Geological Field Trips in Southern Idaho, Eastern Oregon, and Northern Nevada

Edited by Kathleen M. Haller and Spencer H. Wood

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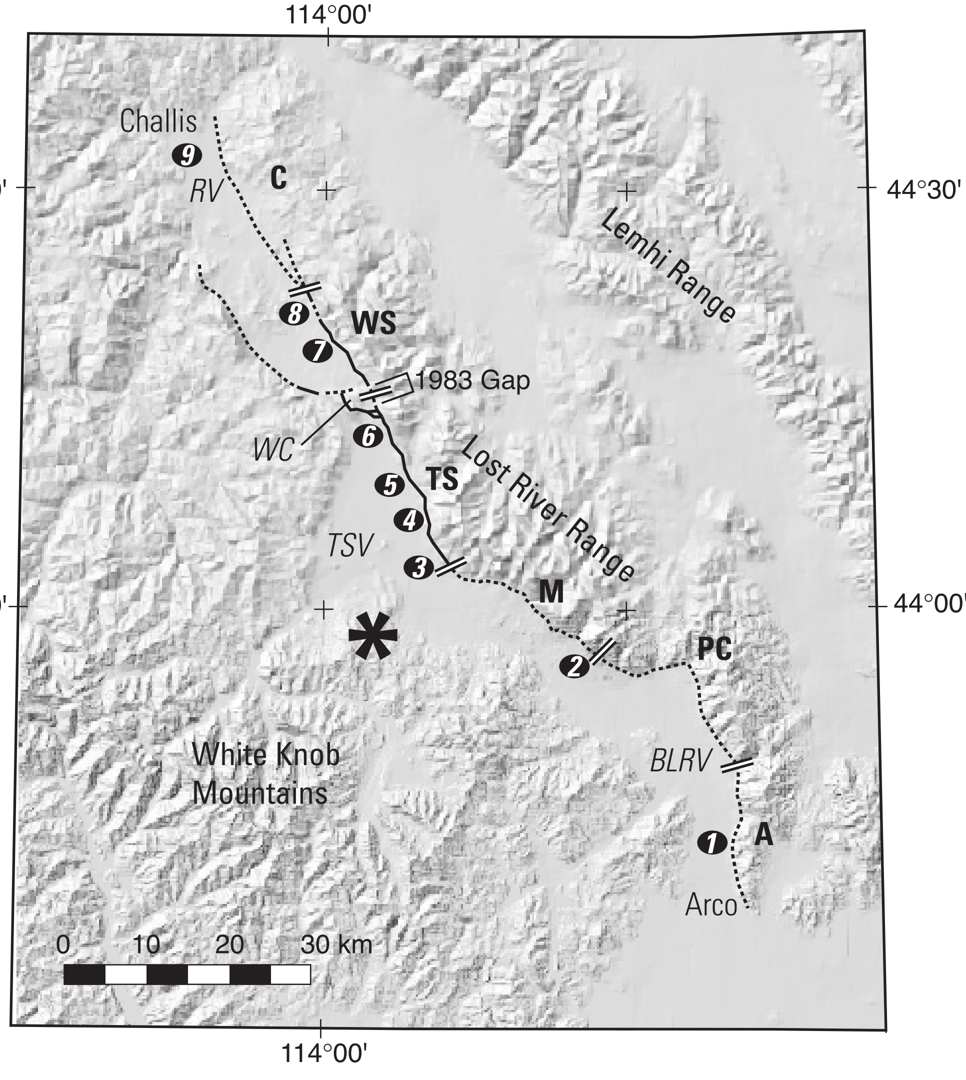

Figure 1. Map of Lost River fault and location of the Borah Peak earthquake (M 7.3, star) in east-central Idaho. Solid line shows the 1983 surface rupture on the Lost River fault; dotted line shows unruptured parts of the fault. Field-trip stops are shown by numbered circles. Selected locations are Big Lost River Valley (BLRV), Round Valley (RV), Thousand Springs Valley (TSV), and Willow Creek hills (WC). Segments, from south to north, of the Lost River fault are bounded by double black line: Arco (A), Pass Creek (PC), Mackay (M), Thousand Springs (TS), Warm Spring (WS), and Challis (C).

Twenty Years After the Borah Peak Earthquake—Field Guide to Surface-Faulting Earthquakes Along the Lost River Fault, Idaho

By Kathleen M. Haller and Anthony J. Crone

Introduction

The spectacular range front on the southwestern side of the Lost River Range has caught the attention of many geologists in the past century. Anderson (1934) and Livingston (1934) were the first to document that faulting was, in part, responsible for the abrupt range front; however, other investigators speculated that erosion was the causative agent (*e.g.*, Ross, 1937, 1947) or that the abrupt range front was caused by thrust faulting (*e.g.*, Kirkham, 1927). Thereafter, Baldwin (1943, 1951) clearly documented the Basin-and-Range style of faulting in this area, as well as the recency of movement and large amounts of throw across the Lost River fault and nearby faults. His 1951 article is one of earliest to use the name Lost River fault for this structure, which defines the 140-km-long southwest flank of Lost River Range (fig. 1). In the late 1960s and early 1970s, the seismic potential of this fault was confirmed in trenching studies by Malde (1971). On October 28, 1983, the Borah Peak (M 7.3) earthquake (fig. 2) ruptured 34 km of the central part of the Lost River fault. Following the earthquake, preliminary results from a multitude of geophysical, hydrologic, geologic, and seismologic studies were summarized in a special volume on the earthquake (Stein and Bucknam, 1985). These studies made the Borah Peak earthquake one of the most comprehensively documented historical ruptures at the time. Only six major, historical normal, surface-rupturing earthquakes have occurred in the intermountain west, thus every one is important and contributes new insight into our understanding of the coseismic failure of major range-front normal faults in extensional tectonic settings.

The Basin-and-Range region of Idaho north of the Snake River Plain, including the Lost River Range and ranges to the east (fig. 3), has a long and complex orogenic history. The mountain blocks are structurally and geomorphically similar to those elsewhere in the Basin and Range province (Reynolds, 1979) in that they are the result of extension on range-front normal faults; however, bedrock in these ranges records episodes of tectonic deformation that occurred in earlier stress regimes. The mountain blocks are composed of allochthonous Precambrain and Paleozoic rocks that were folded and thrust northeastward starting in the Cretaceous and continuing into Eocene time. This earlier deformation produced spectacular folds, some of which are beautifully exposed on many of the high peaks, including Borah Peak. About 4–7 m.y. ago, regional extension began to form the present topography. Borah Peak, which is composed of Proterzoic to Early Penn-

Figure 2. Echelon surface rupture (foreground and middleground) northwest of Borah Peak (in background). View is to the southeast.

