

# ate Quaternary slip rate and seismic hazards of the West Klamath Lake fault zone near Crater Lake, Oregon Cascades

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## ABSTRACT

Crater Lake caldera is at the north end of the Klamath graben, where this N10°W-trending major Basin and Range structure impinges upon the north-south-trending High Cascades volcanic arc. East-facing normal faults, typically 10–15 km long, form the West Klamath Lake fault zone, which bounds the graben on its west side. The fault zone terminates on the south near the epicentral area of the September 1993 Klamath Falls earthquakes. It continues north past Crater Lake as the Annie Spring fault, which is within ~1 km of the west caldera rim, and Red Cone Spring fault. We have determined a long-term vertical slip rate of 0.3 mm/yr for these two faults using high-precision K-Ar and <sup>40</sup>Ar/<sup>39</sup>Ar age measurements on offset lava flows ranging in age from ca. 35 to 300 ka. Holocene offset reported by Hawkins et al. and epicenters of eight M<sub>w</sub> 2 earthquakes in 1994 and 1995 indicate that the West Klamath Lake fault zone is active. Empirical relations between earthquake magnitudes and scarp heights or fault lengths suggest that the fault zone is capable of producing earthquakes as large as M<sub>w</sub> 7¼. Earthquakes on these or other faults of the zone could trigger landslides and rockfalls from the walls of the caldera, possibly resulting in large waves on Crater Lake.

## INTRODUCTION

The Klamath graben is one of the major structures within the Cascades–Basin and Range transition of northern California and southern Oregon (Lakely et al., 1997). The north end of the graben is marked by Mount Mazama and Crater Lake caldera, where geologic mapping and geochronologic data provide age control on lava flows displaced by the Annie Spring and Red Cone Spring faults. Crater Lake and the populated area of the national park (~500 000 visitors/yr) are located on the hanging walls of the Annie Spring and Red Cone Spring faults. We consider these faults to be part of the West Klamath Lake fault zone defined by Hawkins et al. (1989) as a series of normal faults south of Crater Lake National Park (Fig. 1).

The consistency in age and apparent amount of displacement on its various faults suggests that the West Klamath Lake fault zone merges at length in a single throughgoing structure. The parallel Sky Lakes fault zone (Hawkins et al., 1989) cuts older lavas ~6–8 km to the west (Fig. 1). Both of these fault zones pass through Crater Lake National Park and emerge on the north as an ~10-km-wide zone of faulting. The southern boundary of the West Klamath Lake fault zone is marked by a change in strike of faults from north to north-northwest near the epicentral area of the 1993 Klamath Falls earthquakes (see SEISMICITY section). The total length of the fault zone and its northward continuation, between approximately the latitudes of Indian Butte and Mount Bailey, is ~70 km. Scarp heights in young lavas and moraines suggest that earthquakes on the West Klamath Lake fault zone have occurred in events of a few

meters vertical displacement, and that large sections of the zone may have ruptured during large magnitude earthquakes (M<sub>w</sub> 7¼, moment magnitude). The West Klamath Lake fault zone is analogous to other active normal fault zones of the Basin and Range province and is capable of producing large earthquakes (e.g., Crone et al., 1987; Jackson and White, 1989).

In this paper we first review historical seismicity near Crater Lake, and then present K-Ar, <sup>40</sup>Ar/<sup>39</sup>Ar, and paleomagnetic data that define ages of ca. 300 ka to 35 ka for eight lava flows with measured fault displacements. These ages and displacements document the long-term vertical slip rate along the Annie Spring and Red Cone Spring faults. Rates based on measured scarp heights in moraines cut by other faults of the West Klamath Lake fault zone (Hawkins et al., 1989) are consistent with our findings. The combined results suggest that the West Klamath Lake fault zone has a long history of activity and is capable of earthquakes as large as M 7¼.

