Klamath Falls earthquakes, September 20, 1993—including the strongest quake ever measured in Oregon

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INTRODUCTION

Earthquakes struck the Klamath Falls area on Monday night, September 20, 1993, resulting in two deaths and extensive damage. The quakes were felt as far away as Coos Bay to the west, Eugene to the north, Lakeview to the east, and Chico, California, to the south.

A foreshock recorded at 8:16 p.m. had a Richter magnitude of 3.9. The first of two main shocks, measuring 5.9 on the Richter scale, rumbled through Klamath Falls at 8:28 p.m. Following 16 smaller jolts with magnitudes between 2.2 and 3.8, the largest quake struck at 10:45 p.m. This earthquake, measuring 6.0 on the Richter scale, is the largest to hit Oregon since the 1873 Port Orford/Crescent City earthquake (Jacobson, 1986). Oregon has been shaken by stronger quakes, but those quakes originated beneath the Pacific Ocean west of Port Orford.

NATURE OF THE EARTHQUAKES

The epicenters of the Klamath Falls earthquakes clustered around an area near lat 42°20′N. and long 122°05′W. (T. 37 S., R. 2 W.), within the Mountain Lakes Wilderness, 26 km (16 mi) west-northwest of Klamath Falls, in Klamath County, Oregon (Figures 1 and 2). The magnitude 5.9 main shock that occurred at 8:28 p.m. was located at lat 42°18.94′N. and long 122°03.30′W. at a depth of approximately 12 km (7.5 mi). The magnitude 6.0 main shock that occurred at 10:45 p.m. was located about 6 km (3.7 mi) farther to the northwest (lat 42°21.31′N., long 122°06.61′W.) and at a depth of approximately 12 km (7.5 mi). More than400 aftershocks with magnitudes greater than 1.5 had been recorded by October 12 (Figure 3); the 10 largest had magnitudes ranging from 3.0 to 4.3. Hypocentral depths range from 0–12 km (0–7.5 mi), with the best located aftershocks occurring at depths of 5–12 km (3–7.5 mi).

Initially, individual earthquake hypocenters were poorly located due to a lack of permanent seismographs in the area. However, 20 portable seismographs were rapidly deployed by teams from Oregon State University, U.S. Geological Survey, and University of Oregon.

The first records obtained from portable seismographs showed aftershocks occurring at a rate of one per minute on September 21, most of them too small to be detected except by the portable seismographs. By the end of September, this rate had fallen off dramatically.

During the first week of October, the U.S. Geological Survey installed four permanent seismographs in the epicentral region. Data from these instruments are now telemetered to the University of Washington (UW), where they are recorded as part of the UW seismic network. The UW is now able to precisely locate aftershocks as small as magnitude 0.3.

Analysis of the shock waves was used to determine the orientation of the fault plane and the direction of slip in what is known as a fault-plane solution. One fault-plane solution for the magnitude 6.0 main shock at 10:45 p.m. is shown on Figure 4 and is interpreted to represent a northwest- to north-northwest-striking (N. 38° W.), east-dipping (56°) normal fault with a very small component of left-lateral motion.

Hypocenter ("hypo" = "under") is the point within the Earth where the earthquake actually originates.
Epicenter ("epi" = "upon") is the point on the Earth's surface that lies directly above the hypocenter.

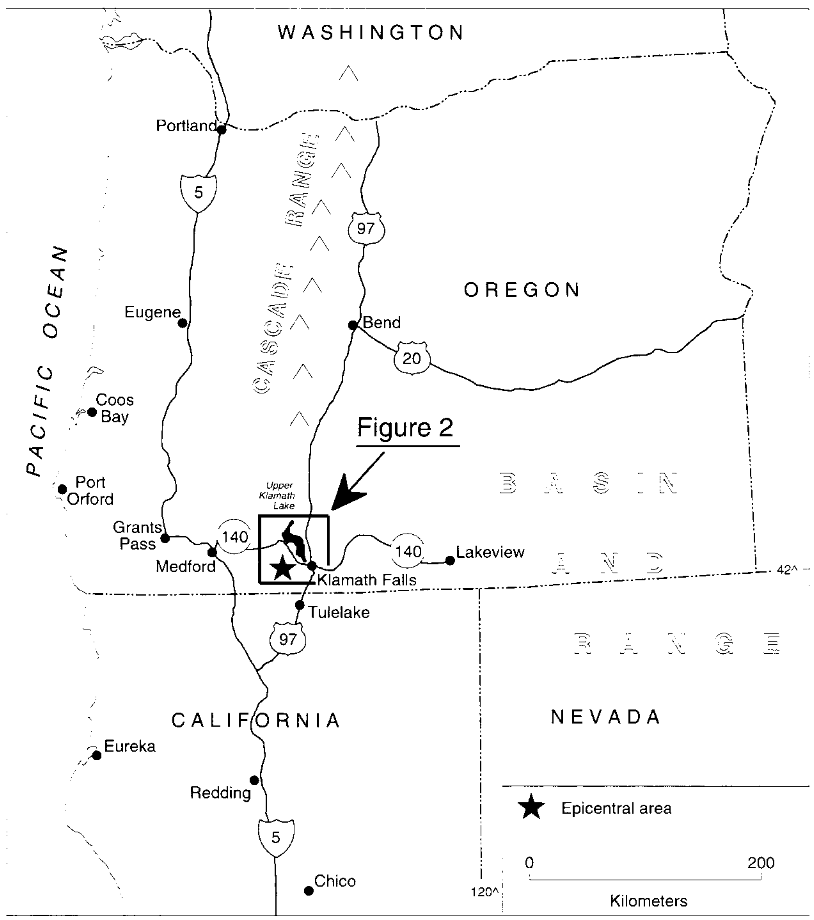

Figure 1. Location map.

