LANDSLIDES IN THE BORAH PEAK, IDAHO EARTHQUAKE OF 1983

by

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INTRODUCTION

At 8:06 a.m. MDT (14:06 GMT) on October 28, 1983, a large earthquake occurred in a mountainous region of east central Idaho. Preliminary determinations established the magnitude as $M_s = 7.3$ ($m_b = 6.2$) and located the epicenter at 44.046°N, 113.887°W. (John H. Minsch, National Earthquake Information Service, Golden, Colorado, oral communication, Nov. 30, 1983). The earthquake was associated with at least 33 km of surface faulting along the western flank of the Lost River Range. The fault rupture, which extended from near Elkhorn Creek on the south to near McGowan Creek on the north (Figs. 1 and 2), had a maximum of about 2 m of primarily normal slip with a small component of left lateral slip (M.G. Bonilla, oral communication, Nov. 30, 1983).

This report describes landslides and related ground-failure effects that were observed after the earthquake. Observations were made from a small fixed-wing aircraft on October 31 and November 8 and on the ground from October 30 to November 9. Ground-based field studies included automobile traverses over most roads in the epicentral region and traverses of selected areas on horseback or on foot.

GEOLOGY, TOPOGRAPHY, AND POPULATION

The earthquake triggered landslides and other ground failures in the Lost River, Boulder, White Knob, and eastern Salmon River Mountains, and in the valleys between these mountains (Figs. 1 and 2). The mountains are steep and rugged with many bare rock slopes and extensive talus deposits as well as areas mantled with glacial deposits and colluvial and residual soils of variable thickness and composition. Many slopes at high altitudes have been glaciated. The Lost River Range contains Borah Peak, the highest in Idaho, which rises approximately 1650 m above the adjacent valley floor to an altitude of 3859 m.

Well-indurated, Paleozoic (Ordovician to Pennsylvanian) sedimentary rocks--dolomite and limestone with lesser amounts of quartzite, shale, argillite, siltstone, and sandstone--predominate in the Lost River Range except in the northern and east-central parts (McIntyre and Hobbs, 1978; Rember and Bennett, 1979a, b, d). Where we observed these Paleozoic rocks, they contained few conspicuous fractures or open joints. The northern and east central parts of the range are composed of generally less-indurated volcanic rocks--basalt, andesite, rhyodacite, breccia, tuff, and volcaniclastic sediment of the Tertiary Challis Volcanics (McIntyre and Hobbs, 1978; Rember and Bennett, 1979 a, b), which are characterized by abundant

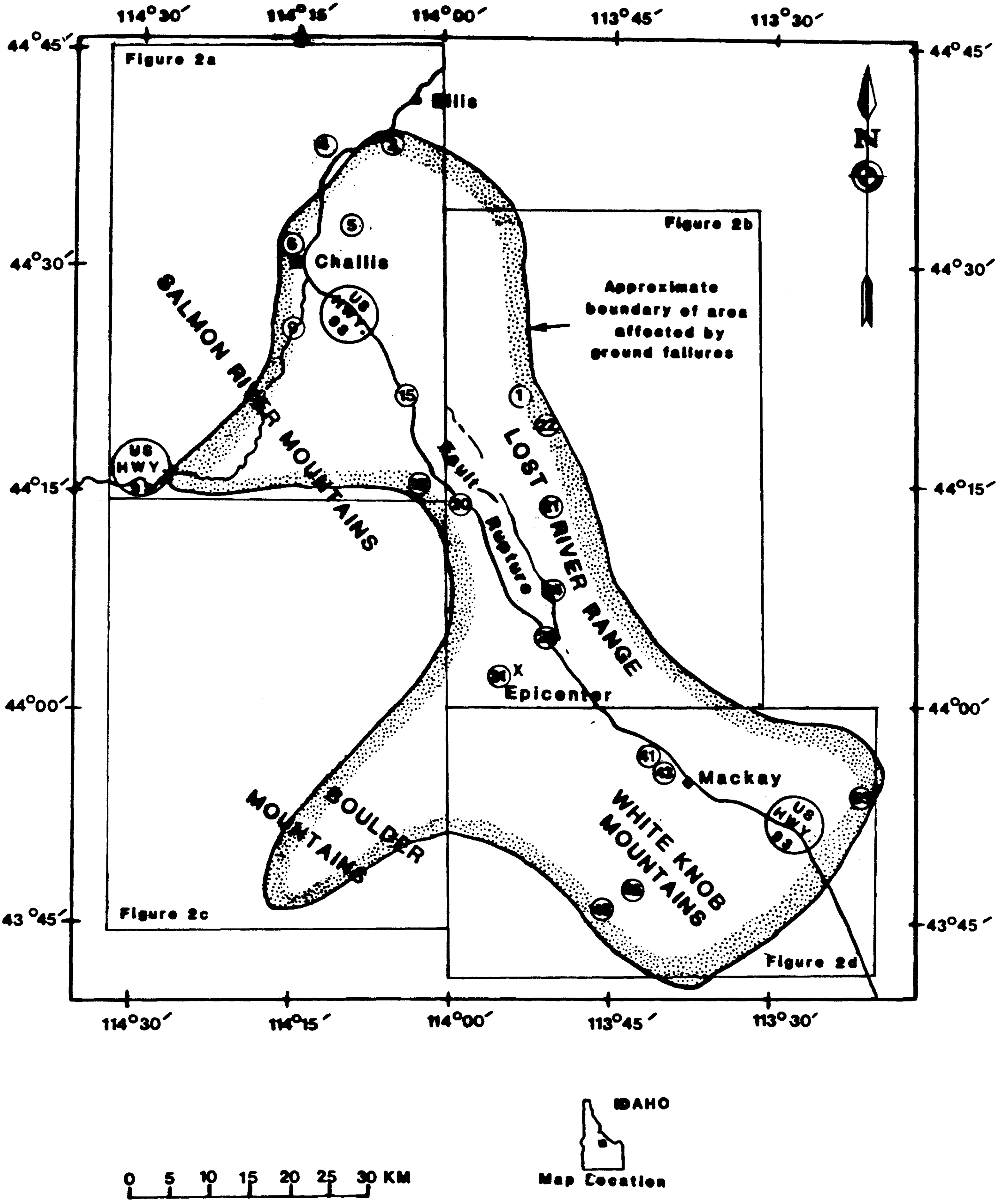

Figure 1. Index map showing areas of Figures 2a.-d., approximate boundary of area affected by earthquake-induced ground failures, major mountain ranges, epicenter, fault rupture, major highway (U.S. 93), and localities described in text (numbered circles).

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Figure 2. Maps showing localities of ground failures.

EXPLANATION

●	Rock fall(s) and (or) rock slide(s)
✪	Mud flow or debris flow
▲	Slump and(or) cracks
■	Soil liquefaction phenomenon
◆	Other type of ground failure
/	Lack of ground failure from apparently susceptible slope
44	Locality number
?	Association with earthquake uncertain
★	Epicenter
— - —	Fault scarp (from Lienkaemper and Bonilla, unpublished data)
Note:	Ground-failure localities without numbers were observed only from the air.

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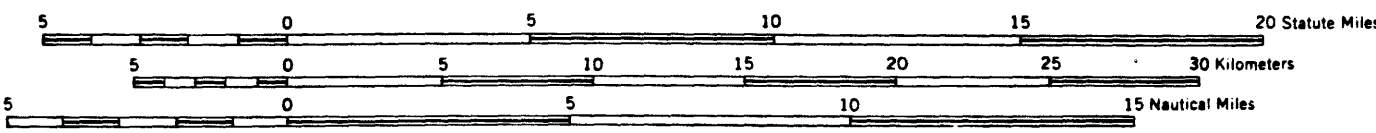

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

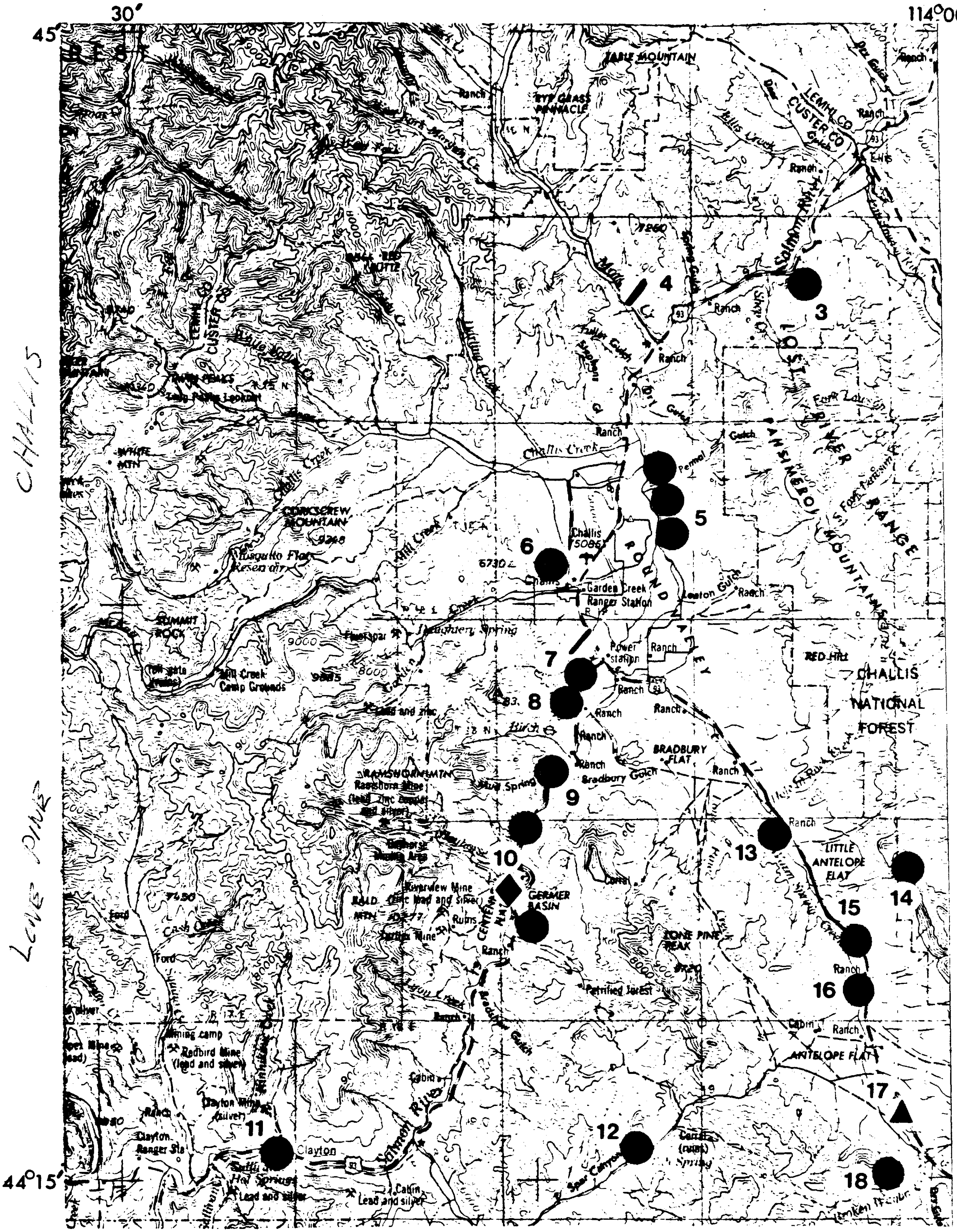

Figure 2a. Northwest part of affected area.