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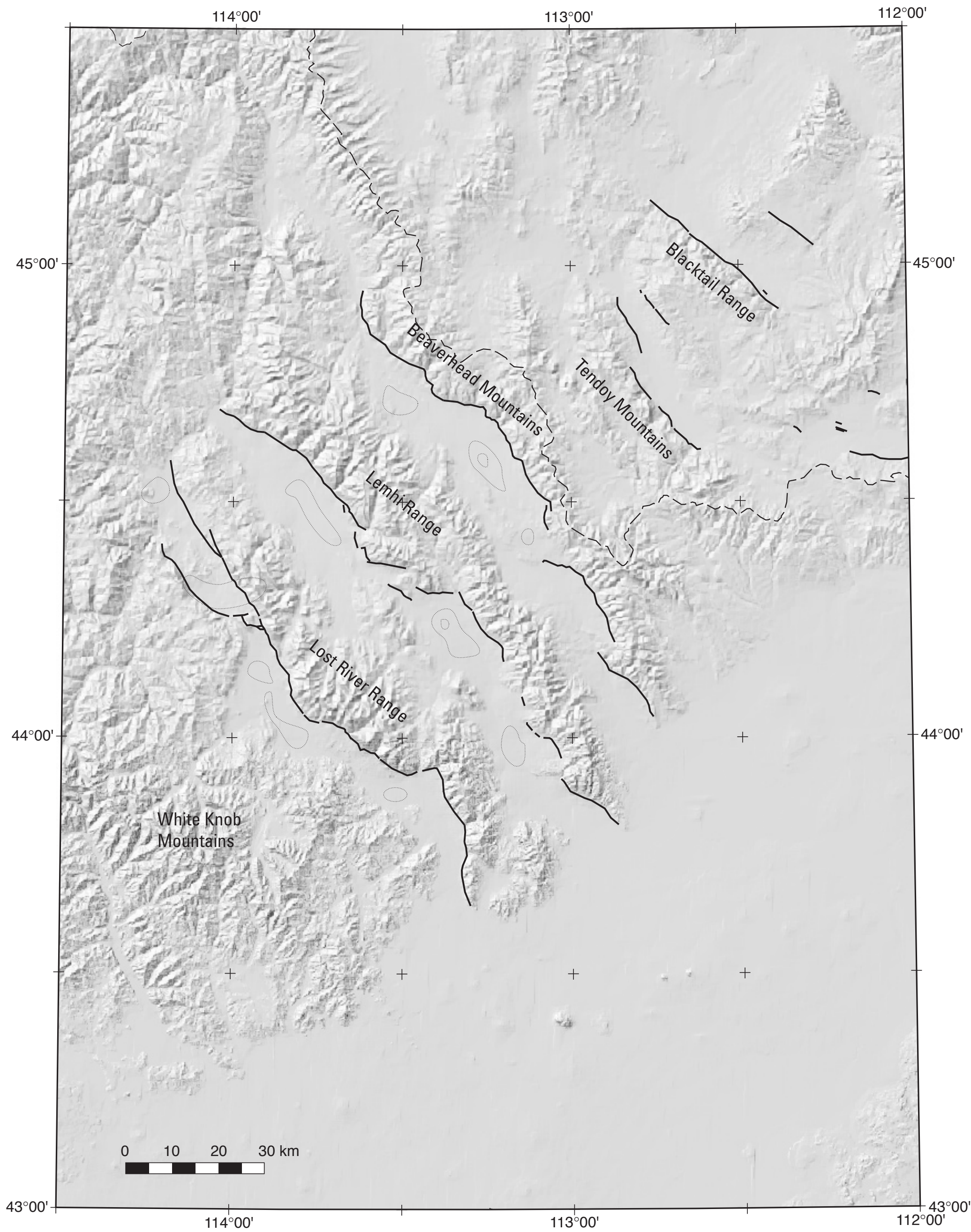

Figure 3. Generalized map of Quaternary range-front normal faults in east-central Idaho and adjacent parts of southwestern Montana. Closed gravity lows in adjacent basins are shown by dotted (gray) lines (from Bankey and others, 1985).

sylvanian rocks of the Lost River thrust plate, is the highest point in Idaho at 3,859 m; many peaks in the central parts of Lost River Range are higher than 3,700 m. In contrast, peaks at the ends of the range, commonly have elevations around 2,500 m. The adjacent valley floors range in elevation from 1,600 m, in the southern Big Lost River Valley near Arco, to 2,500 m adjacent to the central part of the range near the Willow Creek hills, and back down to 1,500 m in northern Round Valley, near Challis.

The two largest historical normal-faulting earthquakes in the United States (Barrientos and others, 1987) are the 1983 Borah Peak earthquake and the 1959 Hebgen Lake earthquake (M 7.5); they occurred 24 years and about 200 km apart. Both are in the Centennial Tectonic Belt (Stickney and Bartholomew, 1987), an east-trending band of seismicity that extends from the Borah Peak aftershock zone to Yellowstone National Park. Interestingly prior to the Borah Peak earthquake, the Centennial Tectonic Belt was poorly defined west of the Idaho-Montana state line because the region surrounding the Lost River Range had a low rate of historical seismicity (Smith and others, 1985). No foreshocks preceded the Borah Peak main shock and, in fact, only two small earthquakes were recorded within 35 km of the Borah Peak main shock in the 4 years prior to the 1983 earthquake (King and others, 1987). In the months following the Borah Peak earthquake, thousands of aftershocks were recorded, mainly northwest of the epicenter on the Thousand Springs and Warm Spring segments. One of the largest aftershocks, the M 5.8 Devil Canyon event, occurred on August 23, 1984, nearly 10 months after the main shock (Jackson, 1994).

Regional Faults

Similar to the Lost River Range, range-front normal faults bound mountain ranges to the northeast, including the Lemhi Range and Beaverhead Mountains in Idaho, and the Tendoy Mountains and Blacktail Range in Montana. The presence of well-preserved fault scarps on Quaternary alluvium along large parts of these range-front faults is clear evidence of ongoing Quaternary tectonism throughout the region. Although the details of each fault's Quaternary behavior remain unresolved, these faults have been studied sufficiently to characterize the age(s) of the most recent event(s) and to show that single earthquakes do not rupture the entire length of any of these faults. From a regional perspective, the prominent range fronts, the heights of mountain blocks, and the lengths of faults tend to decrease toward the northeast, which might imply that the rate of fault activity also would decrease to the northeast. However, the most active, central parts of the faults shown in figure 3 all appear to have recurrent surface-faulting events every several to about ten thousand years, so there does not appear to be any obvious correlation between the length of the fault, the prominence of the range front, or the recurrence time for surface ruptures on the fault's most active segments. The long-term, late Cenozoic activity of these range-front faults has produced 1.5–2 km of topographic relief and as much as 6 km of structural relief (Skipp and Hait, 1977).

The range-front faults that bound the southwestern side of the Lost River and Lemhi Ranges and Beaverhead Mountains in Idaho are subparallel and have similar lengths and two-dimensional shapes. Prominent embayments and salients in the fronts of these ranges roughly align in a north-south direction (fig. 3), which hints at some deep structural control. Typically, each of the faults have either several-kilometer-long gaps in scarps or major echelon steps in the fault trace, which are interpreted to mark discontinuities that define the ends of independent surface ruptures (Crone and Haller, 1991).

Segmentation

Historical observations demonstrate that the entire length of long normal faults (>50–60 km) generally do not rupture during single large earthquakes. The tendency for only part of such long faults to fail coseismically is called segmentation, and in its strictest sense, the term defines parts of a fault that have a distinctly different rupture history than neighboring parts. In the model of a well-behaved segmented fault, surface ruptures are confined to a single segment through several to many seismic cycles. In this part of the intermountain west, surface-rupturing earthquakes are infrequent, thus the change in morphology of fault scarps along strike of the fault may suggest the presence of a segment boundary. Scott and others (1985) divided the 140-km-long Lost River fault into six segments generally based on morphology and continuity of Quaternary fault scarps and the inferred age of faulted deposits. Although the number of segments has not changed in the nearly 20 years since their study was published, the location of some boundaries have been refined and generally now coincide with geologic structures that may be effective barriers to rupture propagation. On this trip, we will travel from south to north along the Lost River fault and look at the geomorphic and structural similarities and differences between the Arco, Pass Creek, Mackay, Thousand Springs, Warm Spring, and Challis segments (fig. 1). The segments average 23 km in length, and all but the Challis segment have evidence of at least one surface-rupturing earthquake in the past 20–30 k.y.

