wenatchee are important in constraining the probable epicenter to the region near the south end of Lake Chelan. The MMI VIII at Entiat is too low, however, to allow Entiat to lie within the preferred (green) confidence contours for location (see the notch at Entiat in Fig. 5). If the MMI assignments at both Entiat and Wenatchee are ignored, the MMI data allow for epicentral locations to the north and northeast of Lake Chelan (see the blue contours in Fig. 5). The Coombs *et al.*'s (1976) assignments of MMI for the 1872 event are not very different from those of Hopper *et al.* (2003), and Coombs *et al.* (1976) assign an MMI of VIII at Chelan (located at the southeast end of the lake). It is not surprising, then, that the intensity center (point B in Fig. 5) obtained with Coombs *et al.*'s (1976) MMI is located at Lake Chelan. The intensity center obtained using the WPPSS (1977) MMI assignments is located farther to the north (point A in Fig. 5), largely because WPPSS (1977) assigned MMI = VI at Wenatchee and did not assign an MMI at Entiat. Appendix B contains an account of the earthquake effects at Wenatchee.

We tested the stability of the location of the epicentral region near Lake Chelan by calculating distributions of intensity centers for subsets of the data (Fig. 6). Deleting the MMI at either Entiat or at Wenatchee, the closest sites to the intensity center, shifts the locations 10–15 km because the distance weighting function (9) emphasizes the MMI at near sites (see Fig. 6a). The shift in location to the west if the MMI V at Snoqualmie is deleted is surprising (see

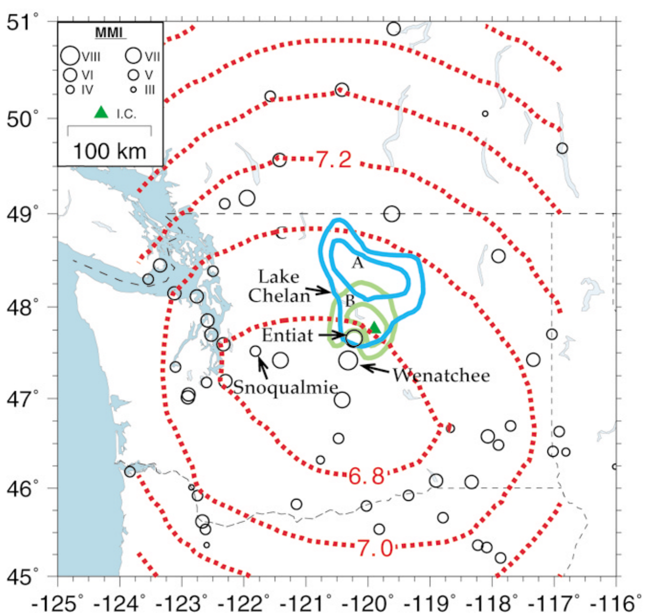

Figure 5. The 15 December 1872 earthquake. See caption for Figure 4. The epicenter lies within the inner green contour at the 67% confidence level and within the outer green contour at the 95% confidence level. The confidence contours for location if the MMI VIII at Entiat and Wenatchee are not used are shown in blue. A and B are the intensity centers obtained using the WPPSS (1977) and the Coombs *et al.* (1976) MMI assignments respectively, and C is the preferred location of Malone and Bor (1979).

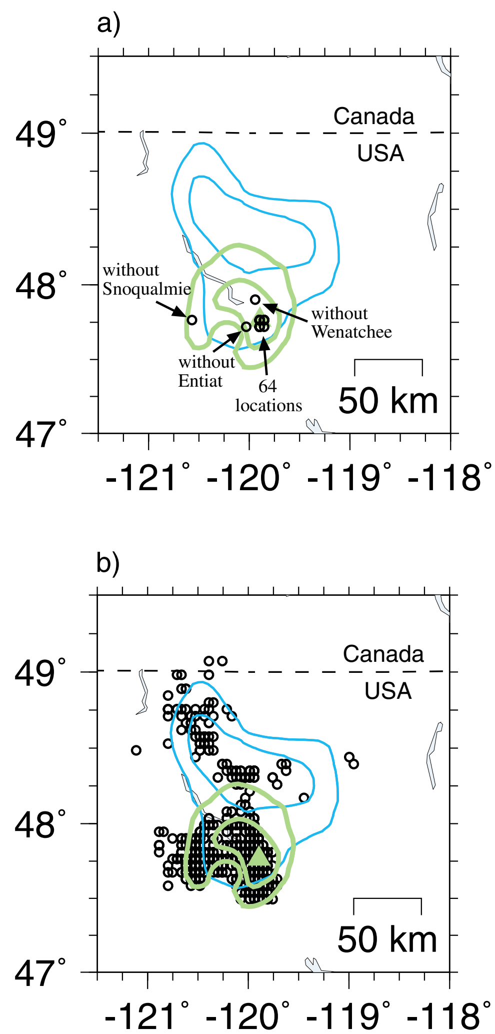

Figure 6. Resampling tests for the location of the 15 December 1872 earthquake using Hopper *et al.*'s (2003) 67 MMI. Circles are intensity centers for (a) a jackknife and (b) a bootstrap with 1000 resamplings. The confidence contours and the intensity center from Figure 5 are shown for reference.