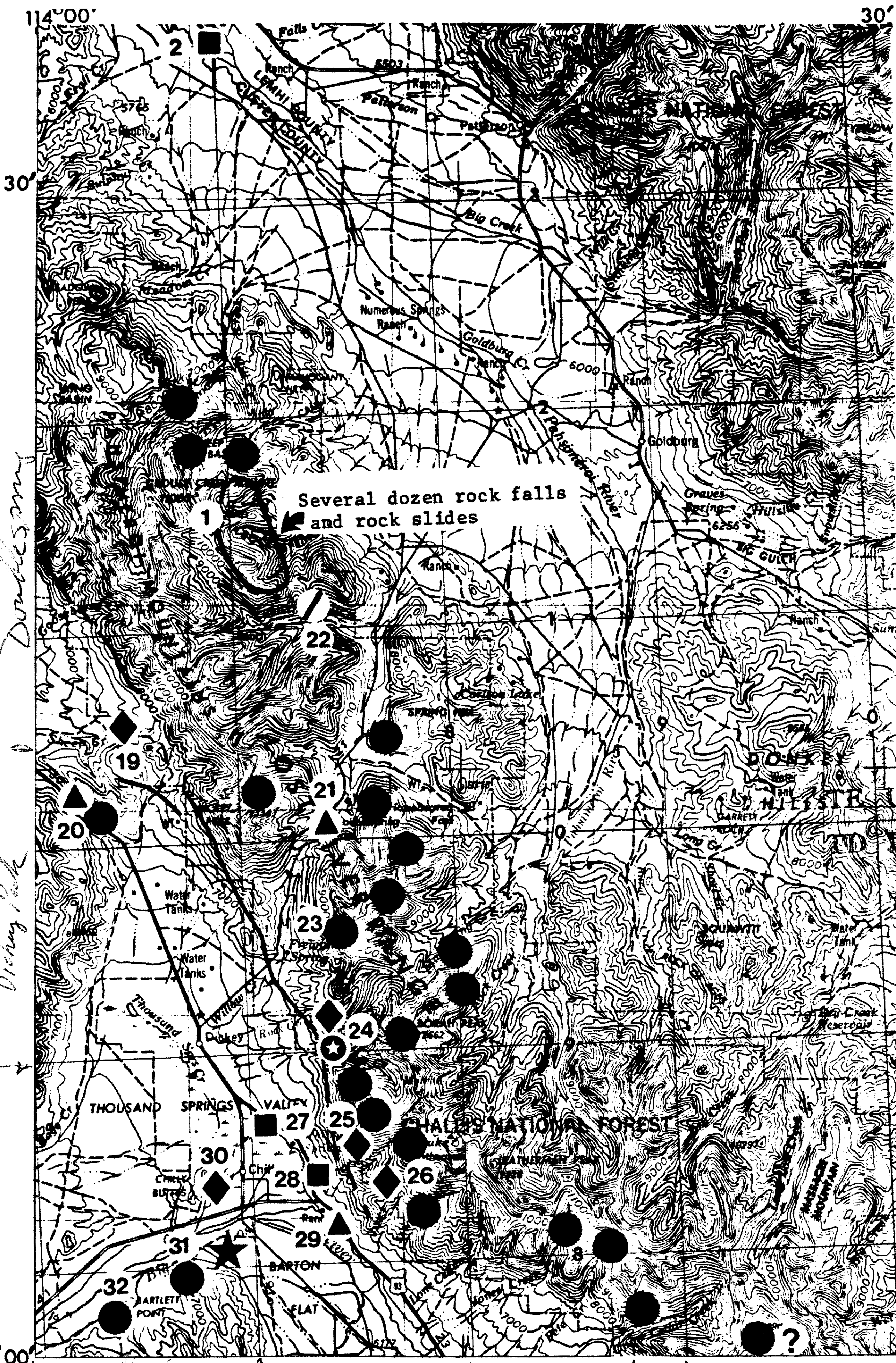

Figure 2b. Northeast part of affected area.

Dickey Peak

C, L, E

L, E, C

L, E

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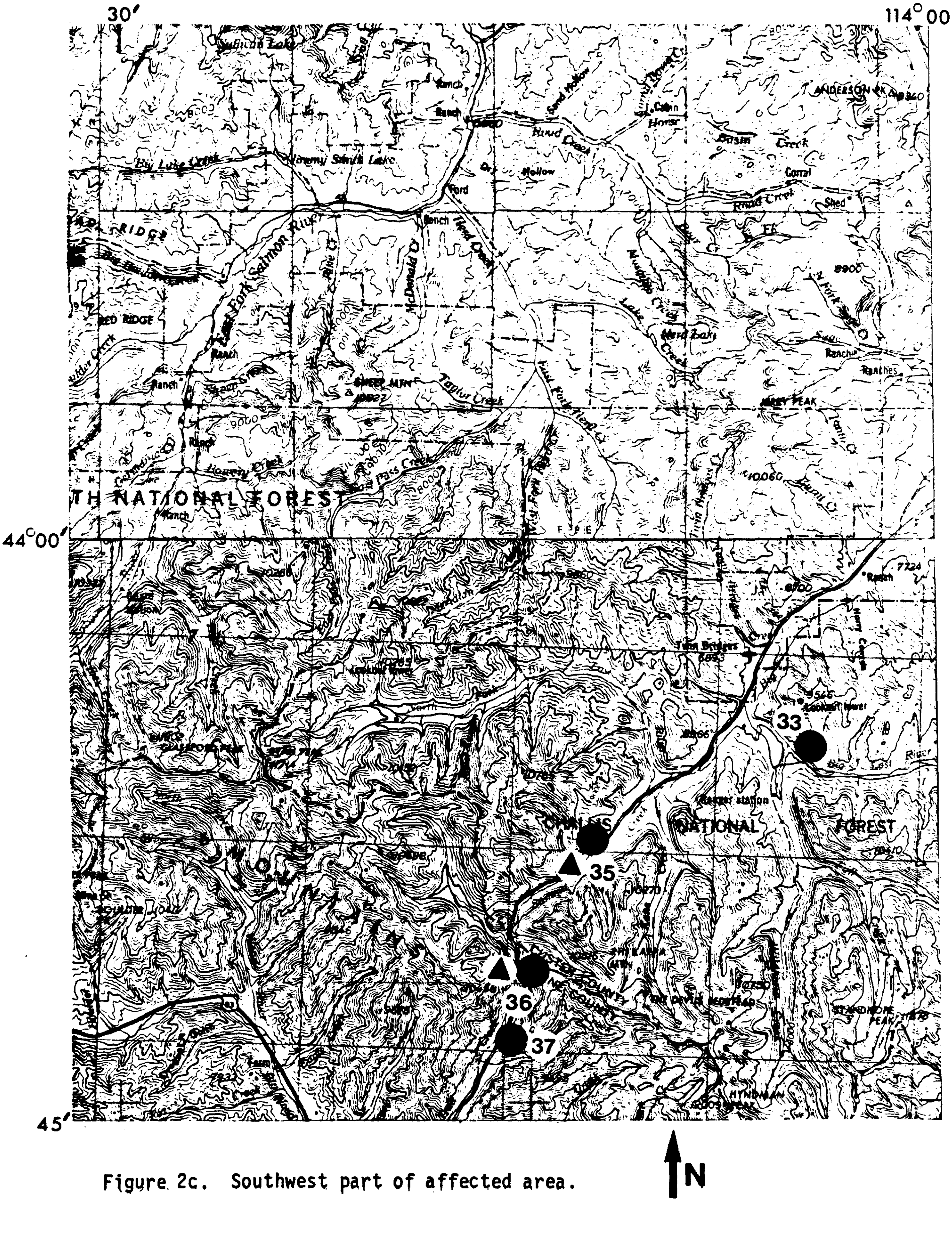

Figure 2c. Southwest part of affected area.

copper Basin Cr?

Mackay Creek?

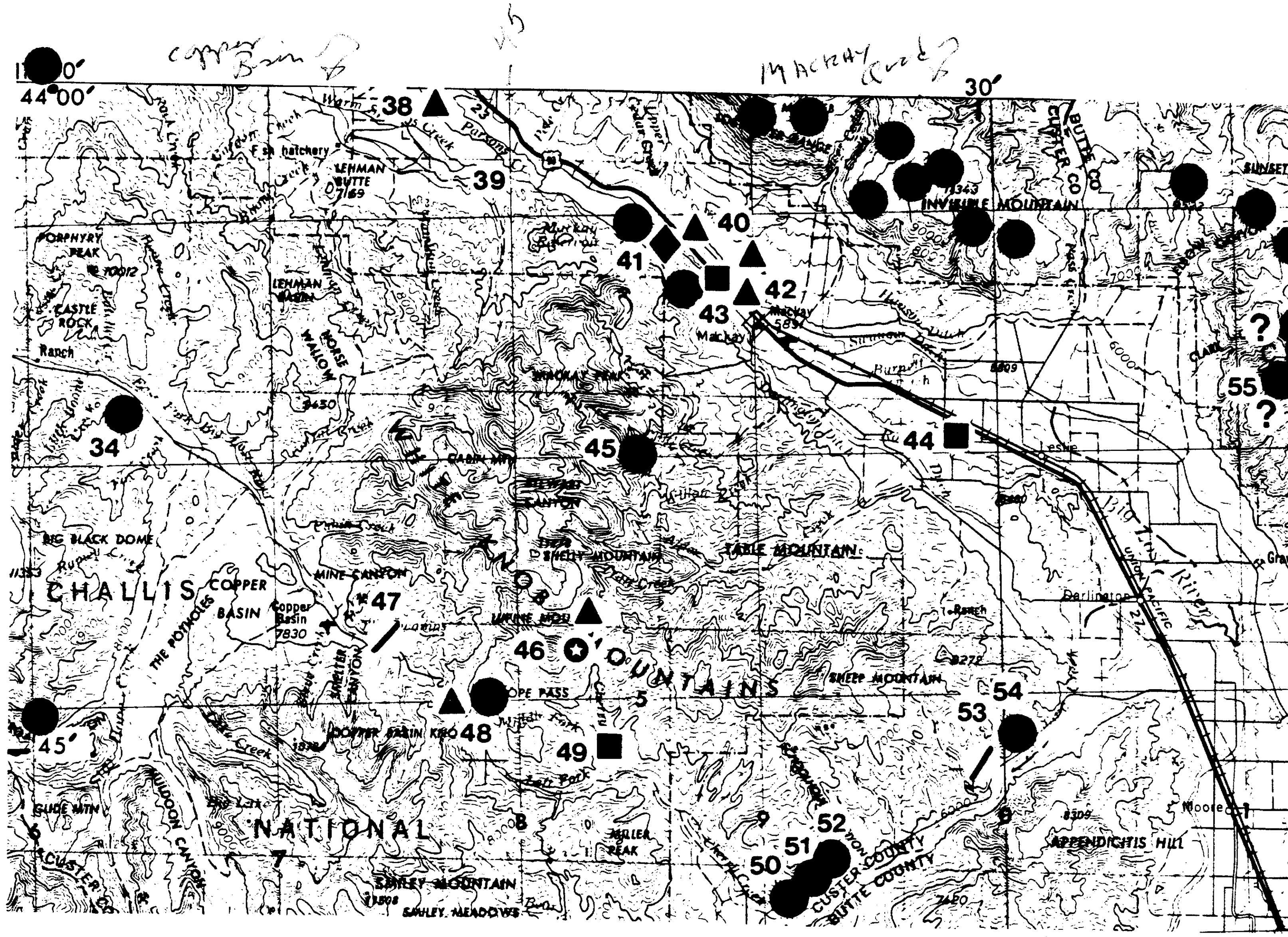

Figure 2d. Southeast part of affected area.