Schwartz and Coppersmith (1984) proposed a model for characteristic earthquakes in which a fault or fault segment tends to repeatedly generate approximately the same maximum-size earthquake. Since the publication of their paper, a great deal of work has been conducted to determine if faults repeatedly rupture in earthquakes having a relatively narrow range of magnitudes near some maximum value for that part of the fault. Thus, when we speak of a part of a fault as behaving characteristically, we infer that the amount of displacement and the part of the fault that ruptures are similar over several seismic cycles. We will see on this trip that some segments of the Lost River fault appear to behave characteristically whereas others do not.

The segmentation model and characteristic behavior are closely linked. If a fault displays segmented behavior and earthquakes are largely confined to a specific segment, then the magnitude of the successive earthquakes should be similar. Since 1983, the refined location of the segment boundaries of the Lost River fault, as well as other nearby faults, have identified several types of structural barriers that seem to effect the propagation of ruptures and, thereby, reinforce the geomorphically based segmentation model that was developed prior to the Borah Peak earthquake (Scott and others, 1985). Most segment boundaries on the Lost River fault are marked by the absence of scarps on alluvium and occur near major changes in the fault's strike. It has been apparent for years that several boundaries coincide with areas of densely faulted bedrock, but the three-dimensional interaction of the faults in the footwall at a segment boundary was only recently addressed (Janecke, 1993). Janecke's (1993) structural interpretations have tremendous potential for providing yet another line of evidence to successfully define segment boundaries. Despite the notion that a segment boundary will usually halt a propagating

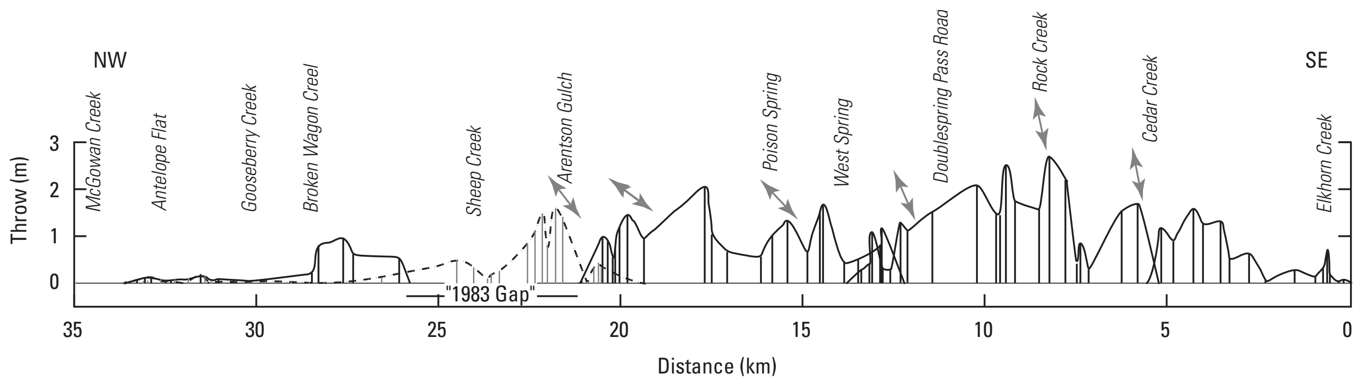

Figure 4. Plot showing the vertical throw resulting from the 1983 Borah Peak earthquake. Maximum net vertical throw was 2.7 m (near Rock Creek at the base of Borah Peak); although, individual scarps are almost twice as high (5 m). Average vertical throw was 0.8 m for the entire rupture, and 1.1 m along the Thousand Springs segment (from Arentson Gulch to Elkhorn Creek). The highest scarps are on the Thousand Springs segment. Scarps along the Willow Creek hills part of the rupture are shown by the dashed line. Offsets northwest of the "1983 Gap" are on the Warm Springs segment. The earthquake epicenter was located southeast of Elkhorn Creek.

rupture, it is clear that at times, surface rupture must propagate through the boundary otherwise the present range-crest morphologies would not exist (Crone and Haller, 1991).

Our paleoseismic record of the Lost River and other similar range-front normal faults is too short and incomplete to confirm the persistence of segment boundaries through multiple seismic cycles, however, gravity data provide some insight into the overall persistence of segment boundaries through time. In alluvium-filled valleys adjacent to these faults, gravity data show the general configuration of the bedrock beneath the valley fill. During individual coseismic ruptures, the amount of vertical slip usually is highest in the middle of the rupture and decreases towards the ends (see fig. 4). If this pattern is repeated many times, the central part of segments should coincide with closed gravity lows where the bedrock is deepest, and the ends of the rupture should coincide with gravity highs (Haller, 1988). This model holds true for the Warm Springs segment of the Lost River fault, which has a well-defined, centrally located gravity low (fig. 3). But elsewhere gravity lows do not necessarily coincide with central parts of segments (fig. 3). In many cases, bedrock highs (gravity highs) in the valley floor do, however, project to segment boundaries in range-front faults, and we will cross several of these on this trip.

The Borah Peak Earthquake

The Borah Peak earthquake occurred on at 8:06 a.m. (local time) October 28, 1983, and was the largest earthquake in the intermountain west in nearly 25 years. It was felt over an area of 670,000 km^2, in part or all of seven adjacent states. The felt area is elongated in the north-south direction and extended from the Canadian border to Salt Lake City (Stover, 1985). The earthquake produced 34 km of surface rupture with a maximum vertical displacement (throw) of 2.7 m, individual scarps nearly 5-m high, and a component of left-lateral movement as much as 17 percent (Crone and others, 1987). In the weeks following the earthquake, field mapping defined a Y-shaped surface rupture (fig. 1); continuous ruptures formed along the entire 20.8-km-long Thousand Springs segment and discontinuous scarps formed to the north along the Warm Spring segment (14.2 km) and to the northwest across the Willow Creek hills (7.9 km) joining the west-dipping Lost River fault and the east-dipping Lone Pine fault (Crone and others, 1987). Characteristics of the scarps are markedly different on the three parts of the ruptures. The largest scarps (fig. 4) are along the Thousand Springs segment where scarps greater than 1-m high exist along more than one-half of the segment. Considerably smaller scarps are present to the north and northwest, where the 1983 ruptures rarely exceed 1 m in height.

The earthquake hypocenter was at a depth of about 16 km and about 15 km southwest of the southern end of the surface rupture. The fault rupture propagated upward, first reaching the surface near Elkhorn Creek and progressed unilaterally to the northwest, producing normal slip with a small amount of left-lateral slip at the surface. The location of the main shock with respect to the surface rupture (Doser and Smith, 1985), the 3-dimensional location of aftershocks (Richins and others, 1987), and geodetic modeling suggest that the fault generally is planar in the upper crust (not listric), and it dips about 40–50° SW. to seismogenic depths (Barrientos and others, 1987). This modeled dip is consistent with the depth, location, and focal mechanisms of the main shock.

Paleoseismology of the Lost River Fault

Paleoseismological studies of the Lost River fault have a long and interesting history. Studies of the fault's seismic potential began in 1969 to address seismic hazards at the National Reactor Testing Station, now Idaho National

Engineering Environmental Laboratory (INEEL), 25 km southeast of Arco, Idaho. These studies included some of the first trenching efforts in the intermountain west; one trench was excavated on the southern part of the Lemhi fault, and a stream exposure was cleaned to expose the southern part of the Lost River fault. (We will visit the latter of the two sites on this trip.) In the 1970s, two additional trenching studies were conducted farther north on the Lost River fault: one trench was excavated at Lower Cedar Creek near Mackay, Idaho, and a second, noteworthy trench was excavated near Doublespring Pass road. The 1983 rupture occurred on this part of the fault and exposed a cross section of the filled trench in the fresh fault scarp. This remarkable circumstance provided an opportunity unlike any other to characterize fault behavior and earthquake cycles.

