Degradation of the Hebgen Lake fault scarps of 1959

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ABSTRACT

Scarps produced during the Hebgen Lake earthquake of 1959 changed noticeably in 19 yr although they still appeared remarkably fresh in 1978. They have degraded much more rapidly than have those produced in 1915 and 1954 in Nevada, but a quasi-stable slope of more than 40° characterizes the Hebgen Lake scarps as compared to an upper limit of 37° on the Nevada scarps.

INTRODUCTION

The morphology of fault scarps can provide a key to their ages, as well as a record of repeated displacement on the faults that have produced the scarps. By relating fault displacements to earthquakes, a record of prehistoric earthquakes can be developed to supplement the short historic seismic record. In quantifying scarp morphology, profiles of scarps are particularly useful. The technique has been developed thus far principally in the Basin and Range province (Wallace, 1977a, 1977b, 1978; Bucknam and Anderson, 1979).

In the present study, the scarps produced during the earthquake of August 17, 1959, near Hebgen Lake, Montana (magnitude 7.1), were re-examined in July 1978 to record the changes in scarp morphology that had occurred during 19 yr. The scarps are well described in U.S. Geological Survey Professional Paper 435 (Myers and Hamilton, 1964; Witkind, 1964), and Pardee (1950) recognized that older scarps were present in the area. Sites photographed by I. J. Witkind and J. R. Stacey of the U.S. Geological Survey and by personnel of the U.S. Forest Service were reoccupied and rephotographed, and profiles were measured in 1978. Profiles of the scarps as they existed in 1959 were reconstructed from the old photographic record and were compared to profiles measured in 1978. Photogrammetric measurements of the 1959 photographs employed such keys as distances to trees, lengths of exposed roots in 1959 and 1978, and slope angles where the slope is normal to the view. The results must be considered approximations, but are considerably more accurate than if estimated without such constraints.

This study also documents the morphology and rates of change of fault scarps in a climate and in materials different from those previously studied in the Basin and Range province. I hope that the data will serve as a datum for studies of future changes. Only a few selected examples of profiles and comparisons of 1959 and 1978 photographs can be included in this short report.

Scarp terminology used in the paper is shown in Figure 1. Related terminology and discussions of processes are well reviewed in Young (1972), Carson and Kirkby (1972), and Cooke and Warren (1973).

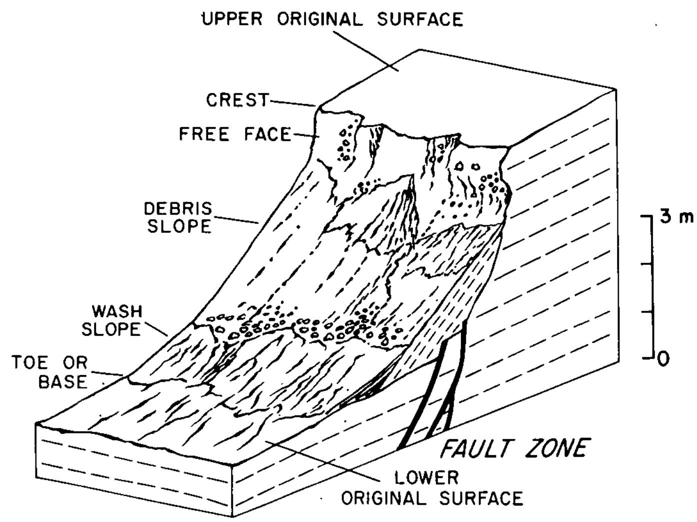

Figure 1. Diagram of fault scarp showing terminology used.

EXAMPLES OF SCARP DEGRADATION

Scarp at Grayling Creek. Myers and Hamilton (1964) recognized that a segment of the Red Canyon fault scarp about 1 km long that lies just east of Grayling Creek (SW¼ sec. 9, T. 12 S., R. 5 E.) represented reactivation of fault displacement precisely along an older scarp of approximately the same height. The scarp in 1959 and 1978 is pictured in Figure 2, and comparative profiles are shown in Figure 3. The scarp is developed in morainal material that is poorly sorted and contains clasts ranging in size from clay to boulders 1 m or more in diameter.