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through-going fractures and open joints. In the northern part of the range a few outcrops of Precambrian quartzite and argillite are also present (McIntyre and Hobbs, 1978; Rember and Bennett, 1979a). In the Boulder, White Knob, and eastern Salmon River Mountains, Challis Volcanics predominate, but Paleozoic (Cambrian to Permian) limestone, quartzite, argillite and clastic sedimentary rocks and small areas of Precambrian gneiss are also present (Nelson and Ross, 1969; McIntyre and Hobbs, 1978; Rember and Bennett, 1979a, b, c, d).

The Lost River Range is separated from the other mountains in the affected region by a chain of valleys; from south to north these are the Big Lost River Valley, Barton Flat, the Thousand Springs Valley, Antelope Flat, Round Valley, and the Salmon River Valley (Fig. 2). The valleys contain a few bedrock hills but generally are flat-bottomed and underlain by deposits of glacial outwash and alluvium estimated to be hundreds of meters deep. The valleys have numerous springs and creeks as well as two major rivers, the Big Lost River and the Salmon River. The valleys are bordered by prominent alluvial fans.

The population in the area affected by landslides is approximately 4,000 to 5,000. The largest town is Challis, with a seasonal population varying between 1500 and 2500 (Charles Taylor, oral communication, Dec. 13, 1983). The second largest town is Mackay, with a population of about 550. Other people in the area live on ranches or in small mining communities.

OVERVIEW OF OBSERVATIONS

Ground failures we observed are described in Table 1 and located in Figures 1 and 2. A few localities that yielded negative results (i.e. no landslides or other ground failures) are also described for the record. Landslides discussed in this report are classified according to the system of Varnes (1978).

The earthquake caused landslides and other ground failures throughout an area of approximately 4200 km^2 (Fig. 1). Most landslides were rock falls or rock slides. From a fixed-wing aircraft we observed several dozen rock falls and rock slides on the eastern flank of Grouse Creek Mountain (Locality 1 in Figures 1 and 2b), several dozen more scattered through the central Lost River Range, and a few dozen more in volcanic rocks in the northern Lost River and eastern Salmon River Mountains. During ground-based studies we observed some of these in greater detail and discovered several additional rock falls and rock slides in the Boulder and White Knob Mountains. Rock falls caused significant damage in Challis (Locality 6 in Figures 1 and 2a).

One complex mud flow and one complex debris flow were attributable to hydrologic changes caused by the earthquake. The debris flow, at Birch Springs (Locality 24 in Figures 1 and 2b), originated less than 200 m upslope from the fault scarp and probably occurred during or shortly after the ground shaking. The mud flow, in the Lupine Creek valley 29 km from the fault scarp (Locality 46 in Figures 1 and 2d), began at least 2 days after the earthquake.

Highways in the epicentral area sustained damage from cracking and slumping at several localities. Most damaged sections of roads were in man-made fill.

The earthquake caused soil liquefaction effects at several localities, including a lateral spread landslide at Whiskey Springs (Locality 28 in Figure 2b). These soil liquefaction effects are described by Youd and others (this volume).

Other ground failures attributable to the earthquake include soil slides,

Table 1: Locations and descriptions of landslides and other ground failures in the 1983 Borah Peak, Idaho earthquake. Locality numbers are referenced to Figures 1 and 2.

Locality	Type of Ground Failure	Description
1	Rock falls and rock slides	See text and Figure 3.
2	Cracks and sand boils	See Youd and others, this volume.
3	Rock falls	See text.
4	No landslides from apparently susceptible slopes	No landslides observed during aerial reconnaissance in spite of near-vertical cliffs extending several kilometers.
5	Rock falls	See text.
6	Rock falls	See text and Figures 4-11.
7	Slide in talus	Slide of approximately 50 m^3 of talus.
	No landslides from apparently susceptible slope	Pinnacle of rock 60 m high with near-vertical sides did not produce any landslides.
8	Rock falls	Two small rock falls.
9	Rock fall	See text and Figure 12.
10	Soil fall	Soil fall from slope above river.
11	Rock falls	Impact marks in highway from bouncing boulders.
12	Rock falls	Rock falls reported by E. D. Sembera (oral communication, Nov. 3, 1983).
13	Rock slides	Small rock slides probably attributable to earthquake.
14	Rock falls	Several boulders fell.
15	Rock falls	See text.
16	Rock falls	Rock falls from promontory and cut slope.
17	Cracks	Cracks in road.
18	Rock fall	See text.

Table 1--Continued.

Locality	Type of Ground Failures	Description
19	Rock falls	Several boulders fell.
	Soil slides	Soil slides from several slopes. Most of one hillside covered with slides.
20	Slump	See text and Figure 22.
	Rock falls	Rock falls from cut slope from 1.5 km southeast to 1.6 km northwest of highway summit.
21	Cracks	Cracks in road.
22	Few if any landslides from apparently susceptible slopes	No landslides observed in Christian Gulch despite presence of steep, high, partly glaciated valley walls. Limestone is bedded, but contains few open joints. Campers reported hearing a few small rocks fall after the earthquake.
23	Rock falls and (or) rock slides	Approximately 10 small rock falls and (or) rock slides from west flank near crest of mountain.
24	Debris flow	See text and Figures 14-16.
	Soil block slide	Block slide in saturated colluvium consisting of several blocks a few meters long and wide and approximately 0.7 m deep. Fault scarp forms crown scarp of block slide.
25	Soil slides	Several soil slides with movement up to 3 m in zone up to 60 m wide adjacent to fault scarp.
	Shattered rock	Quartzite outcrop shattered in zone of surface fault-rupture.
26	Soil slide	Incipient soil slide on slope of 27^{o}.
27	Cracks and sand boils	See Youd and others, this volume.
28	Lateral spread	See Youd and others, this volume.
29	Cracks	Cracking and settlement of fill where highway passes from alluvial fan to flood plain.
30	Craters	See Youd and others, this volume.
31	Rock fall	See text.

Table 1--Continued.

Locality	Type of Ground Failure	Description
32	Rock fall	Several boulders of volcanic breccia fell from slope.
33	Slides in talus	Talus slides on slope on north side of river.
34	Rock fall	Rhyolite boulders up to 1 m in diameter and boulder-impact marks in road.
35	Rock slide	Rock slide onto road probably attributable to earthquake.
	Cracks	Cracks in road fill.
36	Rock slide	Limestone blocks from dip slope of 32-33° slid onto road.
	Talus fall	Boulders $\leq$ .3 m in diameter fell onto road from talus deposit with surface slope inclination of 38°.
	Cracks	Cracks in road fill.
37	Rock fall	Rock fall of 25 m^3 onto road.
38	Cracks	Road cracked.
39	Lateral spread	See Youd and others, this volume.
40	Cracks	10-cm-wide cracks in road fill.
41	Rock fall	See text and Figure 13.
	Incipient soil slide	Soil slide on spur 1 km south of spillway.
42	Rock fall	Rock fall of about 20 m^3 from massive unit at top of steep slope of White Knob limestone.
43	Cracks	See text and Figure 21.
	Sand boils	See Youd and others, this volume.
	Rock fall	See text.
44	Settlement of fill	Fill settled and cracked bridge abutment.
45	Rock fall	Boulders bounced down slope and across mine road.

Table 1--Continued.

Locality	Type of Ground Failure	Description
46	Mud flow	See text and Figures 18-20.
	Cracks	Cracks a few centimeters wide in loose humus on steep slope.
47	No landslide from apparently susceptible slope	No cracks or lateral spreads observed in marsh.
48	Rock falls	Several small (<10 m^3) rock falls along 1-km-stretch of road southeast of summit. Road remained passable.
	Cracks	See text.
49	Soil slump	Small slump (<100 m^3) in stream bank.
50	Rock fall	Several cobbles on road shoulder.
51	Rock fall	Several cobbles and limestone boulders on road.
52	Rock fall	A few fresh-appearing spalls on rock face and cobbles on road at base of slope of White Knob Limestone.
53	No landslide from from apparently susceptible slope	No landslide from vertical slope in White Knob Limestone.
54	Rock fall	Several cobbles on road shoulder.
55	Rock fall	Southernmost rock fall or rock slide in Lost River Range attributable to earthquake.

most of which were adjacent to the fault scarp; small ($< 500\ m^3$) soil slumps, soil block slides, soil falls, and talus slides; a shattered outcrop of quartzite adjacent to the fault scarp; and large craters formed by expulsion of water and sediment at Chilly Buttes (Locality 30 in Figure 2b; described by Waag and Lane, Wood and others, and Youd and others, all in this volume).

The next section of our report describes individual landslides and other ground failures that we observed in some detail.

LOCALITY DESCRIPTIONS

ROCK FALLS AND ROCK SLIDES

Grouse Creek Mountain (Locality 1; viewed only from the air)

The areas with the most numerous rock falls and rock slides were the glacial cirques on eastern flank of Grouse Creek Mountain, at the heads of Rock Springs and Dead Cat Canyons. We observed several dozen small rock fall and rock slide deposits, which consisted of trails of boulders and finer debris a few dozen meters long, a few meters wide, and probably less than 2 meters thick. These landslides originated on steep, in some cases near-vertical, slopes in Mississippian limestone, calcareous siltstone, and sandstone of the Middle Canyon, Scott Peak, South Creek, and Surrett Canyon formations. Typical rock fall and rock slide deposits are shown in Figure 3.

Central Lost River Range

In other parts of the central Lost River Range composed of Paleozoic rocks, rock falls and rock slides attributable to the earthquake were few and widely scattered (Figs. 2b and 2d). Most of this area was viewed only from the air, but observations on the ground along the Doublesprings Pass (Locality 21 in Figure 2b) and Christian Gulch (Locality 22 in Figure 2b) roads confirmed that few rock falls or rock slides had occurred in those regions.

Most rock falls and rock slides in the central Lost River Range occurred on slopes above extensive talus deposits. In spite of their proximity to the fault rupture, however, most talus deposits in this area remained stable; although a few individual boulders may have shifted, the presence of undisturbed animal trails across the deposits indicated that no significant sliding had taken place. Some fresh-looking talus deposits were cut by the fault scarp, suggesting that they had been emplaced before the earthquake.