Fig. 6a). If MMI at Snoqualmie is VI, as assigned by Coombs *et al.* (1976), the intensity center is 6 km east of the location obtained without Snoqualmie. None of the other 64 sites has a significant impact on the location of the intensity center. The results of the bootstrap test (67 random samples with replacement) emphasize the combined importance of the MMI at Entiat and Wenatchee (Fig. 6b). Although 156, or 16%, of the 1000 bootstrap locations lie outside the preferred (green) 95% confidence contour for location, 51, or 5%, lie outside the union of the areas enclosed by the green and blue 95% confidence contours for location. Ninety percent of the bootstrap locations to the north of 48° N were obtained from MMI sets with either Entiat or Wenatchee, or both, not represented. It is unlikely that the MMI assignments at both Entiat and Wenatchee are biased high, but the uncertainty in any MMI assignment is about one MMI unit. Reducing the MMI assignment at Entiat by one MMI unit allows for intensity centers near the north end of Lake Chelan (points C and F in Fig. 7). Other changes in the intensity assignments by one MMI unit at Entiat and Wenatchee suggest locations near the south end of Lake Chelan (Fig. 7). Differences in the MMI assignments (see table 2R B-4 in WPPSS [1977] and Hopper *et al.* [2003]) suggest that MMI = VIII at Entiat and MMI = VII at Wenatchee (see Appendix B) are the most reasonable variations. The resulting intensity center (point E in Fig. 7) is 14 km northeast of Entiat. The Entiat notch in the confidence contours for location is reduced considerably for case E and completely for cases B, G, and D.

Given the sensitivity of the intensity center and the details of the confidence contours for location to the MMI values at Entiat and Wenatchee, the green confidence contours for location probably underestimate the uncertainty in the location of the 1872 earthquake. In particular, the Entiat notch in the contours should probably be ignored, as indicated by the dashed red contour in Figure 7. The dashed red contour in Figure 7 is our preferred 95% confidence contour for the epicenter of the 1872 earthquake. The distributions of intensity centers in Figures 5–7 are consistent with an epicentral region of the 1872 earthquake near Lake Chelan and most likely near the south end of Lake Chelan.

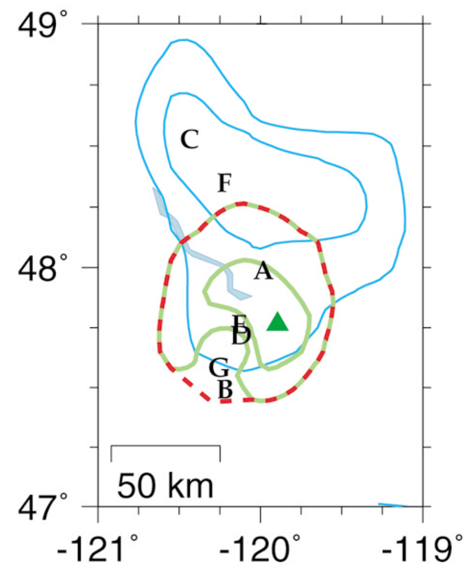

Figure 7. Intensity centers for the 15 December 1872 earthquake for changes in the MMI assignments at Wenatchee (WEN) and Entiat (ENT): A, VII at WEN and VIII at ENT; B, IX at WEN and VIII at ENT; C, VIII at WEN and VII at ENT; D, VIII at WEN and IX at ENT; E, VII at WEN and IX at ENT; F, VII at WEN and VII at ENT; G, IX at WEN and IX at ENT. MMI is VIII at WEN and at ENT for the preferred intensity center (green triangle). The confidence contours from Figure 5 are shown for reference. The dashed red contour, our preferred 95% confidence-level contour for location, removes the Entiat notch, as discussed in the text.

Geologic and Tectonic Constraints

The epicentral region of the 1872 earthquake lies near the boundary of the North Cascades and Columbia Plateau geologic provinces. Regional topography, many decades of geologic mapping, recent regional tectonic synthesis, Global Positioning System (GPS) observations, and recent seismicity all indicate that this area of central Washington is actively deforming.

Throughout the Columbia Plateau of central and eastern Washington, the land surface largely follows the surfaces of Miocene (~15 Ma) flows of the Columbia River Basalt Group. East–west fold ridges of the Yakima fold belt traverse much of the western margin of the Columbia Plateau and demonstrate north–south shortening since eruption of the bulk of the Columbia River Basalt Group about 15 Ma. Thrust faults underlie and cause many anticlines (e.g., Bentley, 1977; Reidel, 1984), and there is little doubt that the Yakima fold belt records significant post-Miocene north–south shortening. The structures of the Yakima fold belt may well extend west into the Cascade Range, but the Columbia River basalt flows are absent within the Cascades north of about 46° N. Topography does not closely follow structure here, and active faults have been difficult to discern and date.