Following the Borah Peak earthquake, trenches on various parts of the fault were excavated to develop a better understanding of the entire fault's rupture history. The exhumed trench at Doublespring Pass road was reopened and remapped shortly after the earthquake. Other sites also were studied including some near those originally excavated in the 1970s. In the 1990s, the issue of seismic hazards at INEEL once again stimulated additional studies, including studies at two new sites on the southern part of the fault and reevaluation of the 1969 site. These site-specific investigations, additional geomorphic studies, and more recent bedrock mapping have enhanced our understanding of this fault.

FIELD-TRIP ROAD LOG

Mileage Inc.	Cum.	
0	0	Intersection of U.S. Highways 20/26 and 93 in Arco, Idaho. Proceed north out of town on U.S. Highway 93.
2.5	2.5	Turn right (east) on to 2700 N. Directly ahead is a typical example of the Arco scarp of Malde (1971, 1985, 1987). As we drive northward along scarps of the Arco segment, note that they are fairly continuous, large (generally about 8-m high) and prominent with slope angles of 18– 27° (Malde, 1985). Road turns northward 0.7 mi from intersection and becomes King Mountain Road.
0.6	3.1	The scar across the scarp to the right is the Arco Peak trench (Olig and others, 1995) excavated in 1994.
3.3	6.4	Turn right on side road for Stop 1 (lat 43.73595°N., long 113.32624°W.).

Stop 1. Trench Site on Arco Segment

The Arco segment is characterized by faceted bedrock spurs (Malde, 1971) and high, dominantly west-facing scarps on alluvium along much of range front. Scarps range from 2 to 25 m in height (Pierce, 1985) but most are about 12 m (Malde, 1985; 1987). High scarps are on deposits thought to be less than 600 ka, whereas 2- to 3-m-high scarps are on late Pleistocene deposits (Pierce, 1985). The youngest unfaulted deposits probably are latest Pleistocene and Holocene in age (Pierce, 1985; Scott and others, 1985). Olig and others (1995) estimate that single-event displacements are 1.2–1.5 m based on 6 m of total offset thought to represent 4 or 5 surface-faulting events.

This site was originally excavated in April 1969 by Malde (1971) and called Site A-2. This specific location (shown as a borrow pit on the 1972 version of the Arco North 7.5 minute topographic map) was selected, in part, because it is near the middle of the part of the fault that Malde defined as the Arco scarp, and he expected the site to yield a faulting history that was representative of the rest of the Arco scarp. In addition, excavation at the site simply required freshening a natural exposure, which was expedient. However, the natural exposure is not normal to the strike of the scarp, which complicates some stratigraphic relations (Olig and others, 1995). It is worth noting here and at the other sites we visit that displacement during these large-magnitude events is typically accommodated in a narrow zone. All of the fault planes in Malde's (1971, 1985, 1987) trench map span a horizontal distance of only a few meters.

The objective of Malde's work, which he clearly proved, was to document that large-magnitude earthquakes occurred here sometime in the past. The stratigraphy exposed in this 15-m-high scarp was interpreted to represent two or more events (Malde, 1971). The earliest event (about 5–6.5 m displacement) occurred when the fan was still active (160 ka) based on the absence of soil on the buried-fan surface. The time of the most recent faulting event was thought to be between 15 and 30 ka (Malde, 1985), based on uranium-series dating of carbonate coats on clasts, which estimates the soil age (23–30 ka) of fan gravels that are displaced by a 3-m-high scarp (Pierce, 1985).

Olig and others (1995) reevaluated the faulting history at this site in 1994 and found evidence of seven surface-faulting earthquakes since deposition of the fan gravels. The age of those gravels was not reevaluated in the 1994 study, so they based their chronology on the 160-ka age for the fan cited by Malde. The composite history of the Arco segment developed by Olig and others (1995) from this site and the one that we drove by earlier suggests that surface rupturing has been episodic with several closely spaced events followed by longer periods of quiescence. Following an initial faulting event, a period of quiescence occurred between 100–130 and 60 ka, followed by two or three faulting events near 58 ka, then another period of quiescence until about 21 ka, when two more closely spaced events occurred. The evidence for these four or five events is in the upper colluvial package

Figure 5. View of southern part of Pass Creek segment from near Darlington. Note the high old scarps above center fence post. Other scarps are apparent as shaded slopes. The range crest is substantially higher along this part of the fault than to the south.

mapped by Malde (1971). The time of the two youngest events is constrained by two nearly identical thermoluminescence ages of 20±4 ka and 21±4 ka from deposits stratigraphically above the most recent event and below the penultimate event, respectively. Interestingly, even though the intervening periods between the events are highly variable, Olig and others (1995) conclude that the displacement per event is fairly uniform.

Mileage Inc.	Cum.	
		Return to cars and proceed north on Hill Road
0.5	6.9	Turn left on 3150 N.
1.6	8.5	Turn right on to U.S. Highway 93.
0.5	9.0	Town of Moore.
5.9	14.9	Darlington, Idaho. The canyon directly east of town is Ramshorn Creek, where the boundary between the Arco and Pass Creek segment is located (Crone and Haller, 1991; Janecke, 1993; Olig and others, 1995). This segment boundary coincides with a down-to-the-north normal fault in the footwall of the Lost River fault (Wilson and Skipp, 1994). Note the significant change in the geomorphic expression of the range. Northward from near Ramshorn Canyon, the range is high, and the mountain front is impressive (fig. 5). In contrast, the Arco Hills to the south are considerably lower and less precipitous. Scarps on alluvium on the Pass Creek segment are short, poorly preserved, and much less continuous than those to the south. However, many of the scarps on the Pass Creek segment are over 20-m high (Olig and others, 1995). To the northeast, there is a prominent embayment in the range front; the fault changes trend by about 70–80° at Elbow Canyon. Although no studies have attempted to evaluate the times of faulting on either side of this prominent change in strike, no one has suggested that this bend might be a segment boundary. In fact, Janecke (1993) states that the cross fault in the footwall that extends up Elbow Canyon has too shallow of a dip to effect rupture propagation.
4.6	19.5	Leslie, Idaho. Jaggles Canyon trench site is located at the range front directly east of Leslie. Olig and others (1995) report evidence for 7–9 surface faulting events at this site; the oldest event is >140-220 ka and 4–5 events are younger than 21 ka based on thermoluminescence ages. Three of these events occurred between 17 and 18 ka; this implies that surface-faulting events occurred on the average every few hundred years during this short time period, as compared to the shortest interval on the Arco segment of about 20 k.y. This highly active period is not evident in the landscape, which Olig and others (1995) suggest is because the fault is at the bedrock-alluvium contact. In contrast to interpretations at the Arco Peak site, faulting here is interpreted to have variable recurrence and variable amounts of displacement per event.
8.1	27.6	Mackay, Idaho. Turn right (east) on Bar Road (the main business street) (lat 43.91485°N., long 113.61261°W.). Bear right 0.4 mi.

The town of Mackay, Idaho, is approximately 5 km southwest of the Pass Creek-Mackay segment boundary. Janecke (1993) characterized the boundary in the footwall of the Lost River fault as a 2.5-km-long, 1-km-wide zone of as many as four faults. At this boundary, the range-front fault changes strike by about 25°. The controlling structure here might be the near-vertical, northeast-striking Paleogene Swauger Gulch fault.

1.3 28.9 Entrance to Mackay town dump (lat 43.91384°N., long 113.59161°W.). Turn right at the southern fence line of the dump. Follow the right fork (not the road along the fence line) to the northeast.

0.9 29.8 At the irrigation ditch, turn due north. Stay on the best road, but make sure you stay on top of the fan. Do not drive into Lower Cedar Creek canyon. There are two ditch crossings farther up the fan. The first is relatively easy to cross; the second (at about 2.5 mi) can be narrow and deep depending on what road you are on. If you do not think you can make the crossing, turn to the southeast along the ditch until you find a suitable crossing (lat 43.95493°N., long 113.58303°W.).