Aerial observations north of the Salmon River (Locality 4 in Figure 2a) and south of Locality 55 (Fig. 2d) indicated that the earthquake had not triggered any landslides in either of these areas.

Challis (Locality 6)

Boulders dislodged from steep south and east-facing slopes on the north edge of town fell into the residential area of Challis in at least six places, damaging at least 3 houses and 2 automobiles. The rock falls did not cause any injuries or deaths. However, two children were killed in the business district of Challis when the earthquake caused the collapse of a heavy masonry building wall.

Several dozen boulders up to 3 m in diameter fell at Site I, which is shown in Figure 4. The boulders fell approximately 100 m from a hillside with an average inclination of 35° and localized near-vertical cliffs. Boulders

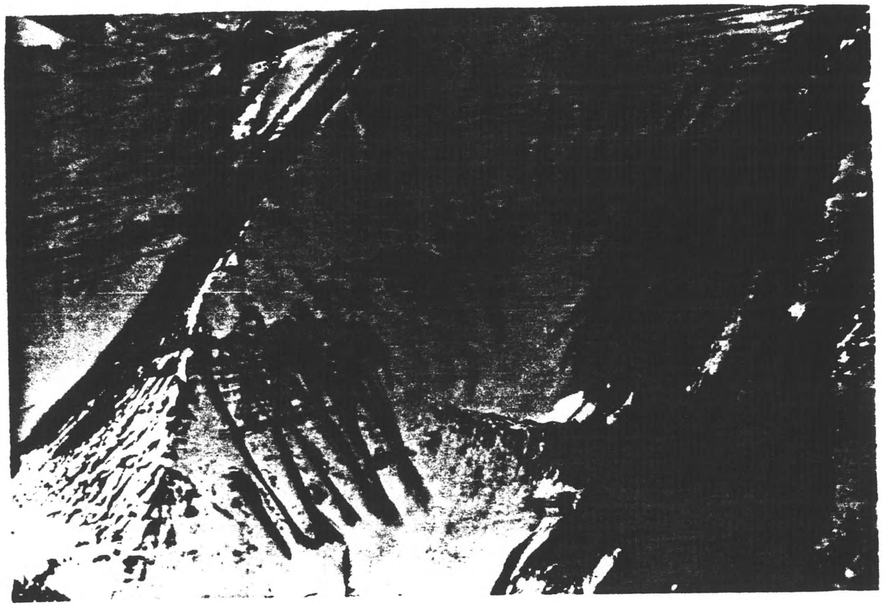

Figure 3. Oblique aerial view of rock falls and rock slides on the eastern flank of Grouse Creek Mountain in the Lost River Range. Deposits of earthquake-induced rock falls and rock slides are dark-toned trails overlying snow in left and central parts of photograph. Longest trails are about 100 m long. Medium-gray deposits to right of snow-covered area are pre-earthquake talus deposits.

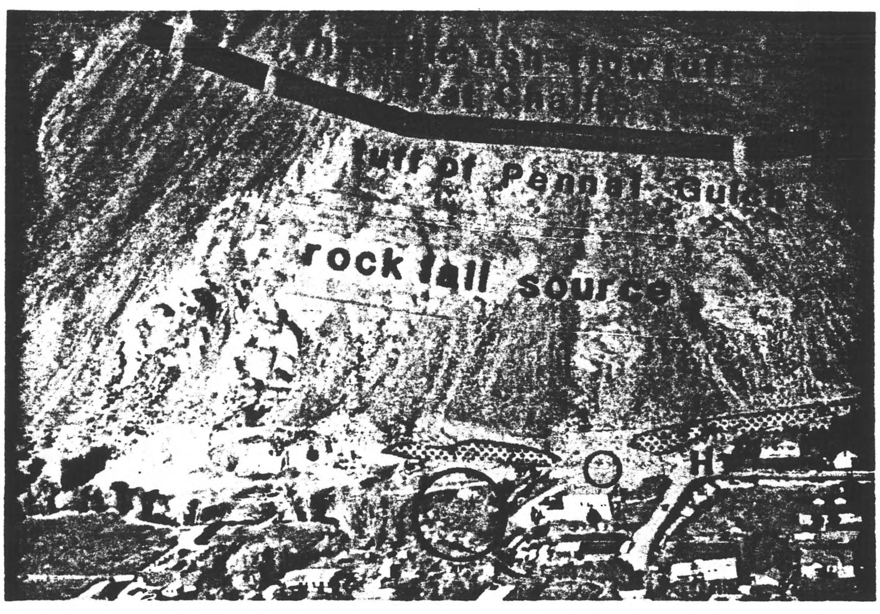

Figure 4. Oblique aerial view northward toward Site I in Challis showing rock-fall source, geologic contact (dashed where approximate), earthen embankment (dotted areas), house damaged by rock fall (H), and areas of visible rock-fall deposits (circled). Boulder causing damage to house was removed before photograph was taken.

bounced and rolled as much as 70 m across the gently sloping ground at the base of the hillside. Other boulders came to rest behind an artificial earthern embankment approximately 5 m high at the base of the hillside, and a few boulders apparently bounced over this embankment.

One of the largest boulders, which weighed an estimated 10 metric tons, bounced into a house less than 10 m from the base of the hillside (Figure 5). The boulder impact moved the house superstructure several centimeters, cracked the cement steps, and smashed into the doorway through which a resident had fled a few moments earlier (Idaho Falls, Idaho, Post-Register, Oct. 31, 1983, p. A-9). The house remained on its foundation. Boulders at Site I also damaged two automobiles (one visible in Fig. 5), dented the metal roof of a garage, and partly blocked a street (Fig. 6) and a parking lot.

The hillside at Site I is composed of two lithologic units of the Challis Volcanics (Fig. 4; McIntyre and Hobbs, 1978). The lower unit, in which the rock falls originated, is the tuff of Pennal Gulch, which locally consists of soft, weakly cemented, weathered, cream-colored tuff, volcanic mudstone, and sandstone. Bedding ranges from thin to massive, and bedding planes dip east-northeast. The hillside at Site I is probably susceptible to rock-fall initiation because of the steep slope inclination and because of the weathering and weak cementation of this rock. The lithologic unit that caps the hillside at Site 1 (Fig. 4) is the rhyolitic ash-flow tuff at Challis, (McIntyre and Hobbs, 1978). At Sites, II, III, IV, and V, (Fig. 7), rock falls originated in this rhyolitic unit. The rock is a red- to yellowish-brown, moderately well cemented tuff that forms steep cliffs and promontories shattered by several sets of conspicuous joints. Some joints are lined with clay, but many are open. One set of joints dips southward, out of the south-facing slope, and provides planes of weakness along which rocks can readily slide.

Figures 8 and 9 show the source, path, and resting place of the largest boulder that fell at Site II (Fig. 7). This boulder, which was detached from a near vertical cliff just above a talus apron, bounced and rolled approximately 100 meters down the 35^{o} talus slope. At the base of the slope the boulder bounced between two houses and smashed a garbage can; bounced again and hit some fence posts; bounced four more times and cracked the planks of a small wooden bridge; then rolled into the front yard of another house, crashed into an apple tree, and crushed a corner of the porch before coming to rest less than 3 m from the front door (Fig. 9). This boulder is 3.3 m in diameter and weighs an estimated 20 metric tons. It traveled 70 m from the base of the steep talus slope. Figure 8 shows that, had the boulder followed virtually any other path from its source, it would have caused significant damage to one or more houses.

At Site III (Fig. 7), several boulders fell into a stretch of Garden Creek adjacent to a trailer park. One boulder bounced across the creek, landing between a propane tank and a trailer (Fig. 10).

The largest boulder we observed in Challis (Fig. 11) fell from a promontory (Site IV in Figure 7) that contained many conspicuous open joints. The boulder, 8 m in diameter and weighing an estimated 50 metric tons, contained painted letters or high-school-class numerals on 3 sides, showing at least 3 edges were exposed prior to the earthquake. This boulder fell and slid approximately 50 m and came to rest a few meters from the base of the slope. Several smaller boulders also fell at this site during the earthquake.

Earthquake-induced rock falls also occurred at several other sites in and near Challis. At Site V (Fig. 7) cobbles and small boulders fell through the

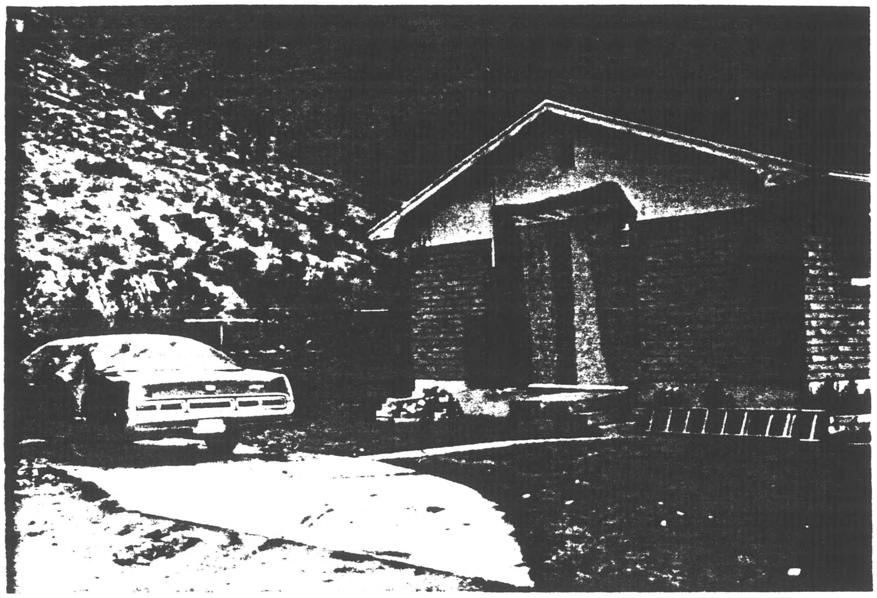

Figure 5. House and automobile damaged by rock fall at Site I in Challis. Boulder crashed into doorway of house, now covered by plywood, and moved house superstructure several centimeters. Boulder removed before photograph was taken.

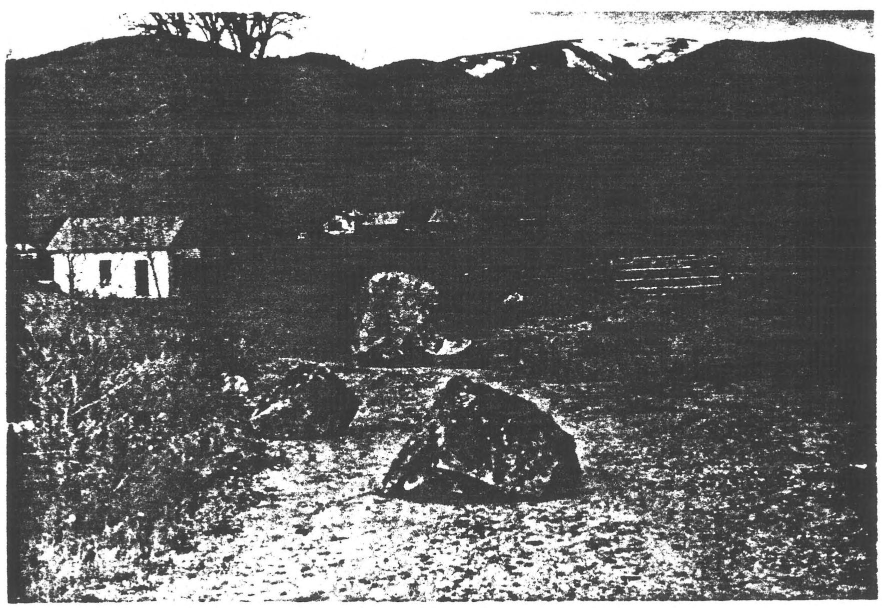

Figure 6. Boulders dislodged by earthquake partly blocking road at Site I in Challis.