Wells *et al.* (1998) synthesized paleomagnetic observations of Tertiary rotations, regional geology, and Very Long Baseline Interferometry (VLBI) geodesy and suggested that the Cascadia forearc in western Oregon is pivoting relative to North America about a pole in south-central Washington, producing both clockwise rotation and northward translation of western Oregon. Deformation is driven by a combination of Basin and Range extension to the northeast, into the Cascadia subduction zone, and northward shear along the Pacific–North America plate boundary. They suggested that western Washington is undergoing north–south shortening at rates of 4–7 mm/yr and that deformation in the Washington portion of the Yakima fold belt is sympathetic. Ongoing GPS studies (McCaffrey *et al.*, 2000a,b) have refined this kinematic picture (see Fig. 8), placing the pivot of western Oregon relative to North America near the Oregon–Washington border (45.9 ± 0.6° N, 118.7 ± 0.7° W, 1.05 ± 0.16°/m.y.), southeast of the pivot proposed by Wells *et*

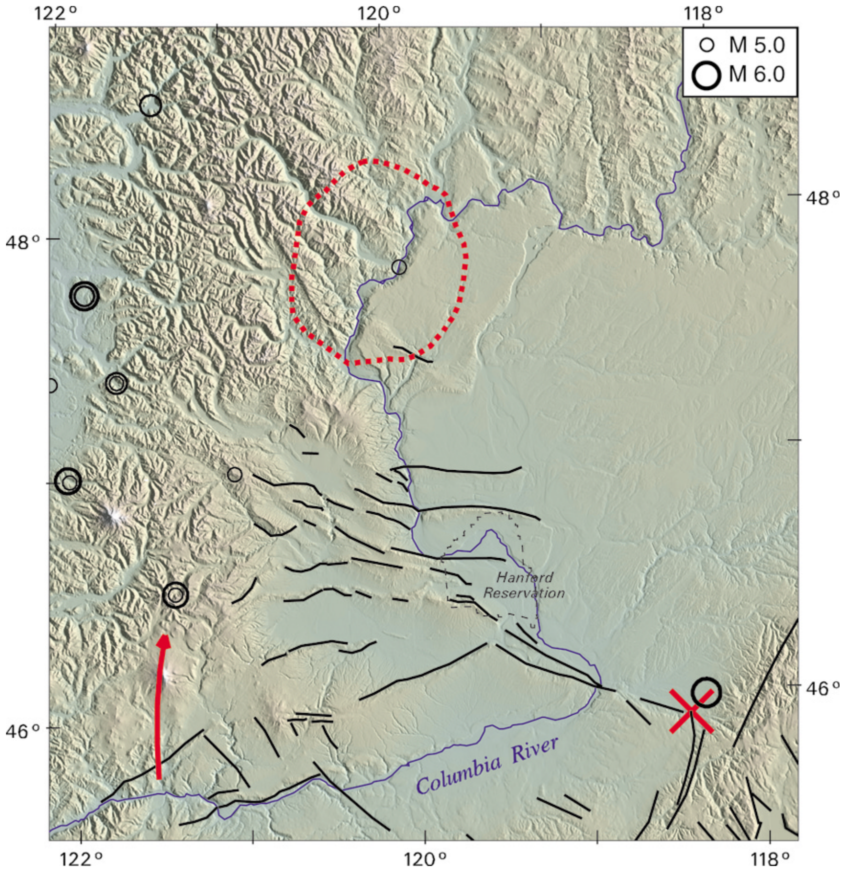

Figure 8. Topography of the western Columbia Plateau (after Haugerud, in press). Faults cutting the ~15 million-year old flows of the Columbia River Basalt Group are shown in black; 95% confidence contour for the epicenter of 1872 earthquake is shown as a red dashed line. McCaffrey *et al.*'s (2000a, b) pole of rotation between western Oregon and North America is shown as a red X, and the red arrow indicates the translation of the forearc in 15 Ma. Locations of $M \geq 5.0$ historical earthquakes since 1872 are shown as black circles. Faults simplified from Walsh *et al.* (1987), Stoffel *et al.* (1991), Schuster *et al.* (1997), and Walker and MacLeod (1991).

al. (1998). GPS results also suggest that displacements throughout western and central Washington largely fit a simple rotation model, with distributed northeast–southwest convergence in northwest and central Washington.

Our proposed epicentral area is seismically active at present (Fig. 9), but there have been no large earthquakes in this region since 1872. Reasonably well-determined focal mechanisms for recent earthquakes indicate ongoing north–south to northeast–southwest shortening in this region.

North Cascades

The North Cascade Range west of Chelan is largely underlain by Mesozoic-to-early Tertiary crystalline rocks and younger plutons of the Cascade magmatic arc (Tabor *et al.*, 1987; Haugerud *et al.*, 1994) (Fig. 10). Unrecognized faults may be present, and only locally are there rocks and deposits with sufficiently well understood internal structure that faults with less than a few kilometers of separation are easily identified. Landforms and surficial deposits of the North Cascade Range record extensive, repeated alpine glaciation. Rugged topography and forest cover make fault scarps hard to recognize, and surface offsets could pass unrecognized.

The most significant fault in this part of the North Cascades is the Entiat fault, which appears to have no Neogene slip. It extends from Wenatchee more than 160 km to the northwest. It truncates the Eocene Chumstick Formation and is overlapped by the latest Eocene to early Oligocene Wenatchee Formation, indicating that activity was largely late Eocene. Linearity of the Entiat fault (Fig. 10), features within the fault zone (Laravie, 1976), and the regional Eocene tectonic pattern (Haugerud *et al.*, 1994) suggest that it was a regional strike-slip fault. At its northern end, the Entiat fault is intruded by, and fails to offset, the 20–22 million-year-old Cloudy Pass batholith (Tabor *et al.*, 1988). The geologic evidence suggests that there has not been sustained Neogene displacement on the Entiat fault, though perhaps young displacement on its southern part should not be ruled out.