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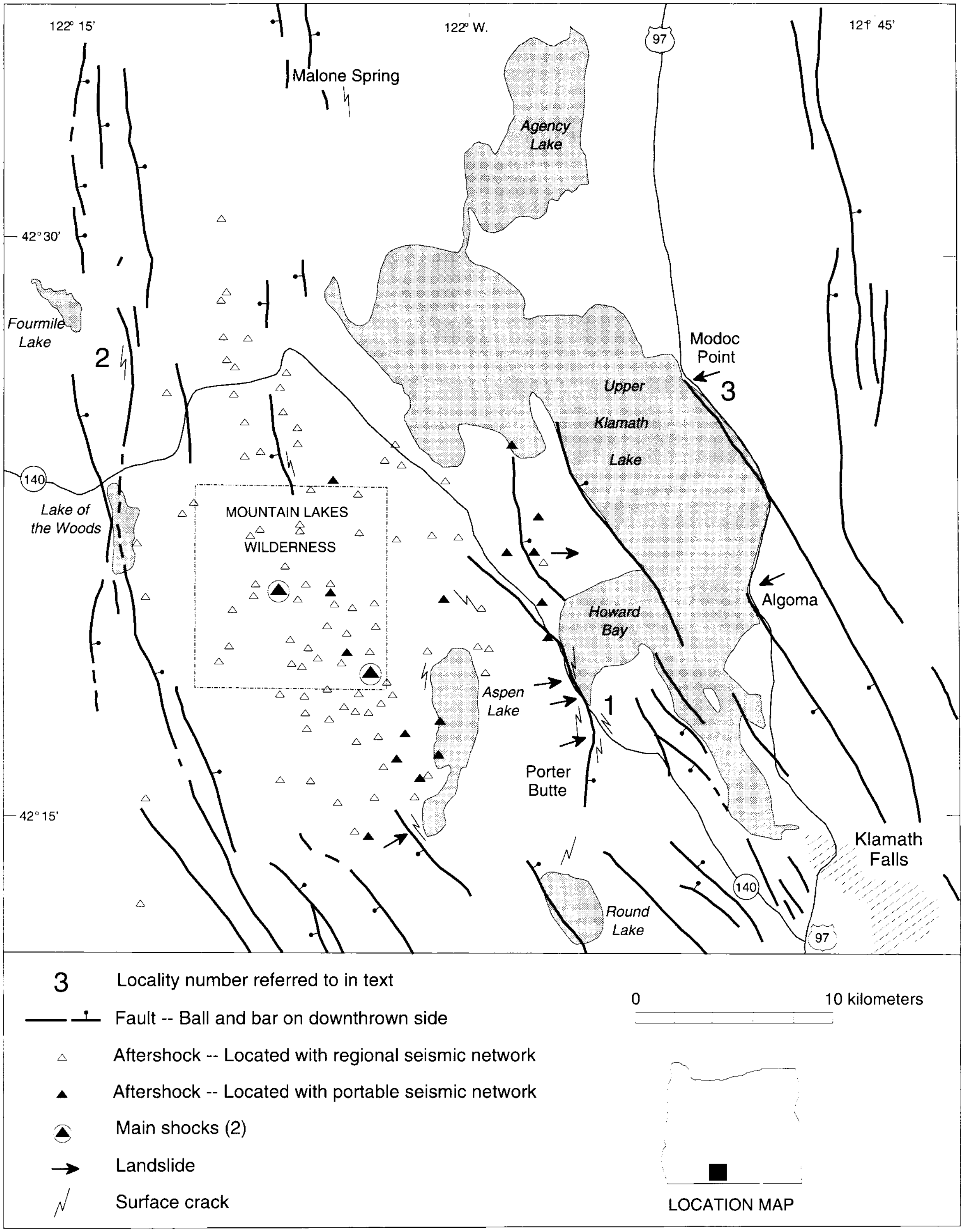

Figure 2. Map showing location of the two main shocks, aftershocks, surface deformation, mapped faults, and localities discussed in text.

SURFACE DEFORMATION

After the earthquake, a search for newly formed fault scarps, newly formed ground cracks, new and reactivated landslides, liquefaction, and related effects was conducted through aerial observation from a small, fixed-wing aircraft and traverses by automobile and on foot. The aerial search was carried out to epicentral distances of about 40 km (25 mi), whereas automobile and foot traverses extended more than 135 km (84 mi) from the epicenter. Neither newly formed ground rupture nor evidence of liquefaction was found. Ground cracks and landslides were the only surface geologic effects that could reliably be attributed to the Klamath Falls earthquakes.