~2.9 32.7 Location of Lower Cedar Creek trenches. South trench (lat 43.96548°N., long 113.58168°W.), north trench (lat 43.96560°N., long 113.58173°W.).

Stop 2. Trench Site on Mackay Segment

One notable characteristic of the Mackay segment (fig. 6) is the high-fan surfaces along this part of the range front. Scott (1982) shows that alluvial deposits on the hanging wall here are older than the majority of valley fill to the south along the Pass Creek segment. The road that we followed to this stop is on middle to lower (?) Pleistocene alluvium; to the north of the road, a higher deposit is identified as being possibly as old as Pliocene. Lower Cedar Creek is entrenched into the fan surface about 10 m below the trench site.

The morphology of the scarps clearly suggests a young (Holocene) age, in contrast to our previous stop, and the size of the scarps suggests multiple-faulting events. Trenches excavated in the 1980s extended across the prominent graben at this site. An earlier trench, excavated by M.T. Hait at this location, showed evidence of at least one surface rupture that postdates Glacier Peak ash (11.3 ka in Schwartz and Crone, 1988). To the north, near Lone Cedar Creek, two faulting events were recognized, one that predates and one that postdates Mazama ash (6.7 ka) (Schwartz and Crone, 1988).

Mileage
Inc. Cum.

5.1 0.0 Return to intersection of Bar Road and U.S. Highway 93 in Mackay. Turn right (north) on U.S. Highway 93. RESET TRIP ODOMETER.

3.0 3.0 Bedrock in valley and old high fan (lat 43°56.662'N., long 113°39.163'W.).

Figure 6. View of Mackay segment looking northwest from U.S. Highway 93. Right edge of photo is at the approximate location of the Pass Creek-Mackay segment boundary. The next drainage northward is Lower Cedar Creek (Stop 2). The farthest high peak is Leatherman Peak (elev. 3,737 m).

1.6 4.6 Entrance to Mackay Reservoir (picnic area and restrooms).

3.4 8.0 Gravel pit on west side of the highway offers a good view of the northern Mackay segment. Leatherman Peak (elev. 3,727 m), on the skyline (fig. 6), is the second highest peak in the Lost River Range. Below it is Lone Cedar Creek, the location of the trenching study briefly discussed at the last stop. The large alluvial fan at the mouth of Lone Cedar Creek canyon is upper Pleistocene in age according to Scott (1982), and based on the poor degree of soil development and relation to moraines and outwash, it probably has an age that is equivalent to Pinedale (about 15 ka). We cross the segment boundary between the Mackay and the Thousand Springs segments in the next few miles. Notice the pronounced change in the trend of the range front as we proceed northward.

7.0 15.0 Trail Creek road intersection.

1.2 16.2 (lat 44.08419°N., long 113.84184°W.) Cautiously pull off to the left side (southwest) of the highway.

Stop 3. Overview of Borah Peak Epicenter

This stop provides a good view (fig. 7) of the spatial relations of a number of geologic effects caused by the Borah Peak earthquake. Looking south-southwest, the 1983 epicenter was directly below the low hills on the far side of the valley (about 13 km from where we stand). Turning a little to the east and looking toward the intersection of Trail Creek Road and the highway, we can see general area that was deformed by a lateral spread. The deformation was confined to the lower part of the alluvial fan. Fissures at the head of the lateral spread were subparallel to topography, as much as 1-m wide and 3-m deep, and extended from Trail Creek Road to near Whisky Springs, about 1.5 km to the south (Youd and others, 1985). Most of the fissures were west of the highway, but locally they disrupted the highway grade.

To the southeast, the mountain front swings eastward out of sight as the trend of the Lost River Range front changes direction by about 55°. At this location near Elkhorn Creek, low, uphill-facing scarps formed in 1983, probably due to gravitational failure in response to violent ground shaking (see fig. 11 in Crone and others, 1987). Wallace and Bonilla (1984) identified similar features near the crest of the Stillwater Range, in the general vicinity of the 1954 Dixie Valley earthquake and the 1915 Pleasant Valley earthquake. Interestingly, uphill-facing scarps existed before the 1983 earthquake, and the scarps we see today are the result of more than one earthquake. The uphill-facing scarps are the southernmost ruptures from the 1983 earthquake, and thus define the approximate location of the segment boundary (fig. 7). This earthquake, like many in the intermountain west, produced a unilateral rupture that extended northwestward from the epicenter along the range front, across the flank of Dickey Peak, and beyond the Willow Creek hills to the north.

The structure exposed in the footwall of the Lost River fault at this segment boundary is complex. The zone of deformation is 10-km long (parallel to the Lost River fault) by 2- to 4-km wide (Susong and others, 1990; Janecke, 1993). Although many cross faults (Susong and others, 1990; Janecke, 1993) and subparallel normal faults (Susong and Bruhn, 1986) are mapped in the footwall near the southernmost ruptures, it is likely that few of them coincide with the segment boundary at hypocentral depths (Janecke, 1993). The prominent northeast-striking Elkhorn Creek, Leatherman Pass, and Mahogany Creek cross faults are far from the epicenter when projected downward (see fig. 4 in Janecke, 1993).

During the Borah Peak earthquake, this segment boundary stopped rupture propagation to the southeast. Aftershocks, which covered a 75 x 10 km area, occurred only north of the main shock (Richins and others, 1987). The segment boundary coincides with a gravity high (Mabey and others, 1974), which is interpreted to be a horst below the modern flat valley floor

Figure 7. Panoramic (nearly 360°) view of Thousand Springs Valley from Stop 3. Labeled features are discussed in the text.

(Skipp and Harding, 1985). The valley fill is thin over this bedrock block (60 m) compared to elsewhere in the valley (up to 1 km). The horst is expressed at the surface by outcropping Mississippian White Knob limestone of Chilly Buttes.

During the 1983 earthquake, Chilly Buttes was the site of unusual ground-water phenomena. In the flat alluvium surrounding the buttes, violent eruptions of ground water created sand boils, and artesian flow from bedrock on the flanks of Chilly Buttes caused local flooding (Wood, 1985). Water and sand in the sand boils were reported to have erupted as much as 6 m into the air. Remains of these eruptions include at least 47 craters, 19 of which are more that 6 m in diameter, and the largest being about 22 m in diameter and 5-m deep. Some craters apparently existed prior to 1983 (Breckenridge, 1985; Waag, 1985) and at least one was active following the Hebgen Lake earthquake (Youd and others, 1985). Erupting water from fractured bedrock on the flanks of Chilly Buttes (Waag, 1985) required as much as 35 m of artesian head and continued for about 48 hours following the main shock. The large volume of water erupted resulted in localized flooding northwest of where we stand.

Mileage Inc.	Cum.	
		Proceed north on U.S. Highway 93.
2.5	18.7	Old Chilly road.
0.9	19.6	Turn right on Cedar Creek access road (to Borah Peak), just past gravel pit (lat 44.11743°N., long 113.88869°W.). The 1983 scarps near Cedar Creek are visible on the treeless slope at the base of the range beyond the curve in the road. This slope is underlain by a Pinedale-equivalent left-lateral moraine that was left by a glacier that flowed down Cedar Creek.
2.8	22.4	Take right fork in road and park (lat 44.13370°N., long 113.84039°W.).