Other recognized faults within this part of the North Cascades are also unlikely sources for the 1872 earthquake. The southern Ross Lake fault is plugged by the 48 million-year-old Cooper Mountain batholith. The Mad River thrust appears to be have moved during or prior to the Late Cretaceous (100–65 Ma) regional metamorphism and has no signs of late Cenozoic activity. The remaining mapped faults are too short to generate a **M** 6.5–7.0 event.

Columbia Plateau

East of Chelan, the crystalline rocks of the North Cascades pass beneath Miocene basalt flows of the Columbia River Basalt Group (Reidel and Hooper, 1989; Reidel *et al.*, 1994). Originally flat-lying basalt flows are excellent structural markers and magnetostratigraphy and whole-rock

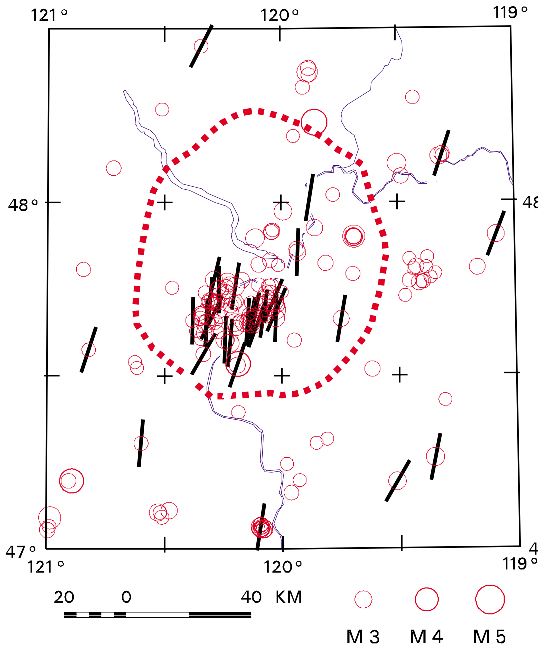

Figure 9. Well-located coda-length magnitude ≥2.3 earthquakes, January 1976 through May 2001, as determined by the Pacific Northwest Seismograph Network. Black bars show the orientation of *P* axes as determined by routine first-motion analysis of well-located events with shallow *P* axes (plunge ≤ 30°). Most first-motion solutions have shallow *P* axes; only one event is omitted because of steep *P*-axis plunge.

chemistry locally permit flow-by-flow mapping. Extensive younger deposits are present only in a few places. Quaternary strata, where present, are mostly catastrophic Missoula flood deposits formed at the end of the last glaciation at about 14 ka.

Late Quaternary deformation in the Yakima fold belt has been demonstrated only locally (Campbell and Bentley, 1981; West *et al.*, 1996; Reidel *et al.*, 1994). The Badger Mountain and Beezley Hills anticlines (Fig. 10) are among the northernmost of the Yakima folds (Fig. 8). Existing geologic mapping (Grolier and Bingham, 1971; Tabor *et al.*, 1982, 1987; Gulick, 1990; Gulick and Korosec, 1990a) discloses a south-dipping thrust associated with the Badger Mountain anticline but does not indicate Quaternary deformation on it or nearby structures. Farther east, no fault has been mapped in association with the Beezley Hills anticline, but topography and aerial photographs suggest that it also may be fault-cored.

A Blind Structure?

The apparent absence of a surface scarp for the 1872 event suggests that this earthquake may have occurred on a blind fault. This would be consistent with evidence for thrusting in the northern Yakima fold belt. This also suggests caution in ruling out the structural involvement of older rocks of the North Cascades province, either northwest of the Columbia River or to the southeast, beneath Miocene basalt.

Discussion

Our source for the 1872 earthquake, a shallow **M** 6.8 event near Lake Chelan, does not agree with the conclusions of Malone and Bor (1979). In particular, Malone and Bor (1979, p. 546) assumed that the 1872 event was a deep source and concluded that its magnitude was 7.4 and that "a location to the east near Lake Chelan is definitely ruled out." Although the assumption of a deep source would increase the magnitude estimate somewhat, it does not explain Malone and Bor's (1979) larger magnitude or their rejection of a source location near Lake Chelan.

MMI Assignments

Neither we nor Malone and Bor (1979) reinterpreted any of the felt reports for the 1872 earthquake. Malone and Bor (1979) used the best assignment of the 1872 intensities available in 1979 (table 2R B-4 in WPPSS [1977]). We use the best assignment of the 1872 intensities available now (Hopper et al., 2003). The intensity center we calculate using the WPPSS (1977) MMI assignments for a source at 60-km depth, as assumed by Malone and Bor (1979), is 13 km north of point A in Figure 5 and 100 km east of Malone and Bor's (1979) preferred source location. Adding the MMI V assignment at Snoqualmie to the WPPSS (1977) MMI assignments does not significantly change the intensity center. The different MMI assignments by WPPSS (1977) and Hopper *et al.* (2003) account for about 85% of the difference in latitude of the source locations, but not for the difference in longitude. Malone and Bor's (1979) assumption of a 60-km-deep source for the 1872 event is responsible for the remaining 15% of the difference in latitude.

Implicit in our adoption of Hopper *et al.*'s (2003) MMI assignments is the view that consensus MMI assignments by a group of independent seismologists conversant with the MMI scale are preferable to those of any single study. Whereas an individual might tend to emphasize some aspects of the descriptive MMI scale, a consensus opinion is more likely to consider all aspects, resulting in a more stable, unbiased assignment of intensities. Consensus MMI assignments are not common and are usually available for only a few large and controversial historical earthquakes that are important in defining seismic hazard. The different MMI assignments, and the significant difference in inferred source location of the 1872 event, suggest that consensus assignments of MMI values should be developed for other important historical earthquakes.