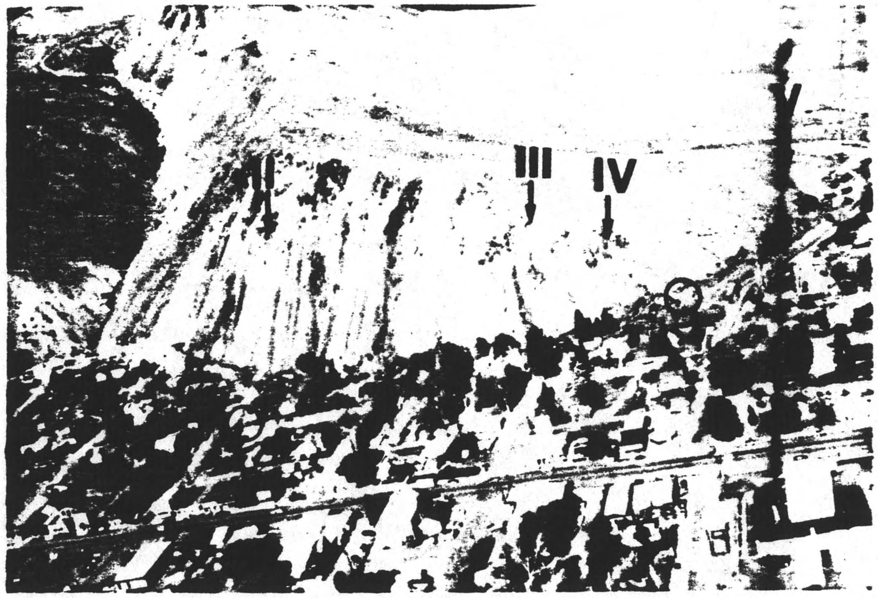

Figure 7. Oblique aerial view northward toward Sites II, III, IV, and V in Challis. Arrows point to rock-fall sources; circles show locations of rock-fall deposits visible in photograph. Hillside in Figure 7 is just east of hillside in Figure 4.

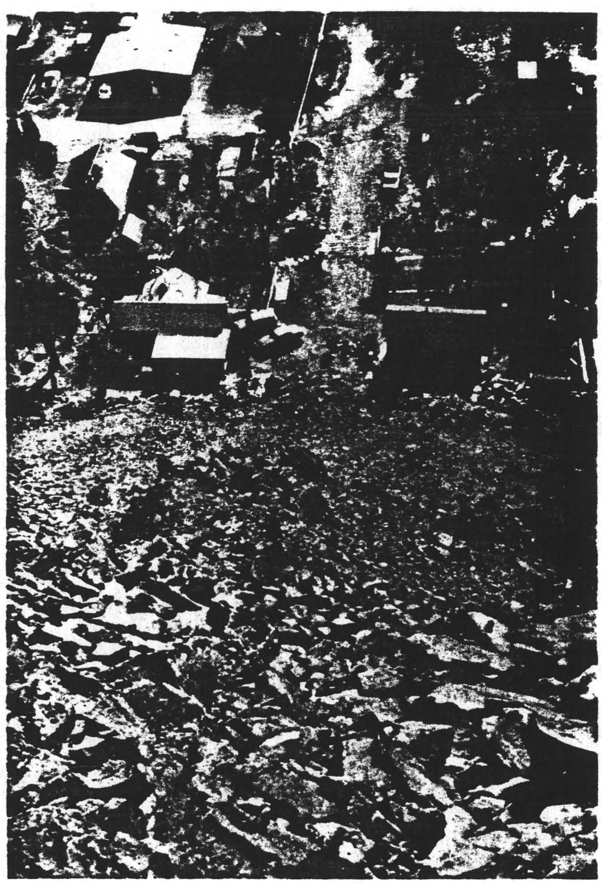

Figure 8. View from source of rock fall at Site II in Challis. Arrows show visible boulder-impact marks. Largest boulder removed before photograph was taken.

Figure 9. Largest boulder dislodged by earthquake at Site II in Challis. The decorations were added the day after the earthquake.

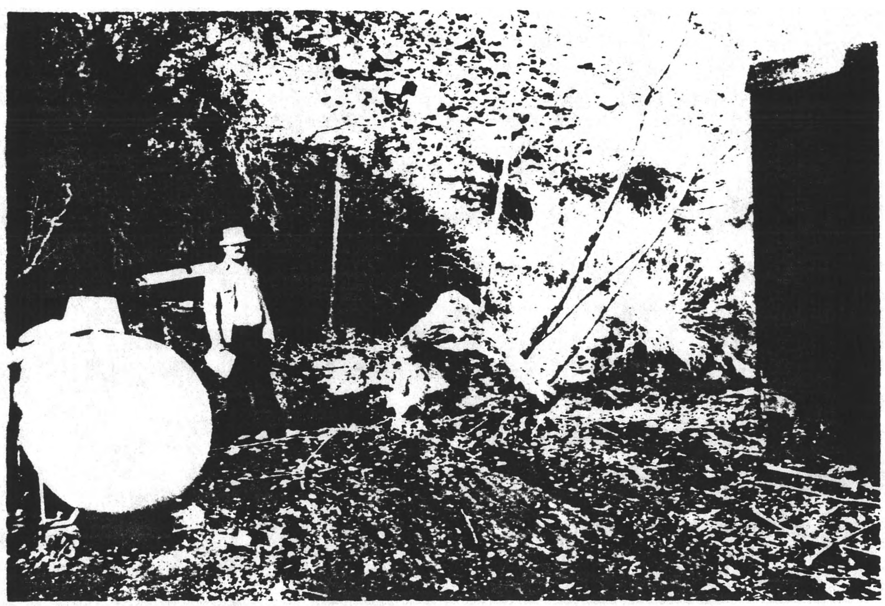

Figure 10. Boulder from rock fall at Site III in Challis. Boulder bounced across creek, landing between propane tank and trailer (right edge of photograph), before rolling part of the way back down the creek bank.

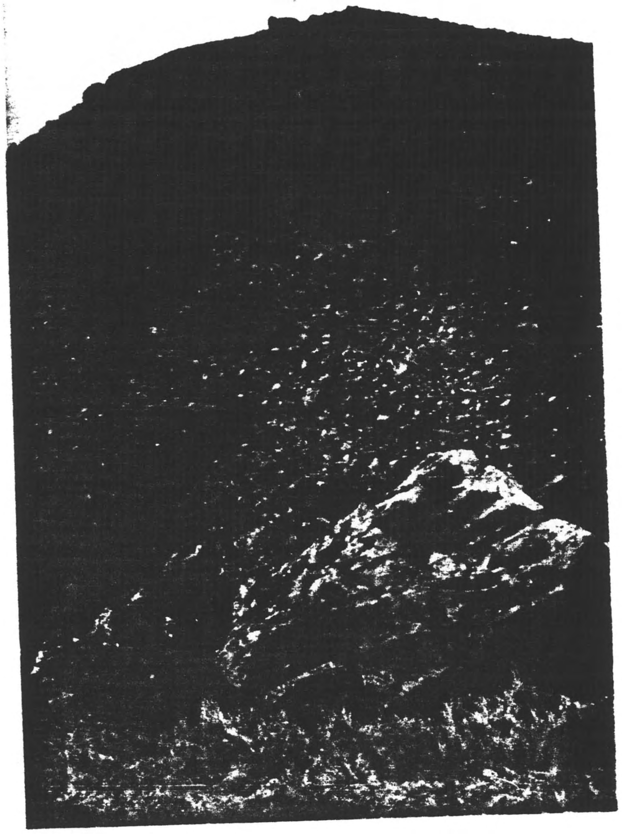

Figure 11. Largest boulder dislodged in Challis by earthquake. Light-toned area is path of boulder down hillside. This rock fall occurred at Site IV.

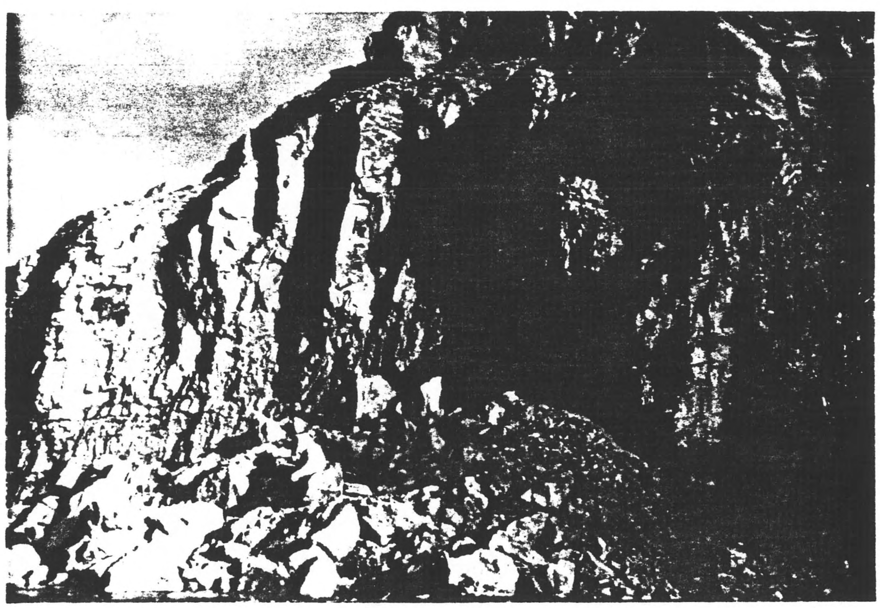

Figure 12. Largest observed rock fall triggered by earthquake, adjacent to Salmon River at Birch Creek. Volume of rock fall is about 10,000 m^3.

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roof of a shed. Elsewhere in Challis, a 200-kg boulder was reported to have crashed through the kitchen window of a house (Blackfoot, Idaho, Morning News, Oct. 31, 1983, p. 3). Boulders also fell into the uninhabited canyon shown on the left side of Fig. 7.

Salmon River at Pennal Gulch (Locality 5)

Several rock falls, of a few tens to hundreds of cubic meters each, occurred along a 4-km-long stretch of cliffs bordering the Salmon River. Rock falls originated only in the tuff of Pennal Gulch (McIntyre and Hobbs, 1978), described above as also producing rock falls in Challis. The cliffs where rock falls took place were 40^{o} or steeper and were being undercut by the Salmon River. The rock falls formed deposits of boulders in the river within a few meters of the base of the cliffs.