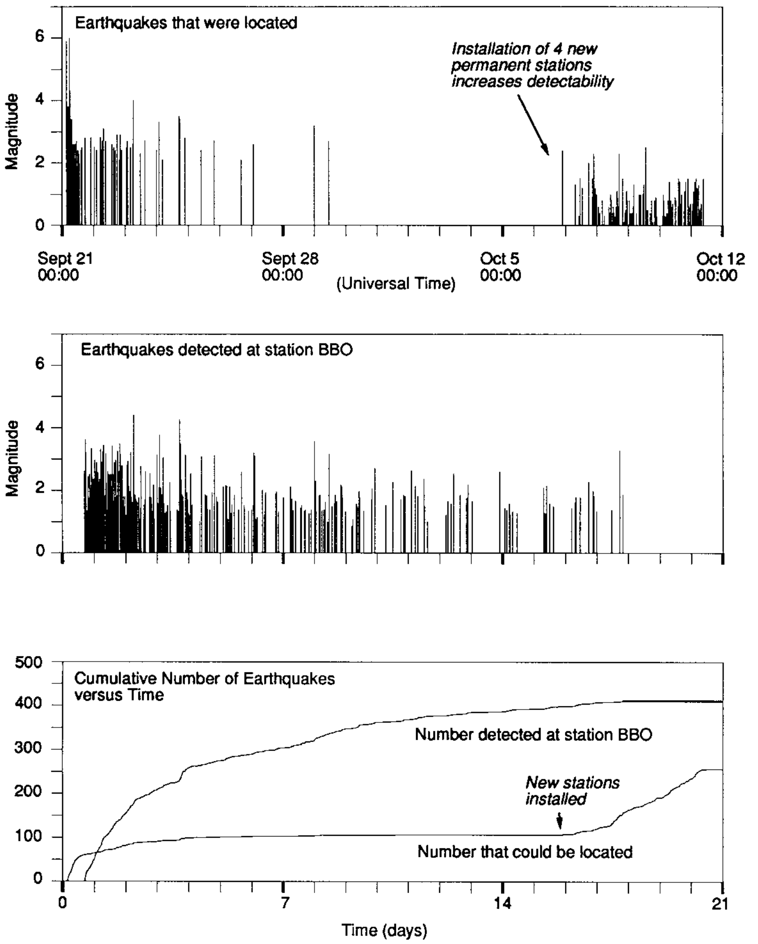

Figure 3. Plots showing earthquake magnitude versus time during first three weeks of earthquake activity. (a) Earthquakes located by University of Washington (UW) seismic network. (b) Earthquakes detected by closest permanent seismograph at station BBO (see Figure 11). (c) Total number of located and detected events. With the addition of the new stations now being recorded at UW, 780 earthquakes had been located by October 22.

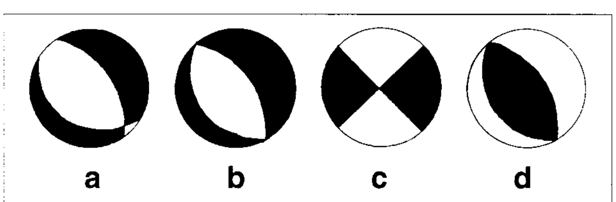

Figure 4. (a) Fault-plane solution for magnitude (M_C) 6.0 main shock at 10:45 p.m. on September 20, 1993 (lower hemisphere stereographic plot). The two planes defined by the boundaries between black (compression) and white (dilation) zones indicate fault orientations that could have produced this earthquake. The N. 38° W. plane dipping 56° NE. parallels many of the known faults in area. (b) Idealized normal-fault solution. (c) Idealized strike-slip-fault solution. (d) Idealized thrust-fault solution.

Ground cracks

Newly formed cracks were typically confined to artificial fill, chiefly in roadways where cinders and crushed rock had been used to elevate roads 30–60 cm (1–2 ft) above the surrounding ground. Newly formed or enlarged cracks were located as far west as Fourmile Lake, as far north as Malone Spring, as far south as Round Lake, and as far east as Howard Bay (Figure 2). Cracking was sparse near the main shock epicenters. Most cracking occurred in an area 3–8 km (2–5 mi) southwest of the epicenters, between Aspen Lake, Howard Bay, and Round Lake. A north-south linear zone with the greatest density of ground cracking, rock fall, and slumping extended from Round Lake to the Highway 140 bridge over the southern end of Howard Bay (Locality 1, Figure 2) and north along Highway 140 where it follows the west shore of Howard Bay. This zone corresponds with a previously mapped north-striking fault whose escarpment forms the east slope of Porter Butte and the west side of Howard Bay. Cracks generally trended north to northwest. Most cracks were only 3–6 m (10–20 ft) in length, but a few were more than 100 m (330 ft) long. Cracks cutting asphalt pavement and bed rock south of Howard Bay are believed to be related to compaction of underlying fill and to landsliding, respectively. Vertical displacements as large as 50 cm (1.6 ft) were found, but only where sliding or slumping was believed to have occurred.

One crack could be traced beyond road fill and into regolith. That crack was one of five or six found along a 30-m (100-ft) stretch of logging road north of Round Lake. Cracks in this set had irregular trends for lengths of 30–60 cm (1–2 ft) and overall trends of N. 5° W., N. 10° W., and N. 15° E., and opened as much as 1 cm (0.4 in.). Slip vectors were east-west (N. 86° W., N. 82° E., and N. 76° W.), as determined by aligning paired features such as gravel clasts and voids or embayments and protrusions.