Attenuation Models

Malone and Bor (1979) used a modification of Evernden's (1975) model to infer an intensity attenuation model for propagation paths west of the Cascades and a different model with significantly less attenuation for propagation

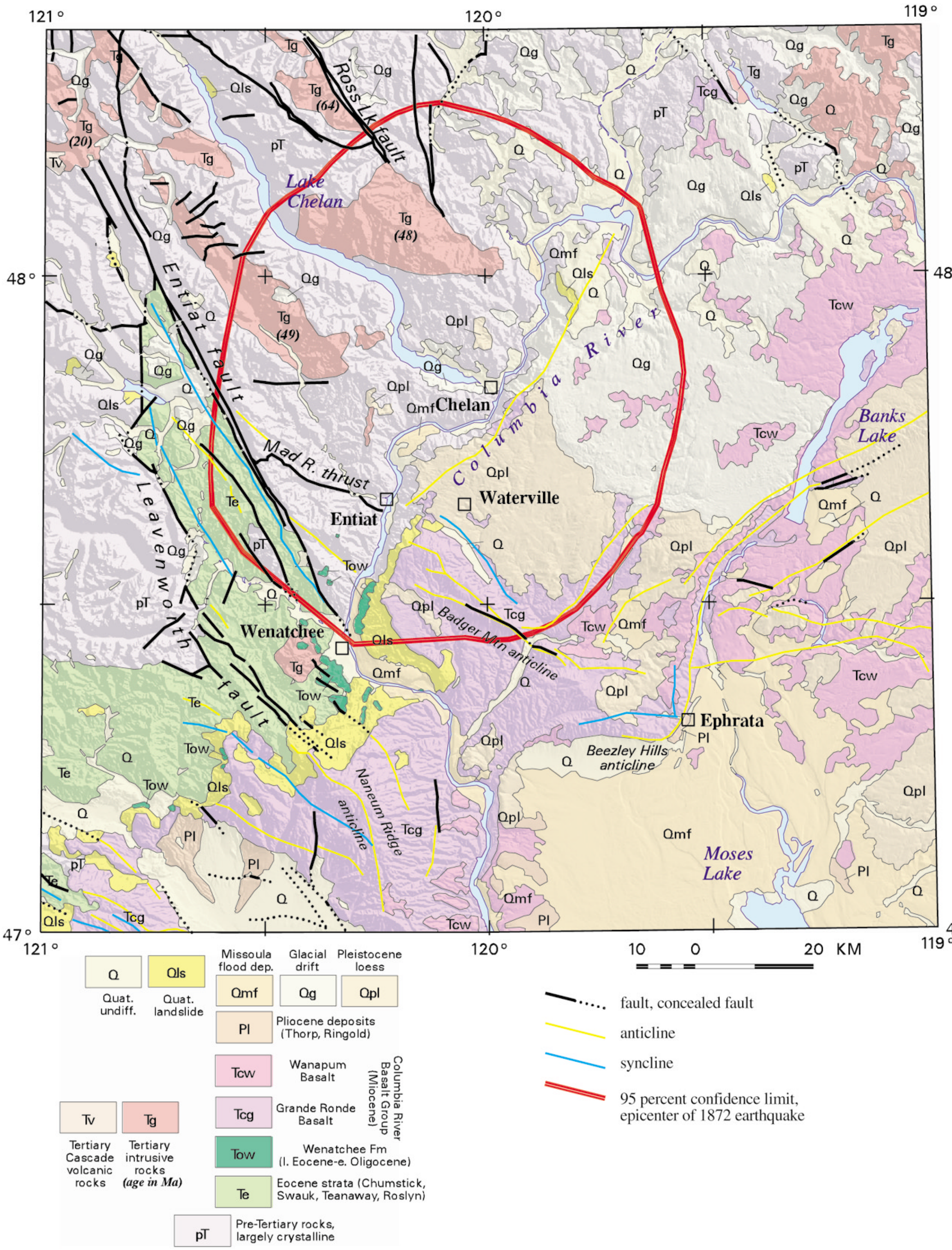

Figure 10. Geologic map of north-central Washington, simplified from Tabor *et al.* (1982, 1987), Bunning (1990), Gulick (1990), Gulick and Korosec (1990a,b), and Dragovich and Norman (1995).

paths east of the Cascades. Our approach is similar to that of Malone and Bor (1979), but our attenuation model for paths east of the Cascades (4) and west of the Cascades (3) are not significantly different for $\Delta < 225$ km. For $\Delta > 225$ km, we find less attenuation for paths east of the Cascades than for paths to the west. In addition to including more recent events and the results of recent analyses of some earlier events, we separated attenuation east and west of the Cascades by omitting MMI assignments with likely mixed east- and west-of-the-Cascades propagation paths. In contrast, Malone and Bor (1979) distributed the attenuation effect in proportion to the length of assumed travel path east and west of the Cascade crest. Also, we considered MMI in restricted azimuth bands to explicitly address the potential bias introduced by lack of MMI assignments at greater Δ (i.e., no sites west of the coastline or in Canada). Note that Havskov *et al.* (1989) found no significant regional differences in the Q of the seismic coda from small earthquakes in Washington at distances less than about 100 km, other than in a very localized region near Mount St. Helens. Havskov *et al.*'s (1989) result is consistent with attenuation relations (3) and (4) and apparently inconsistent with the attenuation models of Malone and Bor (1979).