The nearest population center to the West Klamath Lake fault zone is the city of Klamath Falls, which sustained moderate damage during the 1993 M 6.0 earthquakes (Wiley et al., 1993). Potential M 7 earthquakes on the West Klamath Lake fault zone could result in more severe shaking at Klamath Falls and at small communities near the Klamath graben. Facilities at Crater Lake National Park are located directly above the rupture plane of the Annie Spring fault. Earthquakes on the West Klamath Lake fault zone could produce accelerations sufficient to dislodge the fractured, unconsolidated, altered materials of the caldera walls (Bacon et al., 1997). A sufficient volume of debris, ~10<sup>6</sup> m<sup>3</sup> by analogy with

rockfalls into fjords, could cause one or more large-amplitude waves that could traverse the lake in ~2 min.

## SEISMICITY

The Oregon Cascades south of Mount Hood are seismically quiet when compared to other parts of the Cascades (Weaver, 1989). Prior to the 1993 Klamath Falls earthquakes (see following), seismometers were too few and distant to accurately locate small earthquakes in the Crater Lake region. There is, however, a sparse record of seismicity for Crater Lake and its vicinity (Fig. 1; Bacon et al., 1997). The largest event occurred near Crater Lake in 1920, was felt at intensity V, and had estimated M 4+. In 1947, an event with estimated M 3.7 occurred near the town of Fort Klamath. Two strong earthquakes, M 5.9 and M 6.0, occurred September 20, 1993, ~60 km south of Crater Lake, followed by hundreds of aftershocks during the succeeding weeks (the Klamath Falls earthquakes). The main events had hypocentral depths of ~9 km and apparently took place on a north-northwest-striking normal fault inclined ~45° to the northeast (Braunmiller et al., 1995). Subsequent to the 1993 earthquakes, telemetered instruments were added to monitor ongoing seismicity and locations and detection limits for earthquakes in the region improved (Qamar and Meagher, 1993). Several earthquakes occurred near Crater Lake in 1994 and 1995. Detection of the earthquakes of 1994–1995 may be partly a result of improved instrumentation, as the prior detection threshold for earthquakes that were not felt was probably at least M 3. The recent M 2–3 earthquakes may represent a regional increase in seismicity related to the 1993 Klamath Falls earthquakes because the number of events per year has declined each year since 1993.

## LAVAS OFFSET BY WEST KLAMATH LAKE FAULT ZONE

The long-term slip rate on the West Klamath Lake fault zone near Crater Lake can be estimated from geologic mapping of offset lava flows that have been dated by the K-Ar and <sup>40</sup>Ar/<sup>39</sup>Ar methods. Paleomagnetic orientations confirm the correlation of discontinuous lava outcrops based on geologic mapping.

Eight sites (Fig. 1) constrain fault offset of dated lava flows: six minimum, one maximum, and one measured vertical displacement (Table 1).

Minimum offsets are determined where (1) a lava flow is exposed on the west side (footwall) of the east-facing scarps but the down-dropped block is buried by ignimbrite of the climactic eruption of Mount Mazama, or (2) the higher, west side of the fault is thought to have been more affected by glacial erosion than the down-dropped east side. The exposed lava invariably has been glaciated, leading to an unknown amount of degradation of the original surface and further emphasizing that the offset determined by projecting the present surface east and measuring vertical distance to ignimbrite fill is a minimum value. The single maximum offset is obtained for andesite of Arant Point. This value is a maximum because of un-

certainty in identifying the proper horizon for measurement on the west side of the fault and because the surface of lava on the east side probably has been more significantly eroded. The measured offset is the sharp contact between basal vitrophyre and the holocrystalline (felsite) interior of a flow of dacite of The Watchman south of the main mass of this unit. This contact can be projected to the mapped Annie Spring fault, where it is displaced 15 m vertically.

A chronology of volcanic eruptions of Mount Mazama and of smaller volcanoes in the Crater Lake region has been developed through an extensive program of K-Ar dating, supplemented by  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating experiments

and paleomagnetic measurements. A subset of these data relevant to quantifying slip rate on the West Klamath Lake fault zone is presented in Table 1 (see Table 2 for sample localities). In six cases, offset units have been dated. Ages of the other two offset units are constrained by stratigraphy and K-Ar ages of other units. For example, dacite of Garfield Peak conformably overlies compositionally kindred pyroxene andesite of Applegate Peak, which has an age of  $240 \pm 19$  ka in the area of interest, and is unconformably overlain by  $224 \pm 9$  ka hornblende andesite of Garfield Peak. Therefore, dacite of Garfield Peak vented ca. 240 ka. Descriptions of K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  methods employed at Crater Lake were given by Hildreth and Lanphere (1994) and Lanphere et al. (1994), respectively. The youngest offset unit, basaltic andesite of Red Cone, has been dated by both methods (Table 1). The K-Ar age of  $36 \pm 12$  ka is corroborated by the  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $35 \pm 4$  ka (Fig. 2).