Stop 4. Birch Springs Landslide and 1983 Fault Scarps on the Thousand Springs Segment

(modified from Crone, 1985)

One of the largest landslides that formed in response to the severe ground shaking is located at Birch Springs. The failure of a Bull Lake-equivalent (?) (K.L. Pierce, 1985, written commun.) moraine resulted in a complex rotational slump, near the headwall, that grades downslope into debris flows. The 100,000-m^3 debris flow covered about 4 hectares; the headwall is about 250-m long and as much as 5-m high. Additional subparallel cracks can be found upslope from the headwall. The upper 50 m of the landslide deposit consists of back-rotated slump blocks, but farther downslope the mobilized material is more disaggregated and within about 100 m of the headwall, the landslide consists of four debris-flow lobes. These debris flows bury the fault scarp showing that they postdate the surface rupture. The velocity of the debris flow was estimated at several tens of meters per hour based on splash marks on trees observed to be 1.2 m above the ground surface (Crone, 1985). Based on pre-1983 aerial photography, a preexisting landslide was present prior to the Borah Peak earthquake (Breckenridge, 1985).

The modern fault scarps also are superimposed on preexisting scarps. One can see the rounded crest of the old scarp above the free face of all the scarps that form the graben near the parking area. We will see similar relations, although not necessarily as well expressed, at the next stop to the north. The trail to Borah Peak closely follows the fault scarp; the landslide headwall scarp can be found uphill of the trail.

Mileage Inc.	Cum.	
2.8	25.2	Return to U.S. Highway 93 and proceed north.
1.8	27.0	Turn right onto Doublespring Pass road (lat 44.14020°N., long 113.90488°W.). Two prominent signs are located at a pull out at the northeast corner of this intersection. One describes Borah Peak, which was named for

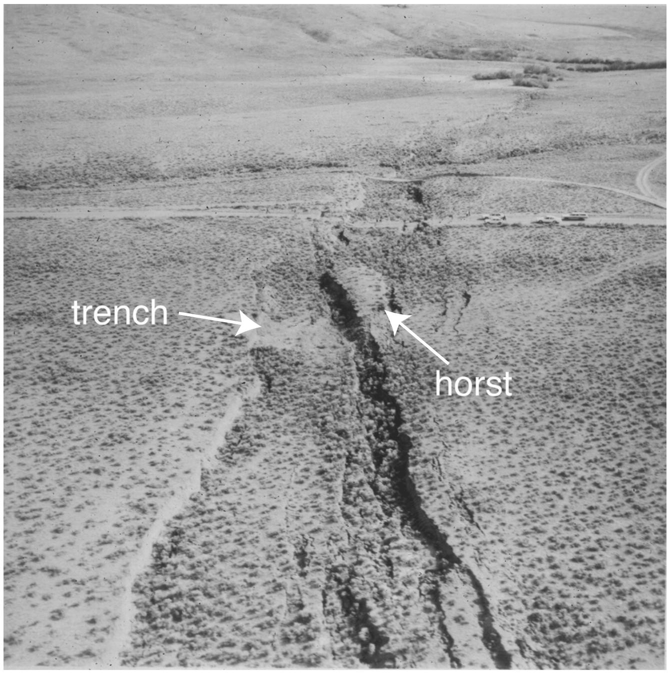

Figure 8. Oblique aerial photograph of surface faulting and location of trench that was excavated before the 1983 earthquake near Doublespring Pass road, view is to the southwest. Note the complex pattern of horsts and grabens that formed on this Pinedale-age alluvial fan. Photograph by R.E. Wallace, November 3, 1983.

William E. Borah, a U.S. Senator for Idaho from 1907 to 1940. The other sign describes the Borah Peak earthquake.

2.5 29.5 Park at U.S. Forest Service interpretive site. There are picnic facilities and a restroom here.

Stop 5. Doublespring Pass Trenches and Fault Scarps of the Thousand Springs Segment

The Doublespring Pass road crosses the 1983 fault scarps about 2.5 km east of the U.S. Highway 93, where the fault scarps cross the broad alluvial fan of Willow Creek. The scarps are nearly as spectacular today as they were 20 years ago. We will discuss the complex surface rupture at this location and visit the site of two exploratory trenches, one excavated prior to the earthquake, the other after the earthquake. The 1983 scarps span a zone that is as much as 35-m wide and contains prominent horsts, grabens, and stair-step scarps (fig. 8). Individual scarps are just a few centimeters to 5-m high; the largest scarp reported is located about 360 m northwest of the old Doublespring Pass road. Notice as you walk around that some of the cracks are still open to a depth of
1–2 m. The U.S. Forest Service erected an interpretive site where the fault scarps crossed the original Doublespring Pass road (fig. 9). It appears that the scarps have faired far worse inside the fence than outside its perimeter.

The Willow Creek fan generally is thought to have stabilized soon after the most recent glacial cycle (about 15 ka according to Pierce and Scott, 1982). The scarps that cross this fan are composite scarps that result from two surface-rupturing events. This is evident at many locations because the crests of the scarps are rounded ("beveled") above the abrupt near-vertical free face. This morphology has long been used as evidence of multiple-faulting events. However, it is important to note that, even though several thousands of years (maybe as many as 11 k.y.) elapsed between faulting events, the bevel is only locally preserved on the fault scarps. The relations of significantly different scarp heights on deposits of various ages, however, is clearly demonstrated here, and provide better proof of multiple movements. If you walk over to the modern Willow Creek flood plain, you will see only the 1983 scarp, which is about 2.5-m high on these young fluvial deposits; whereas, on the older (Pinedale-equivalent), higher fan deposits, the scarps are about twice as high.

Trenching studies (fig. 8) conducted at this location are unique. A trench (lat 44.16587°N., long 113.87034°W.) was excavated in 1976 about 45 m northwest of the road (Hait and Scott, 1978; M.H. Hait in Crone, 1985), and during the Borah Peak earthquake, the back-filled trench was exposed in the newly formed near-vertical free faces. The trench was reexcavated and mapped in 1984 (Schwartz and Crone, 1985)

Figure 9. Photograph of Doublespring Pass road following the Borah Peak eathquake, view to the northeast. Notice the numerous scarps that distribute deformation over a relatively wide zone. Photograph taken by M.N. Machette (U.S. Geological Survey Archive no. 40) on November 9, 1983.

because of this unique opportunity. Figure 10 shows simplified trench logs from the two studies. The logs show that faulting in 1983 closely mimicked the amount and style of prehistoric faulting (Schwartz and Crone, 1985). The prominent horst block, which is abruptly truncated by the post-1983 excavation (fig. 8), within the graben was present prior to the Borah Peak earthquake. Displacement reactivated these subsidiary faults and enhanced topographic relief. Stratigraphic relations show that the amounts of 1983 displacements were similar to those associated with the earlier earthquake; total displacement in 1983 was 174–198 cm and 126–150 cm in the prehistoric event (Schwartz and Crone, 1985). These similarities strongly suggest that the prior paleoearthquake had a magnitude that was similar to the 1983 event. Thus, it appears that the model of the characteristic earthquake (Schwartz and Coppersmith, 1984) fits here. We do not know, however, if the temporal characteristics of faulting are as regular as the displacement characteristics.

At the north end of the Willow Creek fan, the surface ruptures extend northward around the east side of a bedrock block known as the West Spring block (Skipp and Harding, 1985; Plate 1 in Crone and others, 1987). Skipp and Harding (1985) offer a couple of explanations for the origin of this block:

"The West Spring block contains folded, fractured, and sheared limestones of the Upper Mississippian Scott Peak Formation. These rocks have been dropped down at least 200 m to the west into the Thousand Springs Valley along the Lost River fault zone against folded and sheared beds of the upper part of the Lower Mississippian McGowan Creek Formation. The West Spring block may be either slide block resting in part on valley fill, or a down dropped tectonic sliver caught in a broad zone of range-front faults…..The West Spring block appears to be a part of the Lost River thrust plate, not a structurally higher plate such as the White Knob, and, in this respect does not resemble slide blocks on the west sides of the Lemhi Range and Beaverhead Mountains (Beutner, 1972; Skipp and Hait, 1977) that are down dropped fragments of structurally higher thrust sheets."