Since there is little difference between our attenuation relations for paths east and west of the Cascades for $\Delta <$ 225 km, we used one attenuation model, (4), to account for attenuation in our analysis of the 1872 event. We tested whether an attenuation model combining (3) and (4) might significantly shift our location of the 1872 source. Using (3) for paths to sites to the west (epicenter to MMI site azimuths from 225° clockwise to 315°) and (4) for paths to all other sites, we obtained an intensity center located only 6.7 km from our preferred intensity center. The difference between attenuation models (3) and (4) is not important in our analysis of the 1872 event.

Malone and Bor's (1979) preferred location for the 1872 event is about 100 km to the west of the intensity center we obtained using our attenuation relation (4) and the WPPSS (1977) MMI assignments. Clearly, the use of Malone and Bor's (1979) model, or any model with significantly more attenuation in one direction, will tend to shift the source location in that direction and increase the estimate of M_I. That is, the differences between Malone and Bor's (1979) attenuation model and our models (3) and (4) is responsible for our smaller magnitude and our more easterly source location of the 1872 event.

Aftershocks

Aftershocks in the 24 hours following the 1872 event were felt widely over Washington, northern Idaho, and southern British Columbia. However, the felt area and the magnitude of the aftershocks decreased with time (Hopper *et al.*, 2003). After a year, aftershocks continued to be reported only at Wenatchee, Winesap (Entiat), and Lake Chelan, but there are no data on aftershock occurrence for long periods of time for extensive regions near the Wenatchee–Lake Chelan area (Hopper *et al.*, 2003). Although the aftershock locations cannot be constrained to the immediate area near Lake Chelan and aftershocks are not always near the mainshock epicenter, the reports of late aftershocks only near Lake Chelan are consistent with a source location of the 1872 mainshock near Lake Chelan, as suggested by Hopper *et al.* (2003).

Conclusions

We have used the MMI assignments for earthquakes with instrumentally determined magnitudes and epicenters to determine the attenuation relation $\text{MMI} = -2.74 + 1.68\mathbf{M} - 0.0158\Delta_h$ for propagation paths west of the Cascades and $\text{MMI} = -0.54 + 1.68\mathbf{M} - 0.00513\Delta - 1.80\log \Delta$ for propagation paths east of the Cascades. There is no significant difference in the attenuation of MMI for $\Delta < 225$ km, but there is more attenuation at greater distances for paths west of the Cascades. Farther to the east, there is high attenuation for propagation paths through the Yellowstone–Snake River Plain region where $\text{MMI} = -4.51 + 1.68\mathbf{M} - 0.0107\Delta$.

Using these attenuation relations, we estimated **M** and the location of several PNW earthquakes for which there are MMI assignments, epicenters, and instrumental **M**. The location and **M** estimated from intensity data are in good agreement with the instrumental estimates for four events east of the Cascades and for three shallow events west of the Cascades and south of Puget Sound. Mixed results are obtained for the five events located beneath the Puget Sound region. Although the instrumental **M** for all five are within the 95% confidence interval for **M** obtained from the intensity data, two of the five instrumental epicenters are not within the 95% confidence contour for location. Apparently, the simple slant-distance propagation path assumed for paths west of the Cascades does not satisfactorily represent energy propagation through the complicated structure underlying Puget Sound. MMI site corrections, if available, might improve the location estimates.

The vigorous aftershock sequence following the 15 December 1872 earthquake is strong evidence that it was shallow (Hopper *et al.*, 2003). Using our MMI attenuation relation for propagation paths east of the Cascades, we have analyzed Hopper *et al.*'s (2003) MMI assignments for the shallow 15 December 1872 earthquake. We conclude that its epicentral region was near Lake Chelan and most likely near the south end of Lake Chelan. M_I is 6.8 at the intensity center and over most of the area enclosed by the 95% confidence level contour for location. **M** is 6.5–7.0 at the 95% confidence level.

The epicentral region of the 1872 event lies at the boundary of the North Cascades and Columbia Plateau geologic provinces near the northern edge of the Yakima fold belt. Geology of each province is permissive of young deformation, and within the Yakima fold belt there is positive evidence for late Cenozoic faulting. Displacements determined by GPS and suggested by regional tectonic synthesis, mapped geology, and present-day seismicity are all consistent with active north–south contraction. The apparent absence of a surface scarp suggests that the 1872 earthquake may have occurred on a blind fault. Given the continuity of the deformation and seismicity along the Yakima fold belt to the south and southeast of Lake Chelan, we infer that events as large as **M** 6.8 can reasonably be expected over most of south-central Washington.