The basaltic andesite of Red Cone is cut by the Red Cone Spring fault. The outcrop on the west side of this locality is moderately glaciated, whereas the east side is buried under an unknown thickness of climactic ignimbrite. Because this outcrop is physically separated from the dated exposure of basaltic andesite of Red Cone, we have confirmed our compositional and petrographic correlation by determining paleomagnetic orientations of samples from six sites in this unit using methods described by Champion (1980). The unusual steep, northwesterly paleomagnetic direction (inclination,  $77^\circ$ ; declination,  $322^\circ$ ) for the basaltic andesite of Red Cone results in a high degree of confidence in the correlation of isolated outcrops. Small dispersion of paleomagnetic directions ( $\alpha_{95} = 2.2^\circ$ ) suggests that all sites represent lava emplacement spanning no more than a few decades.

#### SLIP RATE ON WEST KLAMATH LAKE FAULT ZONE

Vertical displacements are plotted against ages of units in Figure 3. Seven of the offsets are for the Annie Spring fault (Table 1). Although the 11 m offset on the Red Cone Spring fault is a minimum value, the age of this unit is well constrained at 35 ka, giving a minimum vertical slip rate of 0.31 mm/yr, consistent with the 0.30 mm/yr minimum slip rate for the north end of the Annie Spring fault derived from the 15 m measured offset in 50 ka dacite of The Watchman. The data from all of the offset lava flows suggest an average rate of vertical displacement of 0.3 mm/yr. Should the fault dip  $60^\circ$  and have a purely normal sense of motion, the east-west tectonic extension rate would be 0.17 mm/yr and the slip rate in the plane of the fault would be 0.35 mm/yr. These rates are comparable to those obtained for normal faults in the Oregon Basin and Range by Pezzopane and Weldon (1993) and Pezzopane et al. (1996). They are approximately