Gaping cracks wide enough to insert a hand to the wrist characterized the embankment of Highway 140 along and south of Howard Bay. These cracks were related to spreading and slumping of road fill during and since the shaking events. Cracks along the centers of two gravel roads occurred in areas with thick fill and were similarly thought to result from lateral movement. Cracks were also found associated with culvert crossings.

Several cracks in a truck-turnaround pad constructed on the edge of a cinder cone north of Round Lake had a small component of normal separation, but the downdropped side coincided with the approximate outer (downslope) flank of the cinder quarry, and the downdip separation probably resulted from gravity failure. These cracks, which trended between N. 5° E. and N. 10° W., had opened about 2.5 cm (1 in.). One measured slip direction had a plunge of 15° on trend S. 76° E.

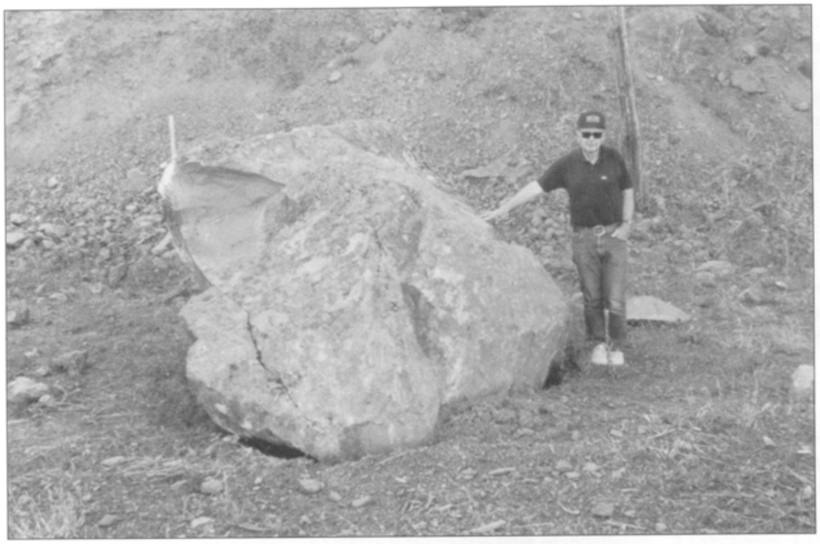

Figure 5. Rock-fall boulder from steep ridge bordering Oregon Highway 140 west of Howard Bay (Locality 1, Figure 2). Boulder fell from near-vertical slope partly visible in background and came to rest on highway shoulder.

The U.S. Forest Service reported a northwest-trending crack 8 m (26 ft) long that had opened as much as 5 cm (2 in.) and was located below water level in the marsh east of Malone Spring (Figure 2). Cracks were reported in fill along Cascade Canal, where it traverses the east slope of Rye Spur southeast of Fourmile Lake (Locality 2, Figure 2).

Landslides

The Klamath Falls earthquakes caused landslides throughout an area of about 420 km^2 (162 mi^2) surrounding the epicenter. Most landslides were rock falls or rock slides from road cuts, quarries, and steep bluff faces; these landslides occurred as far as 29 km (18 mi) from the epicenter of the strongest shock at 10:45 p.m.

The most numerous earthquake-induced rock falls were found along the east- to southeast-facing flank of a ridge immediately south and west of Howard Bay, 17 km (11 mi) east-southeast of the 10:45 p.m. epicenter (Locality 1, Figure 2). This ridge, which is 250 m (820 ft) high, has slopes exceeding 45° in some places. Basalt lava flows crop out in the upper part, and the lower slopes are mantled by boulder-rich colluvium and talus. Several dozen boulders, some as large as 4 m (13 ft) across, broke loose and fell or rolled down the slope during the earthquake. A few boulders came to rest on the shoulder and roadway of Oregon Highway 140 (Locality 1, Figure 2; Figure 5). One of these boulders was struck by an 18-wheeled truck, which then veered off the highway and into more boulders at the base of the cliff. Many more boulders came to rest on the unpaved road that climbs the southeastern side of the ridge.

The largest observed rock slide originated on a steep road cut on the east side of U.S. Highway 97, at a point 3 km (1.8 mi) south of the town of Modoc Point and 23 km (14 mi) from the 10:45 p.m. epicenter (Locality 3, Figure 2; Figures 6 and 7). This rock slide, which contained an estimated 300 m^3 (10,600 ft^3) of material, broke loose from a 60° slope composed of heterogeneous volcanic rock that is locally weakly cemented, intensely fractured, or both. The rock slide moved downslope about 100 m (330 ft); most of the material was contained behind a roadside barrier consisting of concrete sections surmounted by a steel fence, but one large boulder, 3.5 m (11.5 ft) in maximum dimension, crashed through the barrier onto the highway. The boulder hit a southbound vehicle, killing the driver.

Other rock falls and rock slides from road cuts were observed adjacent to Oregon Highway 140 as far as 17 km (11 mi) east and 29 km (18 mi) west of the 10:45 p.m. epicenter. These landslides were small (typically involving only a few cubic meters of material) and occurred from cuts that evidently had a history of spotty instability. One additional rock slide caused minor damage to railroad tracks near Algoma (Figure 2), according to a report in the Klamath Falls Herald and News (September 21, 1993, p. 1).