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Appendix A

Table A1

Three Sets of MMI Assignments for the December 15, 1872 Earthquake

Location	Lat. (°N)	Long. (°W)	MMI*	MMI†	MMI‡
Astoria, OR	46.19	123.84	V		V
Aurora, OR	45.23	122.76			III
Baker City, OR	44.78	117.83	V	IV	V
Bozeman, MT	45.68	111.04			III
Camas Prairie, ID	46.10	116.07			IV
Canyon City, OR	44.39	118.95	IV	IV	IV
Chelan, WA	47.84	120.01			VIII
Chilliwack, B.C.	49.17	121.95	VII	VII–VIII?	VI–VII
Clinton, B.C.	51.17	121.58	VI	VI	VI
Columbia City, OR	45.89	122.81			IV
Colville, WA	48.55	117.90	VI	V	VI
Deer Lodge, MT	46.40	112.74	IV	IV–V?	IV
Elk City, ID	45.83	115.44	III		IV
Entiat (Winesap), WA	47.66	120.22	VIII		VIII
Fort Lapwai, ID	46.41	116.81	IV		IV
Fort Simcoe, WA	46.32	120.77	IV	IV	IV
Helena, MT	46.60	112.03	V	IV	III
Henry House, Alberta	50.05	118.11	III	II–III	III
Kalama, WA	46.01	122.85	III		III
Kittitas Valley, WA	46.99	120.42	VII		VI
Klickitat, WA	45.82	121.15	V	IV?	
Kootenay, B.C.	49.69	116.87	V	IV–V	
LaConner, WA	48.39	122.50	V		V–VI
LaGrande, OR	45.33	118.09	V	III–IV	IV–V
Lewis River, WA	45.92	122.75	V	III–IV?	
Lewiston, ID	46.41	117.02	V	IV–V	V
Lytton, B.C.	50.23	121.58	V	IV	V
Matsqui, B.C.	49.11	122.31	V	V?	VI
New Dungeness, WA	48.15	123.12	VI	VII	VII
Nicola Valley, B.C.	50.30	120.42	VI	VI	VI
Olympia, WA	47.05	122.89	VI	VI	VI
Oregon City, OR	45.36	122.60	III		
Oro Dell, OR	45.36	118.23	V	IV	IV–V
Osoyoos Lake, B.C.	49.00	119.62	VII	VII	VII
Paradise Valley, ID	46.63	116.92	V		IV–V
Pena-wawa, WA	46.70	117.70	V	IV–V	V
Pendleton, OR	45.67	118.79	V	IV	IV–V
Phillipsburg, MT	46.33	133.30			III
Pine Grove, WA	47.43	117.33	VI	V	V–VI
Port Gamble, WA	47.86	122.59	VI	(VI)	V–VI
Port Madison, WA	47.70	122.53	VI	(VI)	V–VI
Port Townsend, WA	48.12	122.76	VI	(VI)	VI
Portland, OR	45.54	122.62	V	V	V
Puyallup, WA	47.19	122.30	VI	(VI)	VI
Quesnel, B.C.	52.98	122.49	IV	IV–V?	IV

Table A1 (continued)
Three MMI Assignments for the December 15, 1872 Earthquake

Location	Lat. (°N)	Long. (°W)	MMI*	MMI†	MMI‡
Race Rocks, B.C.	48.30	123.54	V	V–VI?	V
Reed's Ferry, ID	46.24	116.02	III		IV
Rock Island, WA	47.37	120.14			VII
Salem, OR	44.94	123.03	IV		IV
Seattle, WA	47.60	122.33	VI	V	VI
Shuswap Prairie, B.C.	50.93	119.58	VI	VI–VII	V–VI
Skokomish, WA	47.35	123.10	V	V	
Snoqualmie Pass, WA	47.42	121.41	VII	(VI–VII?)	
Snoqualmie, WA	47.52	121.82	V		VI
Soda Creek, B.C.	52.37	122.30	V	V	V
Spokane Bridge, WA	47.71	117.03	V		
St. Helens, OR	45.86	122.81			III–IV
Steilacoom, WA	47.18	122.60	V	V	VI
Texas Ferry, WA	46.58	118.07	VI	IV–V	VI
The Dallas, OR	44.92	123.32	IV	III	V
Tieton Basin, WA	46.67	121.12			VI
Touchet, WA	46.67	118.67	IV	III	IV
Tukanon, WA	46.48	117.90	V		V
Tumwater, WA	47.02	122.90	VI		VI
Umatilla, OR	45.92	119.35	V		V
Union, OR	45.21	117.87	V	IV	IV–V
Vancouver, WA	45.63	122.67	VI	(VI)	VI
Vernon, B.C.	49.00	119.62			VII
Victoria, B.C.	48.45	123.35	VI	VI–VII	VI
Virginia City, MT	45.30	111.94	III		III
Walla Walla, WA	46.07	118.33	VI	V	VI
Wallula, WA	46.09	118.90	VI	IV	VI
Wenatchee, WA	47.42	120.32	VIII	VI	VII–VIII
Whitestone, WA	47.90	118.55			VI
Willow Creek, OR	45.80	120.03	V		
Willow Forks, OR	45.54	119.82	V	IV	V
Yakima, WA	46.56	120.47	V		VI
Yale, B.C.	49.57	121.43	VI	VI	VI

*Taken from Hopper *et al.* (2003). We use only MMI $\geq$ III that are not based solely on ground failure and/or water effects.

†Taken from table 2R B-4 of WPPSS (1977). The MMI $\geq$ III data used by Malone and Bor (1979).