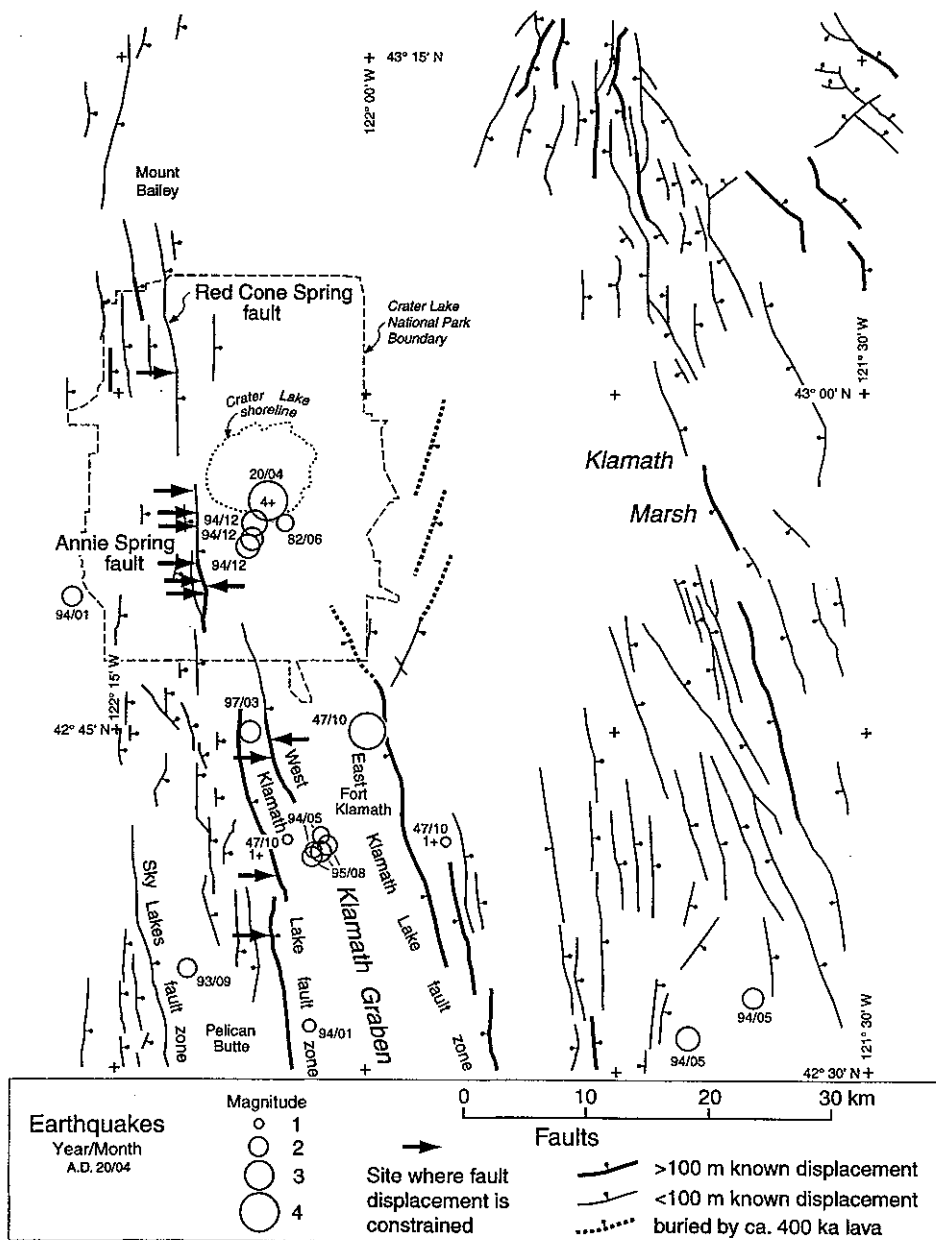


Figure 1. Map showing faults active in past few million years, earthquake epicenters through September 1997, and sites where fault displacement is constrained (Annie Spring fault and Red Cone Spring fault sites, this study; four other sites, Hawkins et al., 1989). After Bacon et al. (1997, Fig. 4).

one-fourth to one-third the rates obtained for normal faults in the California Cascades (Wills, 1991; Muffler et al., 1994).

Estimates of slip rates on faults of the West Klamath Lake fault zone south of Crater Lake are consistent with our data for the Annie Spring and Red Cone Spring faults. Hawkins et al. (1989, table 3) measured offsets in ca. 130–150 ka and ca. 10–30 ka glacial moraines and in early Holo-

cene deposits at the mouths of the canyons of Dry, Sevenmile, Threemile, and Cherry Creeks where they enter the Klamath graben and reported an average slip rate of 0.17 mm/yr for the past ~130 k.y. These data are plotted in Figure 3. When uncertainties in the ages of moraines are considered, these data also are broadly consistent with a vertical component of slip averaging ~0.3 mm/yr. Hawkins et al. (1989) noted that at

least one 1–2 m surface displacement event occurred in the Holocene, on the basis of scarps at Dry and Threemile Creeks.

Recurrence intervals are unknown for earthquakes on the West Klamath Lake fault zone. If all of the displacement on these faults took place in events with about 1–2 m of vertical offset (Weldon et al., 1996), major earthquakes (M7) would be expected to recur at an average rate of