Mileage Inc.	Cum.	
2.5	32.0	Return to U.S. Highway 93 and proceed north.
4.7	36.7	Turn right on Arentson Gulch access road.
0.4	37.1	Park near gate for Stop 6.

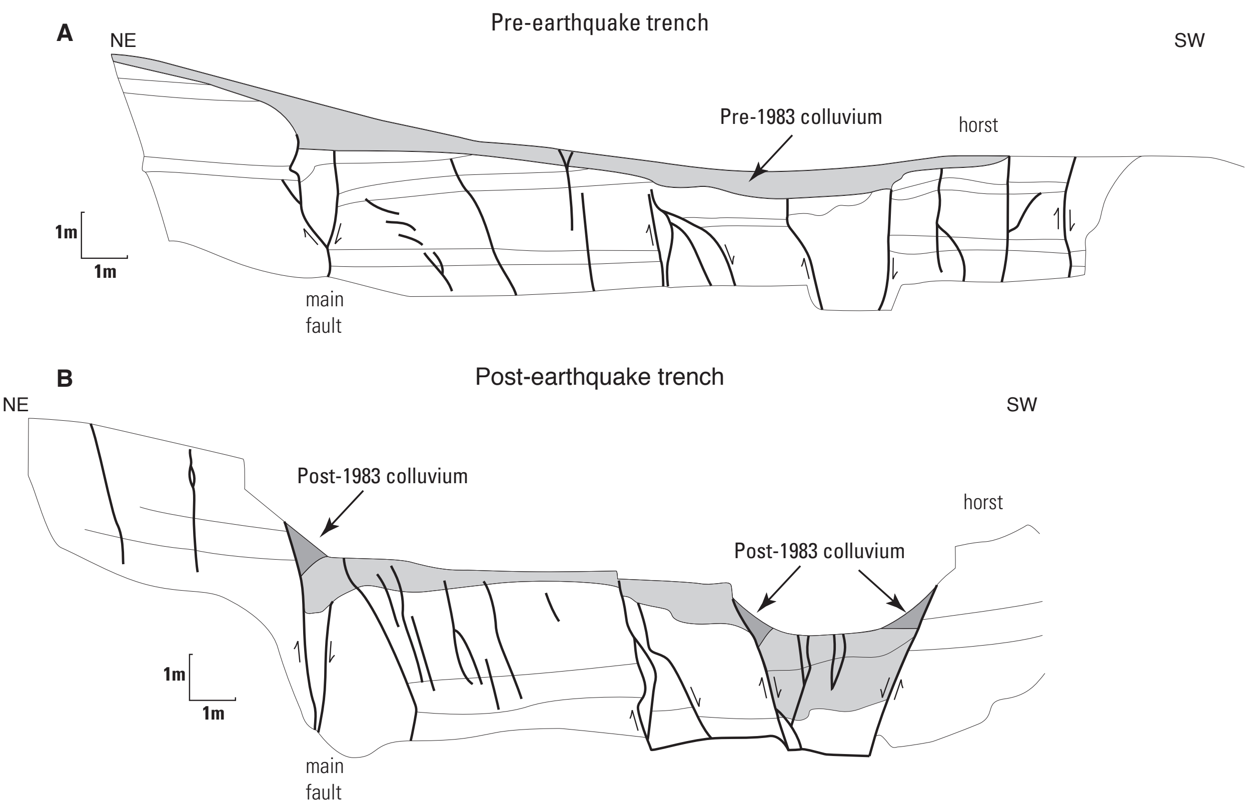

Figure 10. Simplified trench maps from site near Doublespring Pass road. (A) Map of the trench excavated in 1976 by M. T. Hait (modified from Crone, 1985). (B) Map of trench that was excavated in 1984 after the Borah Peak earthquake.

Stop 6. Dickey Peak and the Northern End of the Thousand Springs Segment

From this location, the fresh scarps cross the flank of Dickey Peak. They appear as tan lineaments crossing scree slopes fairly high on the mountain face. This is one of the few places along the surface rupture where the fault plane was exposed in bedrock; there were at least two sets of slightly weathered slickensides preserved. None of the slickensides appeared to be fresh enough to be from the 1983 earthquake, but collectively they show that past movements had both left- and right-lateral slip components at this site.

The hills to the north are the Willow Creek hills, and at 2,200 m, they form a drainage divide and are the highest point in the valley floor. They separate the south-flowing Big Lost River and its tributaries in the Lost River Valley from the north-flowing Warm Spring Creek and its tributaries in Warm Spring Valley. This ridge of transverse bedrock hills is believed to be the topographic expression of the northern boundary of the Thousand Springs segment. These hills are only 20 km from the highest point in the Lost River Range, Borah Peak.

Following the Borah Peak earthquake, rupture propagation slowed, and a large number of aftershocks concentrated near the Willow Creek hills. This segment boundary seems to be complex in the subsurface (Bruhn and others, 1991); the aftershocks sequence suggests that the overall geometry of the surface faulting directly reflects structure at depth. Detailed analysis of the aftershocks shows that they occurred in discrete zones less than 1 km in width between 6 and 10 km below the surface (Shemata, 1989). In part, the arrest of the rupture propagating at depth may be controlled by the Mahogany Creek fault, which is mapped as a northeast-trending, normal fault that daylights near the southern boundary of the Thousand Springs segment (Janecke, 1993). Janecke (1993) suggests that if the northeast-striking Mahogany Creek fault dips 50° to the northwest, it would then intersect the Lost River fault at 10–15 km depth near the Willow Creek hills. This interpretation reinforces the concept that 2-dimensional mapping is not sufficient to prove or disprove what structures may control the initiation or termination of rupture; the critical fault intersections are those at seismogenic depth.

Additionally, the sequence of aftershock activity suggests that there were notable differences in rupture propagation in the area near the Willow Creek hills. Twelve hours after the Borah Peak earthquake, intense aftershock activity began in this area, suggesting that strain was concentrated at the segment boundary. All of the largest aftershocks located here had large stress drops (Boatwright, 1985). About one month after the Borah Peak earthquake, the rate of aftershock activity increased to the north along the Warm Spring segment.

The 1983 scarps are obvious across the south side of the Willow Creek hills; here, the rupture diverged northwestward away from the main range front, leaving a 4.8-km-long gap in surface faulting along the Lost River fault (see “1983 Gap” on fig. 4). From a location along one of the tributaries of Arentson Gulch, and within 100 m of the surface rupture on the Willow Creek hills, we have the following eyewitness account:

> *“Lawana Knox of Challis, Idaho, witnessed the formation of a fault scarp during the M_s 7.3 earthquake of 28 October 1983 along the Lost River Range, Idaho. The earthquake occurred at 8:06 a.m. local time (1406 UTC) while Mrs. Knox was hunting with her husband, William Knox.*
>
> *Mrs. Knox was sitting at a point along a fork of Arentson Gulch…and was watching the southwest-facing slope down which she expected to see her husband driving elk. As she watched, the fault scarp formed before her eyes. At the closest point, the scarp was about 300 m away, but she could clearly see the scarp for at least 1 kilometer both to the northwest and to the southeast. Mr. Knox was on the hill north of and above the fault scarp.*
>
> *Mrs. Knox reported that the 1- to 1.5-m-high scarp formed in about 1 second. She reported that the scarp reached its full height quickly, and that it did not appear to adjust up or down later or oscillate up and down while reaching its full height.*
>
> *Mrs. Knox reported that the scarp did not form until the peak of strong shaking was beginning to subside. Upon being asked how long the strong shaking lasted, Mr. Knox replied, “about a minute.” Mrs. Knox disagreed and said, “it might have been a half a minute, but it felt like a lifetime.” Both Mr. and Mrs. Knox said the earthquake started with noise and that “the earthquake came from the south, from the direction of Borah Peak.” After the first sensations, the ground shook harder and harder, and only after the shaking started to subside or ease did Mrs. Knox see the scarp form.”*

—from Wallace (1984)

This eyewitness account provides some intriguing information. Wallace (1984) infers from his discussions with Mr. and Mrs. Knox that the fault scarp formed within a few seconds and propagated from northwest to southeast, which is contrary to the direction of rupture propagation along the Lost River fault from southeast to northwest. In addition, he believes this part of the surface rupture occurred maybe 10 seconds after strong shaking began. There are few eyewitness accounts of this nature, and their words provide us with another unique perspective of the earthquake.