The Oregon Highway 140 bridge across Howard Bay, 17 km (11 mi) east-southeast of the 10:45 p.m. epicenter (Locality 1, Figure 2), was damaged by slumping and settlement at the north abutment and settlement of the south abutment. At the south abutment, the approach fill settled approximately 10 cm (4 in.). Left-lateral displacements totaling approximately 17 cm (7 in.) occurred across joints in the bridge deck, probably due to slumping and settling that caused the bridge deck to rotate counterclockwise. South of the bridge, the highway is built on a fill causeway at the edge of the marsh. For a distance of several hundred meters, the fill along the west shoulder of this causeway slumped into the marsh, opening cracks 5–10 cm (2–4 in.) wide (Figure 8).

Figure 6. Rock slide from Modoc Rim, 2.9 km (1.8 mi) south of the town of Modoc Point and adjacent to U.S. Highway 97 (Locality 3, Figure 2). Note breach in roadside barrier and impact marks in highway pavement caused by large boulder that hit southbound vehicle and came to rest on road. The boulder was pushed off the road before the photograph was taken and is visible just behind the right side of the breach.

Figure 7. Close-up of large boulder from the Modoc Rim rock slide (Figure 6) that breached barrier along U.S. Highway 97.

Several slumps in fill also occurred along the gravel road below the ridge immediately west of the bridge (Figure 9). These slumps were characterized by crescent-shaped open cracks that were concave downslope in plan view. The largest cracks were more than 100 m (330 ft) long and 30 cm (12 in.) wide. Several such slumps occurred in the quarry and the quarry road on the southeast-facing slope of the ridge, and at least two slumps occurred lower on the road, adjacent to a canal.

The types and areal limits of landslides (Figure 10) caused by the Klamath Falls earthquakes are typical for earthquakes of this magnitude. The area throughout which landslides occurred (Figure 10a), the maximum epicentral distances for rock slides and rock falls (Figure 10b), and the maximum epicentral distances for rotational slumps (Figure 10c) are comparable to similar data from other historical earthquakes. In addition, rock falls, rock slides, and slumps of fill material are among the most common types of landslides in other historical earthquakes of comparable magnitude (Keefer, 1984).

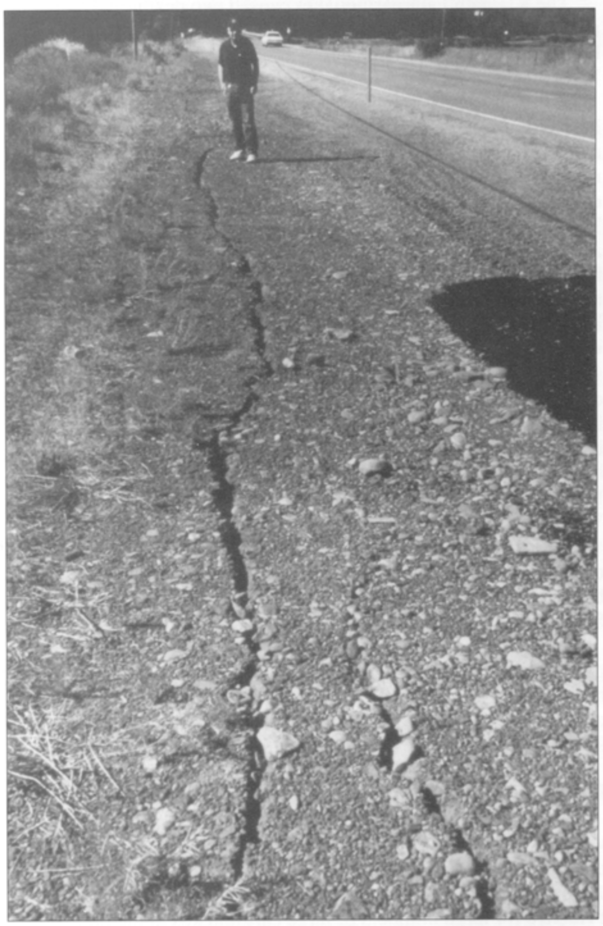

Figure 8. Linear cracks in the causeway fill south of Howard Bay bridge on Oregon Highway 140. These cracks were caused by slumping of fill in a westward direction, toward the right edge of the photograph.