TABLE 1. K-Ar AGES, ANALYTICAL DATA, AND FAULT OFFSETS FOR UNITS CUT BY THE ANNIE SPRING AND RED CONE SPRING FAULTS

Sample number	Eruptive unit*	Fault	Offset† (m)	K <sub>2</sub> O (wt%)	<sup>40</sup> Ar <sub>rad</sub> (10 <sup>-13</sup> mol/g)	<sup>40</sup> Ar <sub>rad</sub> (%)	Calculated ages‡ (ka)
80C355	Basaltic andesite of Red Cone	RCS	>11 <sup>c</sup>	1.178 ± 0.004	0.7560 0.4825	1.4 1.2 ( <sup>40</sup> Ar/ <sup>39</sup> Ar plateau age)	45 ± 18 } 29 ± 16 } 36 ± 12 } 35 ± 4 }
80C381	Dacite of The Watchman	AS	~15 <sup>d</sup>	2.729 ± 0.007	1.956	4.5	50 ± 6
83C965	Dacite north of Castle Creek	AS	>50 <sup>e</sup>	2.410 ± 0.008	7.572 6.324 7.486	27.5 23.5 24.5	218 ± 6 } 182 ± 6 } 215 ± 6 } 205 ± 3 }
80C472	Andesite of Garfield Peak <sup>a</sup>	AS	—	1.259 ± 0.007	4.025 4.093	11.1 10.4	222 ± 12 } 226 ± 13 } 24 ± 9 }
83C1015	Andesite of Applegate Peak <sup>b</sup>	AS	—	1.991 ± 0.006	6.868	5.1	240 ± 19
—	Dacite of Garfield Peak	AS	>67 <sup>c</sup>	—	—	—	~240 <sup>g</sup>
83C1045	Andesite of Applegate Peak	AS	>76 <sup>f</sup>	1.461 ± 0.013	5.266	15.7	250 ± 8
87C1508	Dacite of Munson Ridge	AS	>45 <sup>e</sup>	2.400 ± 0.008	9.544	10.5	276 ± 11
83C1007	Andesite of Arant Point	AS	<160 <sup>e</sup>	0.796 ± 0.003	3.335 3.449	11.1 20.0	291 ± 18 } 302 ± 16 } 97 ± 12 }
—	Basaltic andesite west of Arant Point	AS	>100 <sup>f</sup>	—	—	—	~300 <sup>g</sup>

Note: Red Cone Spring fault is RCS; Annie Spring fault is AS.

Decay constants:  $\lambda_e = 0.581 \times 10^{-10} \text{ yr}^{-1}$ ;  $\lambda_g = 4.962 \times 10^{-10} \text{ yr}^{-1}$ ;  $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4} \text{ mol/mol}$ .

\*a, disconformably overlies dacite of Garfield Peak, b, flow representative of uppermost andesite of Applegate Peak where overlain conformably by dacite of Garfield Peak.

†c, east side of fault buried by climactic ignimbrite, d, measured offset of top of basal vitrophyre, e, outcrops on west side of fault apparently lowered by glacial erosion to greater extent than those on east, f, east side of fault buried by younger units.

‡g, constrained by age(s) of contiguous unit(s).

See Table 2 for sample localities.

TABLE 2. SAMPLE LOCALITIES

Sample	Latitude (N)	Longitude (W)
80C355	42°59'42"	122°10'09"
80C381	42°56'39"	122°10'34"
80C472	42°54'14"	122°07'23"
83C965	42°55'37"	122°14'42"
83C1007	42°51'07"	122°09'47"
83C1015	42°53'55"	122°07'32"
83C1045	42°54'10"	122°10'20"
87C1508	42°57'23"	121°57'47"

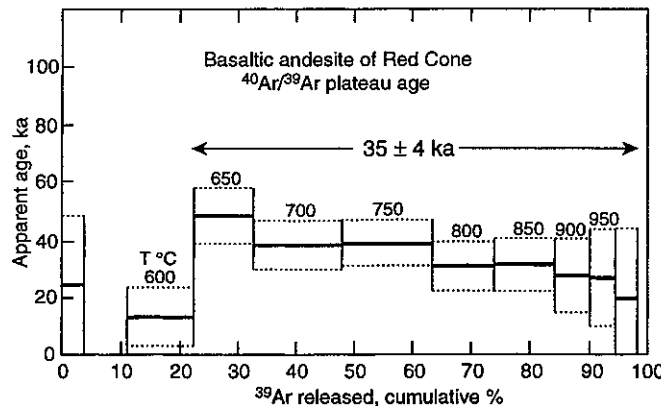
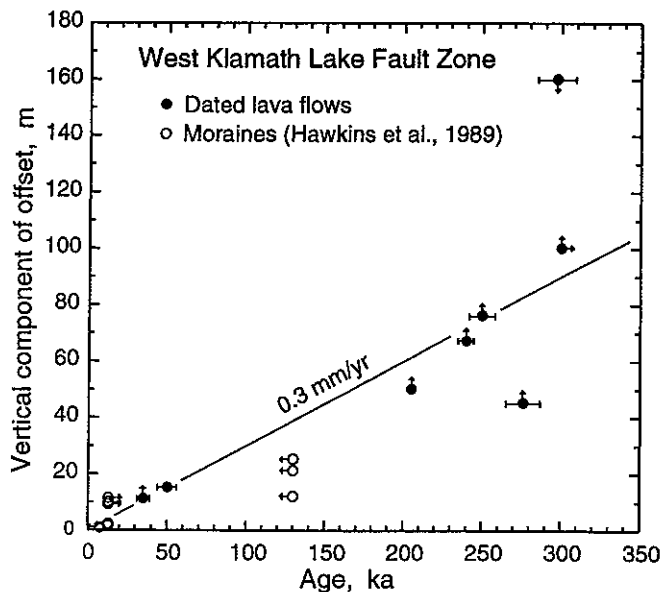