Salmon River at Shotgun Creek (Locality 3)

The only rock falls or rock slides observed along the Salmon River cliffs between Locality 5 and Ellis (Fig. 2a) were from a 400-m-high 35^{o} slope adjacent to the outside of a meander. This slope is composed of quartzite of the Precambrian Swauger Formation (McIntyre and Hobbs, 1978) and is the highest along the Salmon River between Locality 5 and Ellis.

Salmon River at Birch Creek (Locality 9)

A rock fall of about 10,000 m^3, the largest one we observed that was caused by the earthquake, occurred on a near-vertical cliff adjacent to the outside of a meander (Fig. 12). The rock fall involved both massive and thin-bedded tuffs of the Challis Volcanics (Rember and Bennett, 1979a). Bedding dipped into the slope, but angular blocks were detached along two sets of conspicuous, near vertical joints.

Grandview Canyon (Locality 15)

We noted six small rock falls (< 100 m^3) and a few boulder-impact marks in the highway pavement. The slopes in the canyon are composed of thin- to thick-bedded volcanic breccia, are 100 to 250 m high, and are steeper than 35^{o}. The rock is broken by several sets of conspicuous joints. Along some joints breccia pipes have been intruded; along a few joints the rock is highly altered.

Broken Wagon Creek (Locality 18)

A rock fall containing approximately 400 m^3 of material was dislodged from limestone cliffs. Angular blocks of rock were detached at intersections of bedding planes, which dip out of the slope, and steep-dipping fractures.

Bartlett Point Road (Locality 31)

Rock falls originated on near-vertical cliffs near the top of a promontory composed of a well-indurated, but fractured, volcanic breccia in the Challis Volcanics (Rember and Bennett, 1979b). At least 70 boulders larger than 1 m in diameter rolled or bounced beyond the distal margin of the talus deposit that mantles the slope below the promontory. Some boulders crashed into other immobile boulders on the gently sloping ground at the base of the slope, producing shards that flew several meters through the air. Boulders dislodged by the earthquake moved as far as 60 m beyond the distal margin of the talus.

The promontory where the rock falls originated is 80 m high and contains pinnacles separated by open joints along which significant weathering has taken place. Rock in these pinnacles also contains a set of partly open, subhorizontal joints with irregular surfaces.

Mackay Dam (Locality 41)

Falls from an east-facing slope deposited approximately 200 m^3 of rock in the Mackay Dam spillway, but this rock constituted only a small obstruction (Fig. 13). The source of the rock fall was a highly fractured, partly altered, limestone of the White Knob Limestone (Mississippian to Permian) (Nelson and Ross, 1969). The source slope was 80 m high and had an average inclination of 40°.

Sportsmen's Access (Locality 43)

A rock fall and slide of approximately 100 m^3 occurred on a 120-m-high promontory west of U.S. Highway 93. The bedrock, which dips steeply out of the slope, is White Knob Limestone, similar to that at Mackay Dam (Locality 41). The source was in a saddle presumably underlain by rock that is less resistant than the massive, well-cemented beds that crop out on either side.

DEBRIS FLOWS AND MUD FLOWS

Birch Springs (Locality 24)

At Birch Springs, a complex rotational slump-debris flow (Figs. 14, 15, and 16) occurred in colluvium in an area where hummocky topography suggests prior landsliding. The landslide covered approximately 4 hectares and contained an estimated 100,000 m^3 of soft, poorly sorted, material with grains of all sizes from clay to boulders. We estimate that the material contained more than 20% by weight of gravel, cobbles, and boulders of crystalline limestone. One sample of the finer-grained matrix contained 36% by weight sand, 42% silt, and 22% clay ($< 4 \mu m$). The presence of flowing springs within and adjacent to the landslide indicates that the material was saturated at the time of the earthquake.

The arcuate crown scarp of the landslide was approximately 250 m long and up to 5 m high (Fig. 15). Upslope from the scarp was a zone of crown cracks subparallel to the scarp. For approximately 50 m downslope from the scarp, the landslide mass consisted of a jumble of back-rotated slump blocks (Figs. 14 and 15), some of which had partly disintegrated and produced small debris flows. The zone of slumps was bounded on the right flank (facing downslope) by a scarp and on the left flank by a lateral ridge of landslide material up to 2 m high (Fig. 14b).

The landslide material was progressively more disrupted downslope, and the distal part of the landslide consisted of four debris flows several hundred meters long (Fig. 14). The debris flows were complex, with numerous lobes, blocks of less fluid material, and islands of undisturbed ground around which the debris had flowed. These debris flows were bounded in part by complex lateral deposits and had toes a few tens of centimeters high.

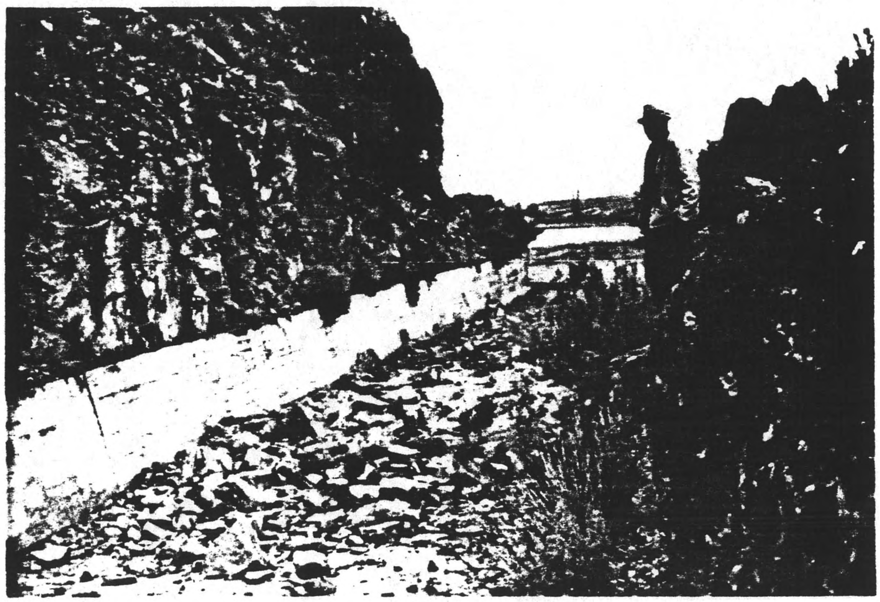

Figure 13. Rock-fall deposit in spillway at Mackay Dam.

Figure 14. Complex rotational slump-debris flow at Birch Springs.

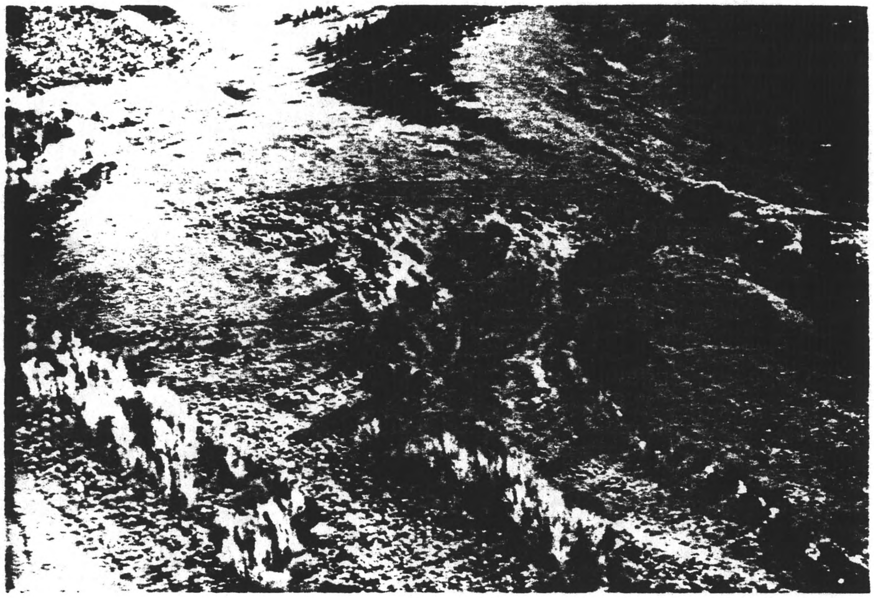

Figure 14a. Oblique aerial photograph eastward toward Birch Springs slump-debris flow.

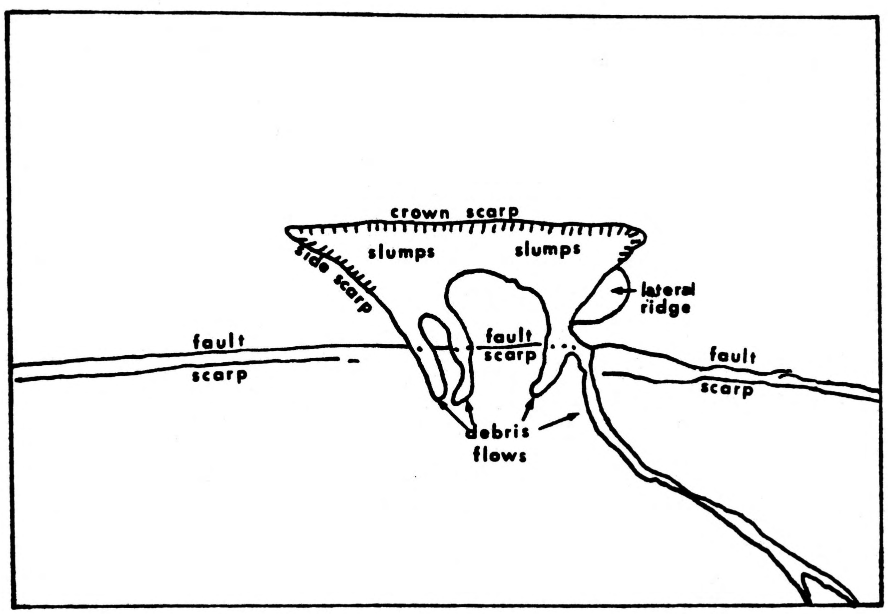

Figure 14b. Line drawing of same area as in Figure 14a, showing main features described in text, including crown scarp, area of slumps, side scarp, lateral ridge, main debris-flow deposits, and fault scarp (dotted where covered by debris-flow material). Crown scarp is approximately 250 m long.

Figure 15. Part of crown scarp and area of slumps of Birch Springs slump-debris flow. View northward. Note human figure for scale. Ponded water at base of scarp is on back-rotated surface of slump block.