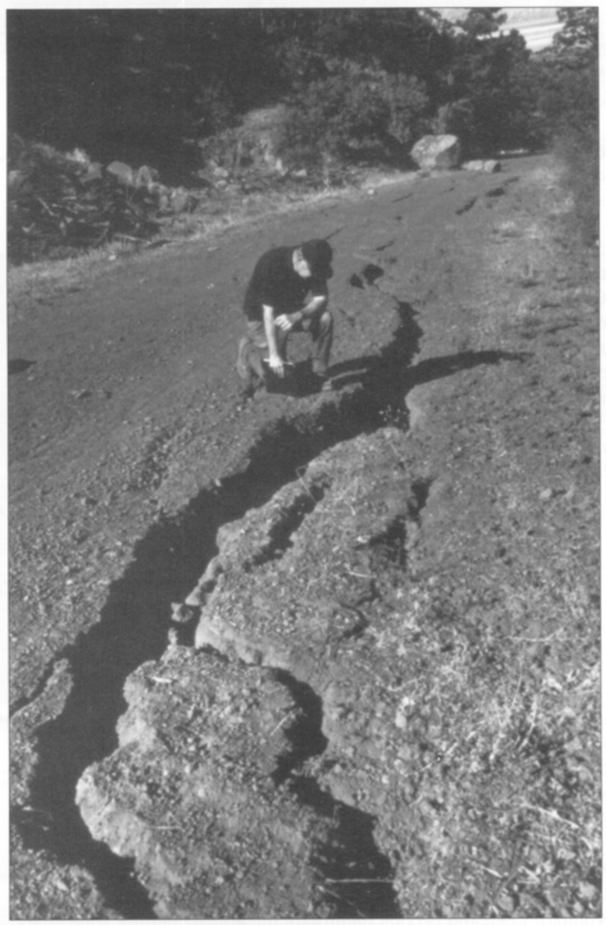

Figure 9. Crescent-shaped cracks associated with rotational slump in fill. Slumps involved unpaved road in quarry at Locality 1 on Figure 2. Boulders on road from earthquake-induced rock falls are visible in background.

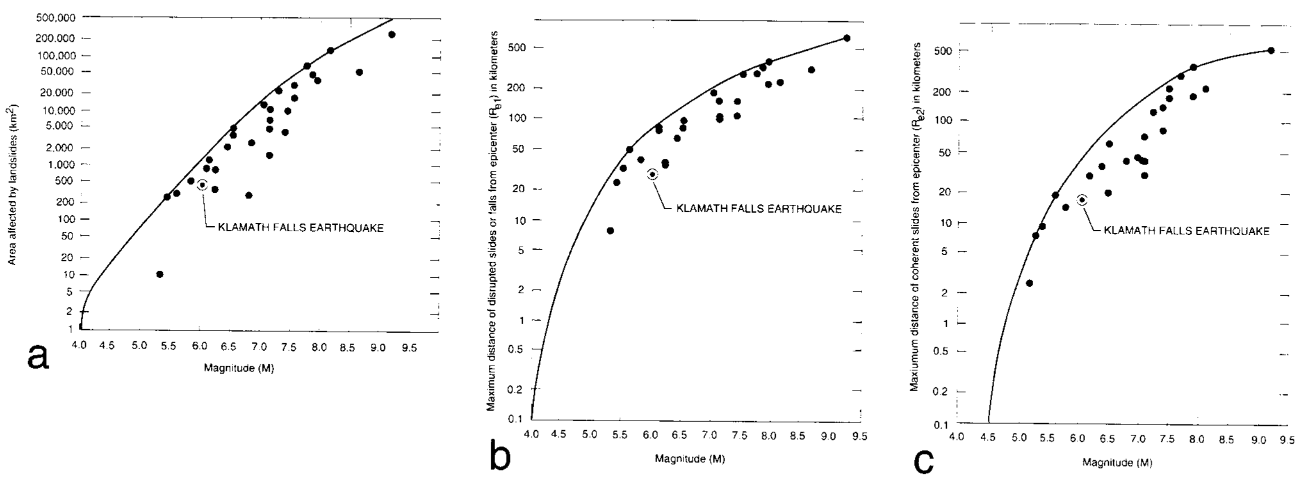

Figure 10. Plots comparing landslides caused by Klamath Falls earthquakes with landslides caused by other historical earthquakes (solid dots). Data on historical earthquakes and solid line denoting upper limit are from Keefer (1984). (a) Area affected by landslides. (b) Maximum epicentral distance of rock falls and rock slides (disrupted slides and falls). (c) Maximum epicentral distance of slumps (coherent slides).

EFFECTS ON SURFACE AND GROUND WATER

No changes in surface water have been reported as of October 11. A rancher with a water gauge on Upper Klamath Lake (Locality 1, Figure 2) reported that the lake level on September 21 and September 24 (after the main shocks) was identical to that measured on September 20 (prior to the earthquakes).

Several residents who rely on ground-water systems near the epicenter reported wells with cloudy or dirty water—"the color of chocolate milk"—that cleared on continued pumping. Piping for several wells was damaged.

Water district employees for the City of Klamath Falls reported that well levels in the urban geothermal system rose 2 ft (60 cm) in the first 36 hours after the quakes and had risen another foot by October 6. This contrasts with a typical year in which water levels decline in late September and early October. In a geothermal system monitored by the Oregon Institute of Technology, water levels reportedly fell 1–7 ft (30–220 cm) before stabilizing on the third day after the earthquake.

One continuously monitored well near Grants Pass, 100 km (60 mi) west of the epicenter, recorded a 35-cm (14-in.) drop in static level following the earthquake and never recovered.

RELATION OF EARTHQUAKES TO NEARBY FAULTS

Dramatic north- to northwest-trending fault-line scarps are the dominant topographic feature throughout the Klamath Falls area (Figure 2; Smith and others, 1982; Hawkins and others, 1989; Sherrod and Pickthorn, 1992). These scarps and the associated system of Basin and Range normal faults trend into the High Cascades volcanic arc in the epicentral area. Fault-plane solutions (Figure 4) suggest that the two main shocks occurred on a northwest- to north-northwest-striking, east-dipping normal fault or several faults. The surface projection of such a fault would lie east of the Lake of the Woods fault zone (Hawkins and others, 1989), assuming a 60° dip and a hypocentral depth of 12 km (8 mi). Aftershocks located by the portable seismic net define two north-trending bands of epicenters (Figure 2): The western band corresponds with the main shock epicenters as located by the regional seismic net. The eastern zone underlies the western shore of Upper Klamath Lake and is coincident with the north-trending zone characterized by the greatest amount of ground cracking and landsliding. Better definition of the fault or faults responsible for these earthquakes must await velocity modeling and thorough analysis of aftershocks recorded by portable seismographs.