Figure 2. Apparent age spectrum for <sup>40</sup>Ar/<sup>39</sup>Ar incremental heating experiment on basaltic andesite of Red Cone. Plateau age is indistinguishable from weighted mean K-Ar age of 36 ± 12 ka.

**Figure 3. Ages of features versus vertical offsets that constrain slip rate on West Klamath Lake fault zone. Error bars on filled symbols are  $\pm 1\sigma$  analytical precision of K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  data. Arrows indicate maximum or minimum values in age or offset. Reference line labeled 0.3 mm/yr is consistent with all data for past 300 k.y. of motion on fault zone.**



one event in ~3–7 k.y. This result assumes a periodic recurrence model and characteristic-sized events having average displacements of 1.5 m.

#### MAXIMUM EARTHQUAKE ON WEST KLAMATH LAKE FAULT ZONE

The maximum earthquake likely to occur on a fault or fault zone can be estimated from fault characteristics such as surface rupture length and downdip rupture area. Critical to this analysis is surface rupture length (Schwartz and Coppersmith, 1986). Although it is impossible to know how much of the fault zone ruptures in a typical event, the empirical relation between earthquake magnitude and surface rupture length for normal faults given by Wells and Coppersmith (1994, Table 1A) and a surface rupture length of 70 km suggests a maximum earthquake of  $M_w$  7.3. This result is similar to the conclusion of Hawkins et al. (1989), who reported a maximum earthquake for the West Klamath Lake fault zone of  $M_S$   $7\frac{1}{4}$  ( $M_S$ , surface wave magnitude,  $\approx M_w$  at this magnitude) and is consistent with the findings of Weldon et al. (1996).

If the hypocentral depths of the 1993 earthquakes represent the downdip limit of the brittle crust, another estimate of the maximum event can be obtained from the empirical relation between downdip rupture area and  $M_w$  (Wells and Coppersmith, 1994, Table 2A). This suggests an  $M_w$  7.1 for a maximum depth of 12 km, dip of  $60^\circ$ , and length of 70 km. Increasing depth to 15 km raises the estimate to  $M_w$  7.3. Depending on the actual rupture length or area in a given event, the various methods of estimating magnitude indicate that earthquakes of  $M$  6 to  $M$   $7\frac{1}{4}$  can occur on the West Klamath fault zone.