‡Taken from Coombs *et al.* (1976)

Appendix B
The MM Intensity at Wenatchee

Analyses of historical earthquakes often depend critically on ambiguous descriptions of earthquake effects. Our location of the 15 December 1872 earthquake near the south end of Lake Chelan is particularly sensitive to the MMI assignments at Wenatchee and Entiat. The only contemporary account, "The Earthquake Eastward," appeared in the *Washington Standard* published in Olympia, Washington, on 11 January 1873, p. 2:

It appears that our earthquake experience, on the 14th ult., although it awakened considerable interest in the future state, was insignificant compared to that of our neighbors east of the mountains, who were forced to believe at the time that the end of all things sublunary had indeed come. The following account is furnished the Portland Herald, by Mr. McBride, an "eye-witness" of the tumult: 'The informant, Mr. McBride, and another man owned a ranch some three miles back from the mouth of the Wenatches river, which is about 170 miles from Wallula. On the night of the 14th of last December he and his partner had retired and were asleep, when they were suddenly awakened by noise as if the stove had been upset. They immediately sprang from their couch, and were about donning their clothes, when they were thrown to the floor in rather a sudden manner. Mr. McBride, who had experienced the shocks of earthquakes in Valparaiso, June 2, 1851, and in San Francisco in 1859, now realized the fact that there was an earthquake asserting itself. He turned to his partner and hastily informed him of his opinions, advising that they should leave. They made for the store on the river, some six miles distant, the ground undulating in a disorderly manner as they rode along. Arrived at the store they found everything in confusion. Messrs. Freer Bros. and one of their partners, named Miller, had also been awakened by the shocks and started from their beds. Mr. Miller ran down stairs and found the door blocked. He then imagined that the store had been attacked by Indians, and shouted to his partners, who came to his aid with shotguns and pistols. In the morning an examination was made, when it was discovered that in the store sacks of flour which had been piled in four feet deep were thrown around in confusion. The two upper logs of the cabin and the roof were misplaced, and the kitchen separated from the main building. The effect outside, Mr. McBride says, was terrible. He declares that the shocks, which lasted until five o'clock Sunday morning, December 15th, were sixty-four in number, eight being very severe. He also says that the peaks of several of the hills on the Kittitas and Columbia range of mountains were hurled over and broken. Trees were crushed to pieces and the river became very muddy, raising three feet inside of ten minutes. Great masses of earth, as if from a tremendous landslide, rushed down the mountain side, mixed with stone and wood, and the gulches lost their identity by being filled with debris. The third shock, which occurred about eleven o'clock P.M., was proceeded by an explosion—apparently on the mountain—sounding like the discharge of several pieces of artillery simultaneously. The people thought that the entire Grand Tule country was sinking, and were making preparations to leave. To add to the general confusion, the Spokane Indians, old and young, male and female, gathered around the settlers, alarmed and exclaiming that the world was coming to an end. They asked for advice and counsel from the whites, interspersing their sentences with fragments of prayer. Mr. McBride says the shocks continued at intervals until the 16th ult. The entire country was still alarmed and unsettled when he left there, fifteen days ago, to come to Portland."

Other accounts of the earthquake effects at Wenatchee appeared years after the event and are less useful for assigning an MM value. For example, the 13 July 1960 issue of the *Wenatchee Daily World* (p. 4) included the note: "The only other white residents of Wenatchee—Phillip Miller and the Freer Brothers—reported they were awakened by the quake some time before midnight. The whole framework of their log houses shook, and some earthen jugs of fruit wine were smashed, they said."

Hopper *et al.* (2003) used histograms of the intensity assignments for each site to assign MMI values for the 15 December 1872 earthquake. For Wenatchee, their 10 assignments were: 1 MMI = VI; 4 MMI = VII; 4 MMI = VIII; and 1 MMI = IX. Hopper *et al.* (2003) usually selected the mode of the distribution of assignments, but if four assignments were higher than the mode, then the next intensity above the mode was selected. Hopper *et al.* (2003) assigned MMI = VIII to Wenatchee. Coombs *et al.*'s (1976) MMI = VII at Wenatchee is also consistent with the mean and mode of the distribution of Hopper *et al.*'s (2003) MM assignments; the MMI = VI assigned by WPPSS (1977) is not.

Who was John McBride, and how reliable is his contemporary account of the effects of the 1872 earthquake at Wenatchee? A contemporary described McBride and his partner as "border ruffians . . . scoundrels who, for pure cussedness, could not be excelled anywhere on the border" (Splawn, Andrew Jackson, 1944 Ka-mi-akin, the last hero of the Yakimas; originally published in 1917). John McBride and his partner Jack Ingram were the founders of the first commercial enterprise in the Wenatchee area, the trading post mentioned in the earthquake account. By the early 1870s McBride and Ingram were in trouble for selling liquor to the Indians. Their legal problems started in Yakima where they were arrested and brought to trial but, according to the story, were freed after bribing the prosecutor (Splawn, Andrew Jackson, 1944 Ka-mi-akin, the last hero of the Yakimas) (originally published in 1917). McBride and Ingram apparently sold the trading post to Sam C. Miller and his partners, David and Frank Freer in 1871 or early in 1872 (Wenatchee, 1963). After escaping justice in Yakima for their illegal sales of liquor to the natives, McBride and Ingram were denounced to Federal authorities in Walla Walla and John McBride was arrested on 15 May 1872. He posted bail in September of 1872 and was awaiting trial at the time of the 1872 earthquake. At the time of the earthquake, McBride and Ingram lived on the west side of the Columbia River, three miles from the Wenatchee River and six miles from the Miller-Freer Trading Post. Subsequently, McBride was convicted in May of 1873. In early June 1873, he broke out of jail in Walla Walla and, by early 1874 was "reported to be with his partner, Ingram, at Rock Creek in British Columbia, dealing in horses" (*Spirit of the West*, Walla Walla, 6 February 1874).

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