INTENSITY AND DAMAGE

The Klamath Falls earthquakes caused two deaths and damaged more than 1,000 buildings. One person died when a car was struck by a boulder on U.S. Highway 97 near Modoc Point (Locality 3, Figure 2). The second fatality was the result of a heart attack.

Damage assessments reported by the Oregon Emergency Management Division (OEM) and the Federal Emergency Management Agency (FEMA) showed that residential, commercial, nonprofit, and government buildings and facilities suffered an estimated total dollar loss of more than $7.5 million (Table 1). The Klamath County Courthouse (built in 1924) and Courthouse Addition suffered the greatest damage, with a combined dollar loss of $3.14 million. Many unreinforced masonry buildings in the city of Klamath Falls were severely damaged. FEMA lists two residences as destroyed. Well-built wood-framed houses that were bolted to their foundations and commercial buildings constructed to modern building codes generally suffered little or no damage. The few modern structures that sustained damage may indicate areas where local conditions, building geometry, or building conditions resulted in more severe damage. Damage to buildings was reported from Tulelake, California, to Modoc Point, north of Upper Klamath Lake (Figure 11, Mercalli zones VI and VII).

Table 2 shows a comparison with the Scotts Mills earthquake of March 25, 1993, demonstrating how a smaller earthquake can be more damaging if it is centered beneath a more populous area. See the May issue of *Oregon Geology* (Madin and others, 1993).

An intensity questionnaire published in several Oregon newspapers resulted in intensity reports from the public that have yet to be compiled. Readers with observations from personal experience or who sustained damage to their homes are urged to fill out and send in the form at the end of this article (page 135).

HISTORICAL AND EXPECTED FUTURE EARTHQUAKES

During the last 50 years, at least 12 earthquakes have occurred within 33 km (20 mi) of Klamath Falls. Seven of these were larger than magnitude 3 and were large enough to be felt (Jacobson, 1986). Evidence from this historic record, combined with geologic evidence for large numbers of large earthquakes in the prehistoric past, suggests that one or more earthquakes capable of damage (magnitude 4–6) hit south-central Oregon every few decades. Earthquakes as large as magnitude 7 have probably occurred (Hawkins and others, 1989).