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#### REFERENCES CITED

- Bacon, C. R., Mastin, L. G., Scott, K. M., and Nathenson, M., 1997, Volcano and earthquake hazards in the Crater Lake region, Oregon: U.S. Geological Survey Open-File Report 97-487, 32 p.
- Blakely, R. J., Christiansen, R. L., Guffanti, M., Wells, R. E., Donnelly-Nolan, J. M., Muffler, L. J. P., Clyne, M. A., and Smith, J. G., 1997, Gravity anomalies, Quaternary vents, and Quaternary faults in the southern Cascade Range, Oregon and California: Implications for arc and backarc evolution: *Journal of Geophysical Research*, v. 102, p. 22513–22527.
- Braunmiller, J., Nabelek, J., Leitner, B., and Qamar, A., 1995, The 1993 Klamath Falls, Oregon, earthquake sequence: Source mechanisms from regional data: *Geophysical Research Letters*, v. 22, p. 105–108.
- Champion, D. E., 1980, Holocene geomagnetic secular variation in the western United States: Implications for the global geomagnetic field: U.S. Geological Survey Open-File Report 80-824, 314 p.
- Crone, A. J., Machette, M. N., Bonilla, M. G., Leinkaemper, J. J., Pierce, K. L., Scott, W. E., and Bucknam, R. C., 1987, Surface faulting accompanying the Borah Peak earthquake and segmentation of the Lost River fault, central Idaho: *Seismological Society of America Bulletin*, v. 77, p. 739–770.
- Hawkins, F. F., Foley, L. L., and LaForge, R. C., 1989, Seismotectonic study for Fish Lake and Fourmile Lake dams, Rogue River Basin Project, Oregon: Denver, Colorado, U.S. Bureau of Reclamation Seismotectonic Report 89-3, 26 p.

- Hildreth, W., and Lanphere, M. A., 1994, Potassium-argon geochronology of a basalt-andesite-dacite arc system: The Mount Adams volcanic field, Cascade Range of southern Washington: *Geological Society of America Bulletin*, v. 106, p. 1413–1429.
- Jackson, J. A., and White, N. J., 1989, Normal faulting in the upper continental crust: Observations from regions of active extension: *Journal of Structural Geology*, v. 11, p. 15–36.
- Lanphere, M. A., Kuntz, M. A., and Champion, D. E., 1994, Petrography, age, and paleomagnetism of basaltic lava flows in coreholes at Test Area North (TAN), Idaho National Engineering Laboratory: U.S. Geological Survey Open-File Report 94-686, 349 p.
- Muffler, L. J. P., Clyne, M. A., and Champion, D. E., 1994, Late Quaternary normal faulting of the Hat Creek basalt, northern California: *Geological Society of America Bulletin*, v. 106, p. 195–200.
- Pezzopane, S. K., and Weldon, R. J., II, 1993, Tectonic role of active faulting in central Oregon: *Tectonics*, v. 12, p. 1140–1169.
- Pezzopane, S. K., Sarna-Wojcicki, A. M., Weldon, R. J., II, and Langridge, R. L., 1996, Slip rate and recurrence intervals for the Ana River fault, Oregon: *Geological Society of America Abstracts with Programs*, v. 28, no. 5, p. 101.
- Qamar, A., and Meagher, K. L., 1993, Precisely locating the Klamath Falls, Oregon, earthquakes: *Earthquakes & Volcanoes*, v. 24, no. 3, p. 129–139.
- Schwartz, D. P., and Coppersmith, K. J., 1986, Seismic hazards: New trends in analysis using geologic data, in Wallace, R. E., ed., *Active tectonics*: Washington, D.C., National Academy Press, p. 215–230.
- Weaver, C. S., 1989, Seismicity of the Cascade Range and adjacent areas, in Muffler, L. J. P., Weaver, C. S., and Blackwell, D. D., eds., *Geological, geophysical, and tectonic Setting of the Cascade Range*: U.S. Geological Survey Open-File Report 89-178, p. 74–93.
- Weldon, R. J., II, Pezzopane, S. K., Hemphill-Haley, M. A., Langridge, R. M., and Stimac, J. P., 1996, Evidence for and likelihood of  $M$  ~7 earthquakes in the arc and backarc of central Oregon: *Geological Society of America Abstracts with Programs*, v. 28, no. 5, p. A122.
- Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: *Seismological Society of America Bulletin*, v. 84, p. 974–1002.
- Wiley, T. J., Sherrod, D. R., Keefer, D. K., Qamar, A., Schuster, R. L., Dewey, J. W., Mabe, M. A., Black, G. L., and Wells, R. E., 1993, Klamath Falls earthquakes, September 20, 1993—including the strongest quake ever measured in Oregon: *Oregon Geology*, v. 55, p. 127–134.
- Wills, C. J., 1991, Active faults north of Lassen Volcanic National Park, northern California: *California Geology*, v. 44, p. 51–58.

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