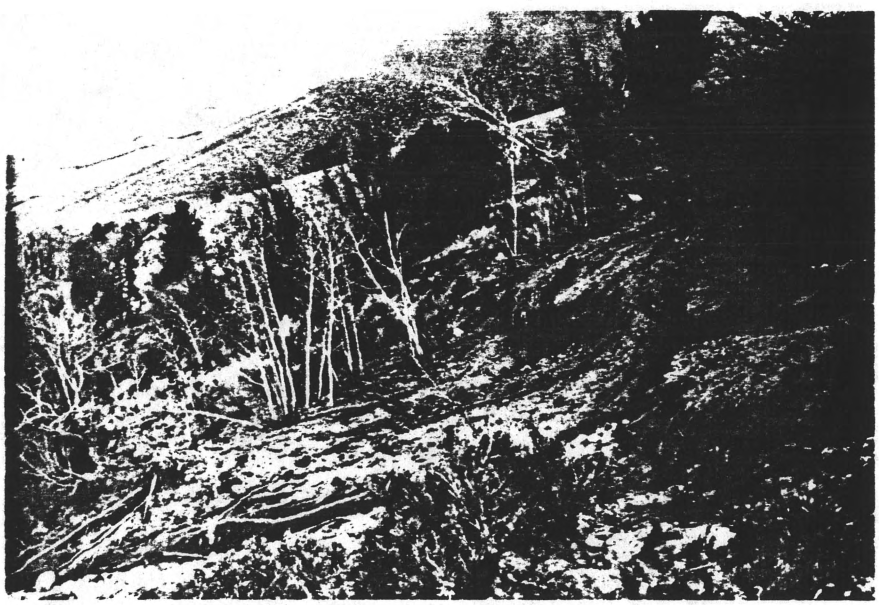

Figure 16. Birch Springs slump-debris flow. View northward showing debris-flow material lapping over fault scarp.

Debris lapped over the fault scarp 200 m downslope from the crown (Fig. 16), showing that debris-flow movement took place after rupture on the fault. The morphology of the debris flows and splash marks at least 1.2 m above the surface on trees suggest that the debris flowed rapidly, at least several tens of meters per hour.

Factors probably contributing to initiation of this landslide include the presumably low strength of the saturated colluvium, temporarily elevated pore-water pressures caused by strong earthquake shaking near the fault, and (or) changes in ground-water flow due to the faulting.

Lupine Creek (Locality 46)

Following the earthquake, a large complex mud flow occurred in the valley of Lupine Creek. The deposit of this mud flow contained an estimated 200,000 m^3 of material and covered virtually all of a 3.5-km-long stretch of the Lupine Creek flood-plain to an average depth of about 50 cm. The mud-flow material was a black organic-rich silty sand containing some clay and gravel and many trunks and limbs of trees broken by the mud-flow movement. Where sampled near the toe, the inorganic matrix was 15% by weight gravel, 41% sand, 30% silt, and 14% clay (Fig. 17). The water content of matrix sampled on November 4, 1983 was 108%[1]; the water content was probably greater when the mud flow was moving.

The source of the mud flow was a 10-m-thick deposit of colluvium, derived from rocks of the Copper Basin Formation (Nelson and Ross, 1969; Betty Skipp, oral communication, Nov. 4, 1983). When we examined the source area (Fig. 18) on November 4, 1983, we noted that a mass of this colluvium 200- to 300-m long had been removed by landslide movement, providing the material for the mud flow. The presence of small rotational slump deposits on and near the 10-m-high crown scarp (Fig. 18) suggests that the colluvium moved initially in a retrogressive series of rotational slumps. Lobate lateral deposits of mud-flow material are present less than 200 m downstream from the crown scarp. The proximity of these deposits to the scarp suggests that the slumps disintegrated into mud flows in a short distance. This rapid disintegration was probably partly due to the high water content of the material. The mud flowed more than 3 km down the valley of Lupine Creek on an average gradient of less than 8^{0}, spreading out to cover most of the flood plain (Figs. 19 and 20). The mud flow broke numerous trees and even near its distal margin, 3.5 km from its source, was sufficiently powerful to snap aspen trees more than 20 centimeters in diameter.

Effects of this mud flow were first reported by Grant Daniels, owner of the property downstream from the mud flow. He noticed that Cherry Creek, into which Lupine Creek drains, was muddy early in the morning of October 31, whereas Cherry Creek had been clear the previous evening. He estimates that several hours would have been required for the muddy water to travel from the mud-flow deposit to his property. This estimate suggests that the flow occurred on October 30--two days after the earthquake.

When Daniels examined the valley of Lupine Creek on October 31, he discovered the mud-flow deposit. He also discovered two new clear-water

[1]Water content = $\dfrac{\text{weight of water}}{\text{weight of solids}} \times 100\%$

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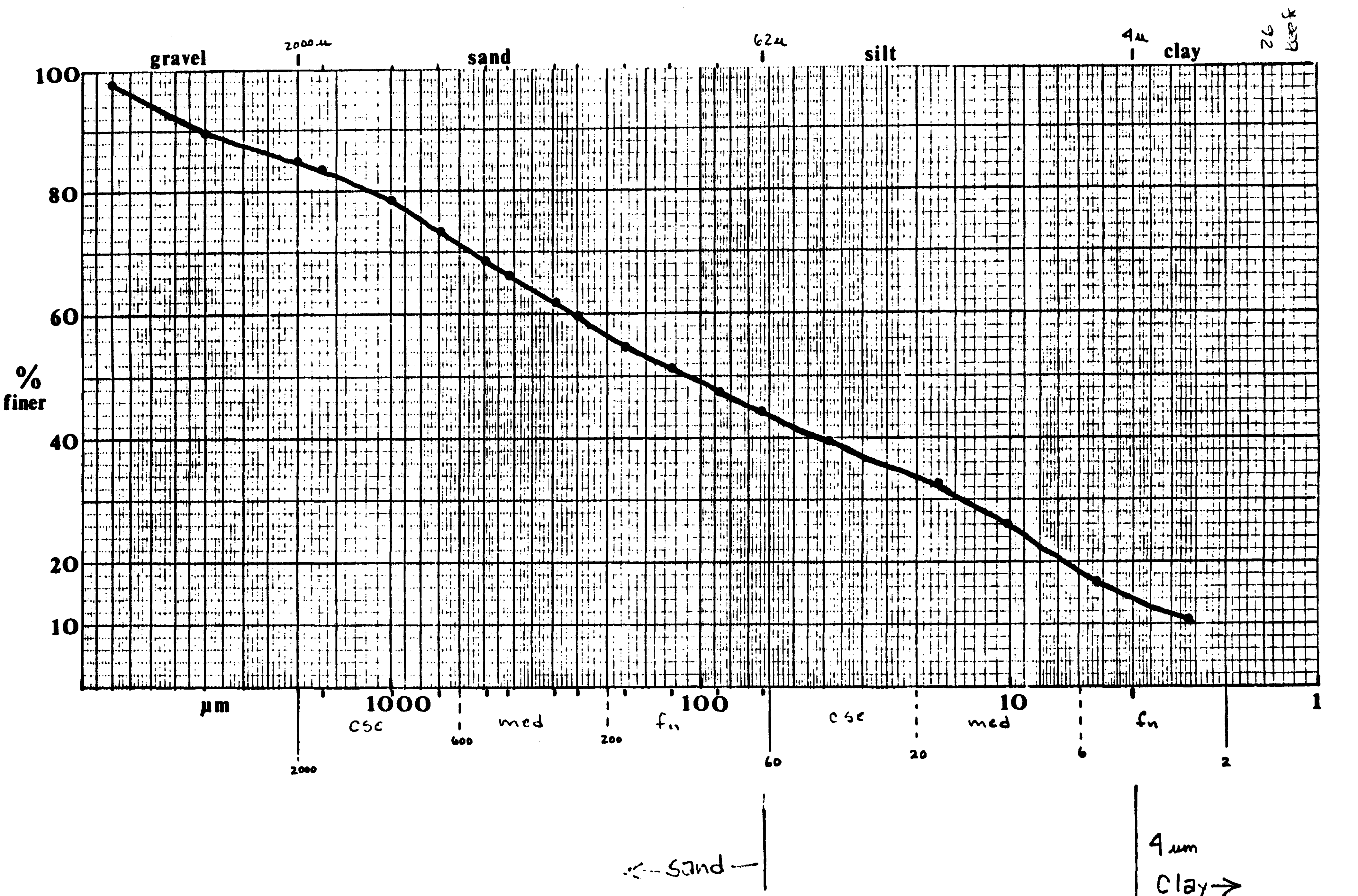

Figure 17. Grain-size distribution curve of sample collected near the toe of the Lupine Creek mud flow.

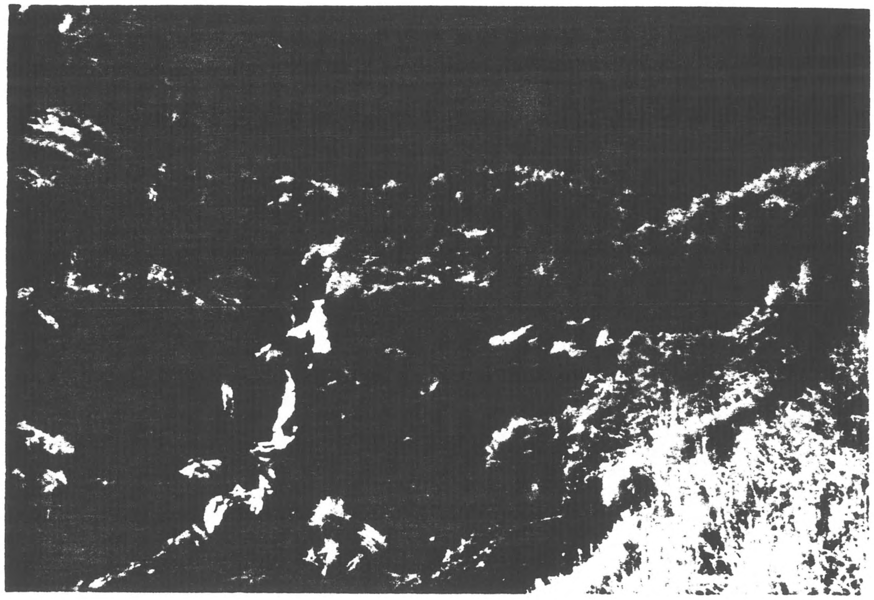

Figure 18. Crown scarp of Lupine Creek mud flow. Blocks of sod-covered (light-toned) earth on scarp are deposits of small slumps. Light-toned streak on left-center of scarp marks course of stream with flow that increased after earthquake. Note human figure above right end of scarp for scale.

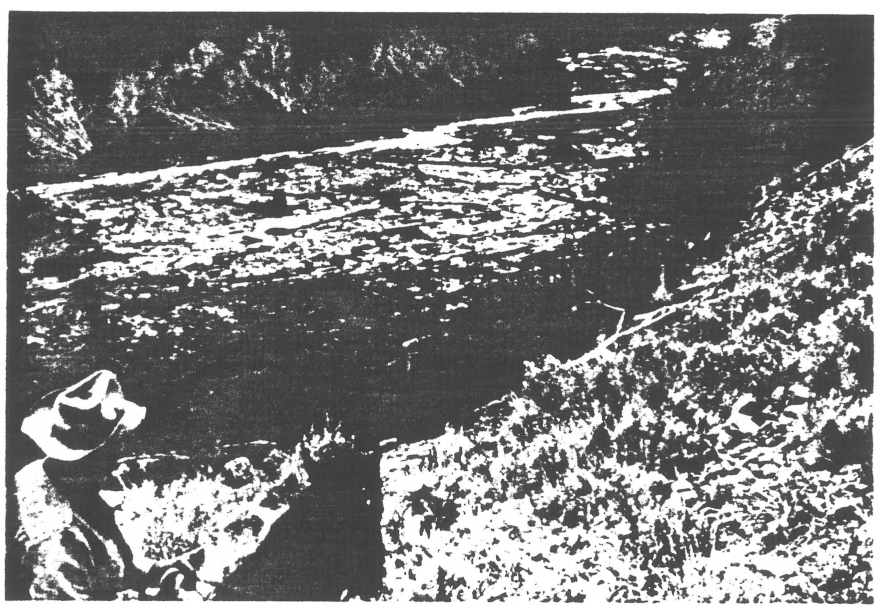

Figure 19. Mud-flow deposit (dark-toned area) in Lupine Creek valley, containing numerous trunks and limbs of trees broken by mud-flow movement.