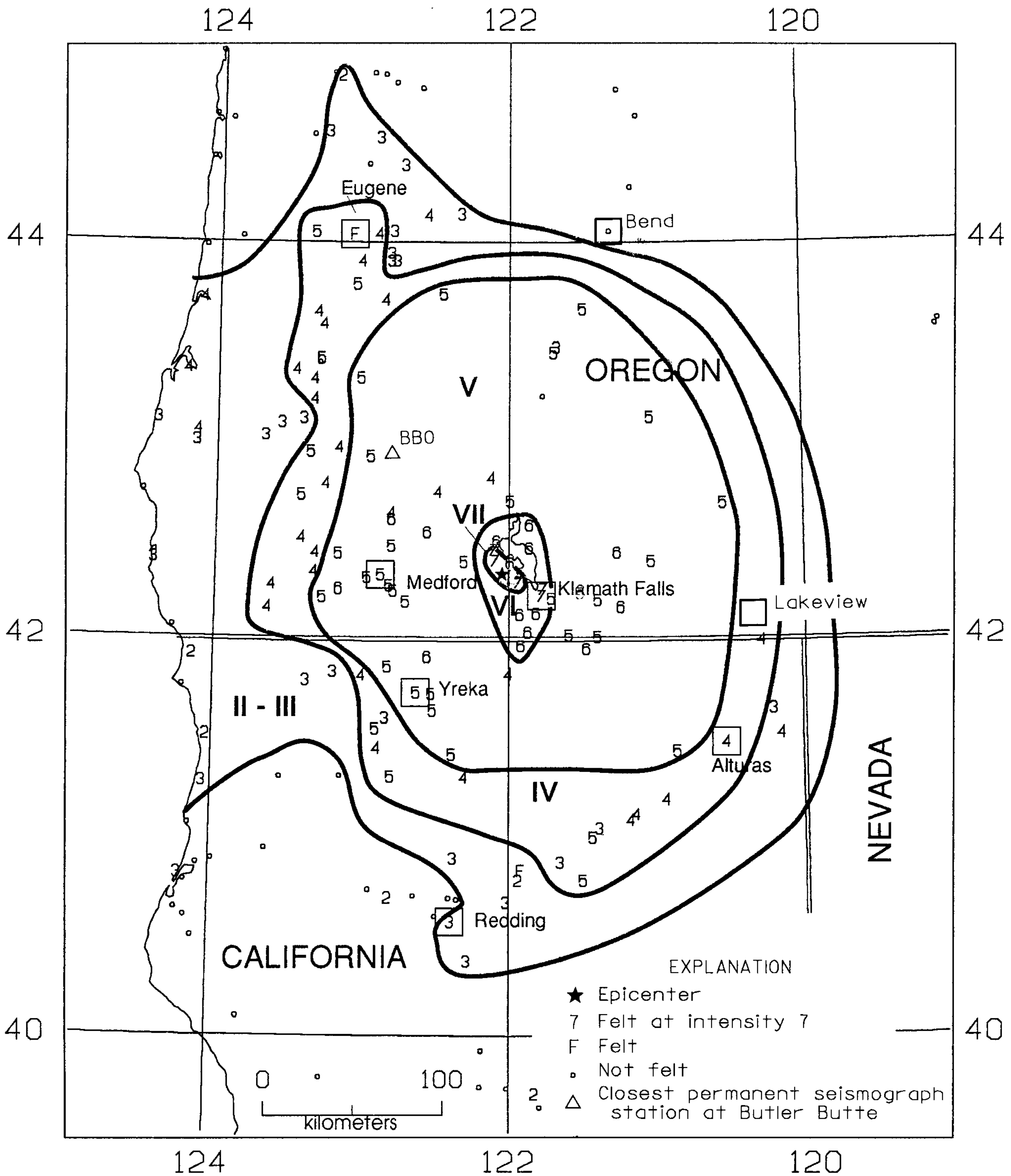

Figure 11. Preliminary Modified Mercalli intensity map for the September 20, 1993, Klamath Falls earthquakes. Explanation of intensities (Roman numerals) in Table 3.

Table 1. *Damage and cost estimates by FEMA*

Klamath County Public Facilities

Klamath County Courthouse	$1,720,000
Klamath County Courthouse, New Addition	$1,420,000
Klamath County Library	$5,000
Klamath County Schools	$26,000
Klamath County	$727,000
Klamath Falls City Schools	$113,000
City of Klamath Falls	$151,000
Klamath Tribes Medical Office	$3,500
Klamath Tribes Chiloquin Hatchery	$44,000
Klamath Tribes Algae Building	$3,000
Merle West Medical Center	$5,000
Oregon Department of Transportation	$15,000
Estimated total dollar loss	$4,232,500

Individual assistance damage estimates in Klamath County

Number of residences		
Destroyed	2	
With major damage	20	
With minor damage	142	
Affected habitable	777	
Total	941	
Estimated dollar loss		$1,140,000
Number of businesses		
Destroyed	0	
With major damage	25	
With minor damage	76	
Total	101	
Estimated dollar loss		$1,963,000
Number of others—non-profit		
Destroyed	0	
With major damage	2	
With minor damage	7	
Total	9	
Estimated dollar loss		$258,000
Total—residences and businesses		
Number	1,051	
Estimated total dollar loss		$3,361,000

Table 2. *Comparison between Klamath Falls earthquakes and Scotts Mills earthquake. Note that area in which the Scotts Mills earthquake was felt was limited by the Pacific Ocean and might have been 20 percent larger if the earthquake had occurred inland.*

	Klamath Falls	Scotts Mills
Magnitude	6.0 and 5.9	5.6
Depth	18 and 20 km	18 km
Maximum intensity	VII	VII
Area felt (km2)	131,000	134,000
Fatalities	2	0
Damage (millions of dollars)	~7.5	~12.6
Buildings destroyed	2	0
Landslides	out to 29 km	no
Ground cracks	yes	no

Table 3. *Excerpts[1] from Modified Mercalli intensity scale of Wood and Neumann (1931) as used in Figure 11*

Intensity	Description
II–III	Observations range from "felt by a few persons at rest" to "felt quite noticeably."
IV	Felt indoors by many, outdoors by few. Dishes, windows rattle; walls creak; standing cars rock noticeably.
V	Felt by nearly everyone, many awakened. Some dishes and windows broken; cracked plaster in a few places; unstable objects overturned; trees, poles, and other tall objects disturbed.
VI	Felt by all, many people run outdoors; some moderately heavy furniture moved.
VII	Everybody runs outdoors; damage negligible in buildings of good design and construction, considerable in poorly built or badly designed structures; some chimneys broken; noticed by persons driving cars.

[1] More complete versions of this scale have been published lately in, e.g., *Oregon Geology* (Sept. 1993, p. 118, and Jan. 1989, p. 17–18; *California Geology* (Sept. 1991, p. 203); and in the U.S. Geological Survey free pamphlet *The Severity of an Earthquake.*

The Klamath Falls earthquake sequence was a multiple event, with two main shocks that probably ruptured different parts of a fault at different times. Aftershocks since then have followed a commonly observed decline curve, decreasing dramatically in both number and magnitude.

This behavior contrasts with earthquake swarms, which are characterized by numerous temblors of similar magnitude and no recognizable main shock. Historic earthquake swarms in the region produced magnitude 4–5 earthquakes that continued for a month or more. For example, earthquake swarms struck 70 km (44 mi) south of Klamath Falls in the 1978 Stephens Pass, California, earthquakes (Bennett and others, 1979) and 160 km (100 mi) to the east in the 1968 Warner Valley earthquakes (Couch and Johnson, 1968).

However, since earthquakes are unpredictable, there is still a chance that significant aftershocks may strike the Klamath Falls area in the months ahead.

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