Optional Stop. Prehistoric Fault Scarp in the “1983 Gap”

Proceed north on the Arentson Gulch road (you will encounter several gates along the way—Please leave them as you find them). This side trip does not venture far from the highway, but the road is locally impassable when wet.

Mileage Inc.	
	Left turn through gate.
1.6	Gate.
0.6	Stay left.
0.4	Turn right. In 0.1 mi the road will cross the fault scarp and in another 0.2 mi, the northern end of the rupture on the Thousand Springs segment is visible to the right.
0.6	Challis National Forest boundary (lat 44.24678°N., long 113.92425°W.).
0.1	Turn right.
0.2	Prehistoric fault scarp.

This fault scarp did not rupture during the Borah Peak earthquake. We are in a 4.8-km-long gap, the previously mentioned "1983 Gap", between the historic scarps of the Thousand Springs segment and the Warm Spring segment to the north. The scarp here is older than the Holocene scarps of the Warm Spring, Thousand Springs, and the Mackay segments (Crone and others, 1987). Thus, surface rupture of this short part of the fault has not occurred in the past three events on the Warm Spring or Thousand Springs segments. The scarp is 3–5 m high with a maximum slope angle of 9–11°. Based on comparative geomorphology, the scarp is most likely older than 15 ka (Crone and others, 1987).

Mileage Inc.	Cum.	
		Return to U.S. Highway 93 and proceed north.
2.7	39.8	Willow Creek Summit (lat 62.73719°N., long 113.97530°W.).
2.8	42.6	Pull off highway (lat 64.73769°N., long 114.00864°W.)

Stop 7. Overview of Warm Springs Segment

As we look down valley to the north, the end of the 1983 ruptures is less than 1 km south of McGowan Creek at the end of the prominent mountain front. The preponderance of evidence, geologic, geodetic, and seismologic, suggest that rupture of the Warm Spring segment following the Borah Peak earthquake was in the form of secondary slip. The amount of vertical offset (fig. 4) along this segment was substantially less than to the south, scarps were less continuous, and there was one report that indicates movement may have occurred on this segment many hours after the main shock. Most of the reported surface ruptures were on two approximately 3-km-long parts of the fault. The southern one extended from the northern end of the "1983 Gap" to about 1.5 km southeast of Gooseberry Creek. The northern one extended between Gooseberry Creek and McGowan Creek. The southern part of the rupture generally had net vertical offsets of 60–110 cm. Along the northern rupture, net vertical offsets rarely exceeded 20 cm (fig. 4).

To the west of the pull out, small ruptures formed on preexisting scarps of the Lone Pine fault. The Lone Pine fault is antithetic to the Lost River fault and probably intersects it at depth (Jackson, 1994). There has been no geologic characterization of the Lone Pine fault; however, fault scarps are clearly evident along the part of the fault that is not covered by a tree canopy.

Mileage Inc.	Cum.	
		Return to U.S. Highway 93 and proceed north. Turn right on Gooseberry Creek access road.
1.1	43.7	Fence (lat 44.31074°N., long 113.98858°W.).
1.1	44.8	Turn right (lat 44.30039°N., long 114.01429°W.).
1.5	46.3	Fence (lat 44.31074°N., long 113.98858°W.).
1.4	47.7	Gooseberry graben (lat 44.31348°N., long 113.97813°W.).

Stop 8. Characteristics of Scarps on the Warm Spring Segment

The 1983 ruptures on the Warm Spring segment consist of minor, nearly continuous ruptures (<1 m) on prehistoric scarps (up to 5.7-m high) (Crone and Haller, 1991). The morphology of prehistoric scarps on the Warm Spring segment is similar to Holocene scarps on the Mackay segment. Their size suggests that the prehistoric earthquake that formed them typically produced scarps that were much larger than seen in 1983.

At Gooseberry Creek, surface faulting has formed a graben that is similar to the grabens we visited on the Mackay segment and at Doublespring Pass road. The graben here is 0.5-km wide and contains as many as four antithetic and synthetic scarps. Only small (<5 cm), isolated scarps formed in 1983; thus, the vertical offset of 4 m here occurred in prehistoric time.

Two trenches were excavated near the ends of the Warm Spring segment (about 7.5 km apart) that suggest a prehistoric surface-rupturing event occurred shortly before 5.5-6.2 ka (Schwartz and Crone, 1988). No other surface faulting events have occurred since about 12 ka.

Mileage

Inc.	Cum.	
		Return to U.S. Highway 93 and proceed north.
1.1	48.8	Entering bedrock exposed in valley near Warm Spring-Challis segment boundary.
1.7	50.5	Entering Grand View Canyon. The highway extends for more than 5 mi through Mississippian McGowan Creek Formation and the Devonian Grand View and Jefferson Dolomites.
		Note the pronounced change to a subdued range front with low relief where the road rises to the top of the alluvial-fan sequence. This morphology is typical of the Challis segment. The low hills in the foreground are bounded on both sides by down-to-the-west faults.
		The Devil Canyon earthquake (M 5.8) occurred in this general area on August 22, 1984, and is considered to be a late aftershock of the Borah Peak earthquake. Its epicenter is near the segment boundary between the Challis and Warm Spring segments. Jackson (1994) places the epicenter just north of the Challis-Warm Spring segment boundary, near the northern end of the mapped surface rupture of the Borah Peak earthquake. At least 50 aftershocks greater than M 3.0, five greater than M 4.0, and one M 5.0 occurred in the following month (Jackson, 1994); some of the aftershocks were on the Lost River fault and some on the east-dipping Lone Pine fault on the west side of the valley.
10.1	60.6	Hot Springs road. Pull off on right provides a good view the Challis segment. Ahead is Challis, the end of the trip.

Stop 9. View of Challis Segment

This view of the Challis segment (fig. 11) illustrates the basis for assigning a low activity rate on the northern Lost River fault. Here the range is characterized by low topographic and structural relief. The fault is not marked by scarps on alluvium, and its location is poorly constrained by the bedrock-alluvium contact; likewise, the faulting history is poorly understood. There is no evidence of late Quaternary

Figure 11. View of Challis segment from Hot Springs road, south of Challis, Idaho. Note the subdued topography of the range front, which indicates that the slip rate on this segment of the Lost River fault is considerably lower than the rate on segments to the south.

(<130 ka) movement (Scott and others, 1985), and the slip rate is suspected to be an order of magnitude lower than other parts of the fault. It is obvious from the overall geomorphology, that the activity rate of this segment is substantially lower than any of the segments to the south.

Summary

The Lost River fault is one of the best-expressed segmented faults in the intermountain west. The Holocene record of surface ruptures on the central three segments of the fault provides a picture of characteristic behavior that indicates thousands of years between faulting events. However, where longer records are available, as for the two southern segments, the most recent faulting events may not be regularly spaced in time and may vary in size and rupture different parts of the fault. The episodic character of surface-rupturing events along the southern segments, and the exceedingly high variability in slip rates over the course of 4–7 events may be the rule rather than the exception. We do not have a similarly long record for the central and northern parts of the fault and, thus their long-term behavior remains unknown.

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