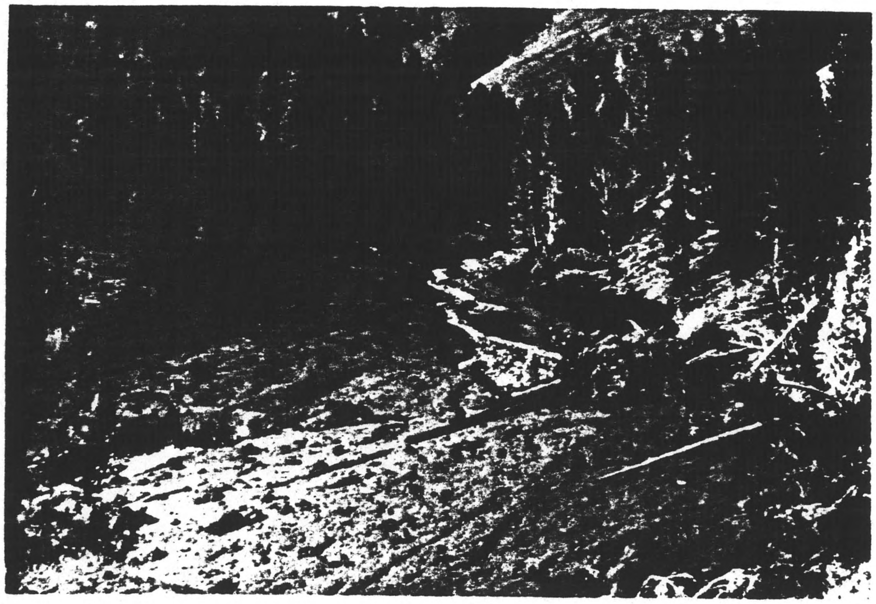

Figure 20. Mud-flow deposit (medium- to dark-toned area) covering the Lupine Creek flood-plain.

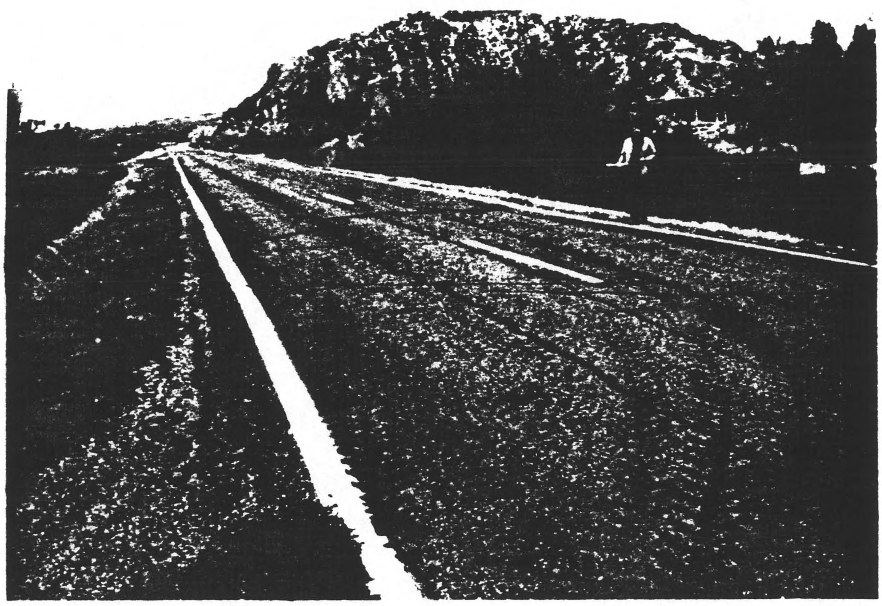

Figure 21. Cracks in shoulder and pavement of U.S. Highway 93 at Sportsmen's access. View northeast.

springs in the valley and observed that the flow in Lupine Creek was at least triple the pre-earthquake flow. The mud flow was thus probably caused by saturation of the colluvium owing to increased surface and subsurface water flow due to the earthquake.

CRACKS AND SLUMPS IN HIGHWAYS

Sportsmen's Access (Locality 43)

U.S. Highway 93 at this locality is on a 12-m-high man-made embankment composed of cobbly fine-sand fill built on the flood plain of the Big Lost River. Longitudinal cracks were present along both shoulders, and longitudinal and oblique cracks disrupted the pavement (Fig. 21). Material on the western shoulder settled and moved horizontally to the west a few centimeters, but much of the roadway and eastern shoulder moved 10 to 20 cm horizontally toward the east. Eastward movement likely predominated because both the road surface and the natural ground surface beneath the embankment sloped toward the east and because water flowed in an unlined canal along the east side of the embankment, presumably creating soft foundation conditions.

Willow Creek Summit (Locality 20)

A slump approximately 20 m wide disrupted the highway pavement and west shoulder of U.S. Highway 93 (Fig. 22). The southbound lane and part of the northbound lane of the highway moved several centimeters westward, and fill in the shoulder west (downslope) of the pavement was cracked into blocks several centimeters on a side. The highway is on a cut-and-fill slope, and the crown of the slump appeared to be at or near the boundary between cut and fill.

Antelope Pass (Locality 48)

Cracks in fill were observed in the downslope shoulders of the graded dirt and gravel road that switchbacks downs to the southeast from the summit of Antelope Pass. Cracks occurred intermitently from the summit to a point about 1 km to the southeast of the pass. Individual cracks had lengths of up to 10 m and displacements (openings) of up to 5 cm; zones of cracks were up to 100 m long. The cracks appear to have resulted from the downslope component of the vibratory compaction of the fill during seismic shaking.

SIGNIFICANCE OF FINDINGS

The Borah Peak earthquake caused a few hundred rock falls and rock slides; a large debris flow; a large mud flow; several slumps and cracks in man-made fill; several instances of soil liquefaction; and few ground failures of other types throughout an area of about 4,200 km^2. The earthquake caused rock falls and rock slides up to 48 km, slumps up to 46 km, and mud flows up to 29 km from the fault rupture. The number of landslides, area affected by landslides, and maximum distance of landslides from the fault rupture of the Borah Peak earthquake are small compared to other historical earthquakes of comparable magnitude (Keefer, 1984). The maximum distance of soil liquefaction effects from the fault rupture (38 km; see Youd and others, this volume) is also small compared to other earthquakes of comparable magnitude (Youd and Perkins, 1978; Keefer, 1984).

The low number and restricted geographic distribution of landslides are

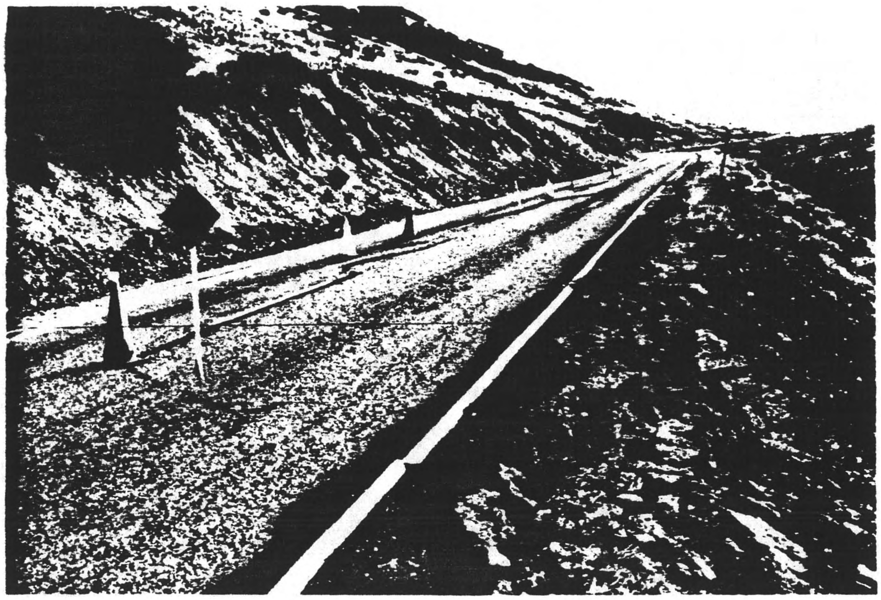

Figure 22. Slump at Willow Creek Summit along U.S. Highway 93. Material on shoulder broken into blocks by slump movement. View south.

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probably due primarily to the ground-motion characteristics of the Borah Peak event and secondarily to the nature of the Paleozoic rocks in the Lost River Range, near the fault rupture. Observations of building damage and preliminary analysis of ground-motion records from the main shock and aftershocks suggest that shaking intensities and peak accelerations in the earthquake were relatively low for a M_s 7.3 event (John Boatwright, oral communication, Dec. 13, 1983). The Paleozoic rocks that predominate in the Lost River Range are well cemented, massive, and contain few conspicuous, open joints.

Where we observed rock falls, they were associated with conspicuous, through-going, open joints or, in a few cases such as Site I in Challis, with weak cementation. The Challis Volcanics are probably more susceptible to rock falls than the Paleozoic rocks partly because weathering of these volcanics has produced numerous open joints. Rock falls and rock slides were restricted to slopes steeper than 35°, a finding that conforms to data from other historical earthquakes (Keefer, 1984).

The mud flow at Lupine Creek, that occurred two days after the earthquake is one of the few documented landslides to have occurred as a delayed consequence of a seismic event. The only similar documented instance that we know of is the Kirkwood earth flow, which was reactivated more than 5 days after the 1959 Hebgen Lake, Montana earthquake (M 7.1). Reactivation at Kirkwood was probably due to tectonic tilting that increased the slope inclination and to earthquake-induced increases in ground-water flow (Hadley, 1964). At Lupine Creek, earthquake-induced hydrologic changes probably increased water flow into the colluvial source material. This increased flow presumably saturated the material and caused pore-water pressures to build up until, two days after the earthquake, the pressures were sufficient to cause landslide initiation. The increased flow may have been caused by tectonic tilting or earthquake-related hydraulic fracturing of the local aquifers (Wood and others, this volume.)

The most significant landslide damage associated with the earthquake was in Challis, where several houses are located at or near the bases of steep, marginally stable hillsides. Damage from rock falls in Challis was all within 70 m of the bases of these hillsides, which remain marginally stable, with steep cliffs composed of loose and shattered rock. These hillsides could produce future rock falls both in seismic and nonseismic conditions.

Other landslide damage associated with the Borah Peak event was due to slumps and cracks along highways and to soil liquefaction phenomena (discussed by Youd and others, this volume). Most slumps occurred in man-made fill, a material that has also proved very susceptible to slumps in other earthquakes (Keefer, 1984).

ACKNOWLEDGEMENTS

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