The free face on the scarp in 1959 stood at slope angles estimated to have been between 70° and 80° in the view shown. The crest of the scarp, supported over a slope length of between 0.2 and 0.5 m by roots in the soil, overhung the free face. Loose pebbles and cobbles containing little or no matrix of fines accumulated at the base of the scarp in the few days following the earthquake but before the photographs were taken. The slope angle of these accumulations apparently stood at the angle of

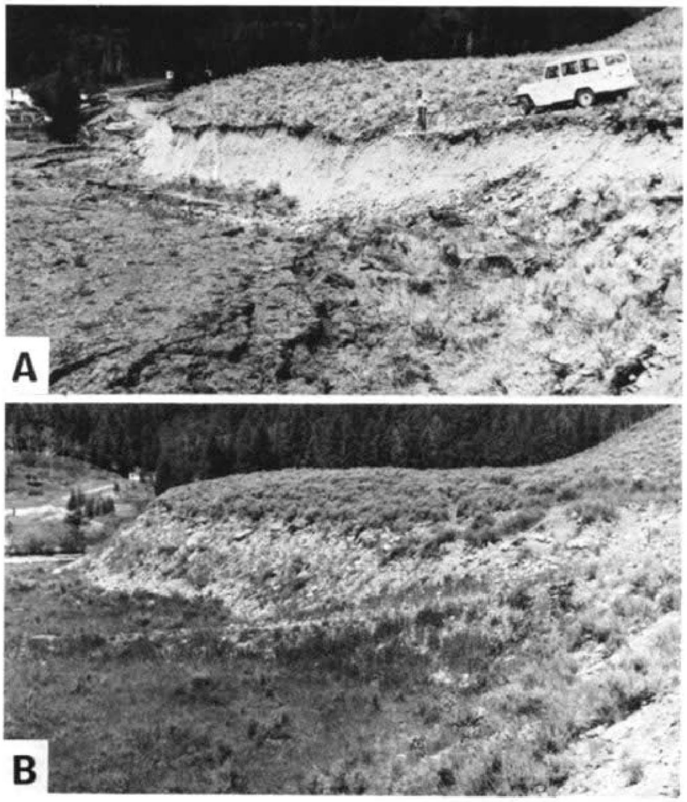

Figure 2. Red Canyon fault scarp where it crosses Grayling Creek in (A) 1959 (photo by J. R. Stacey) and (B) 1978.

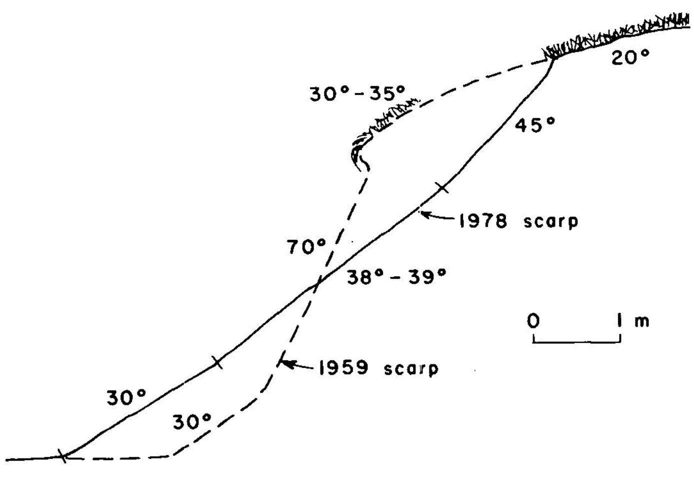

Figure 3. Profiles of Red Canyon fault scarp at Grayling Creek. Solid line measured in 1978. Dashed line estimated from photographs taken in 1959.

repose, 30° to 35° for this type of unbonded clast, and is clearly visible in other 1959 photographs.

In 1978 the slope of the main part of the scarp was between 35° and 40°. The upper part of the scarp stood more steeply at angles of about 45°, and at the crest a narrow part overhung in places where roots have bonded the soil particularly well. At the toe of the scarp a 2-m-wide band of loose cobbles and boulders stood at the angle of repose.

In the 19 yr between 1959 and 1978, the fine and coarse fractions in general had been differentially eroded, and a concentration of cobbles and boulders in the scarp face was left. At angles of 38° to 40°, these large clasts are unstable and are

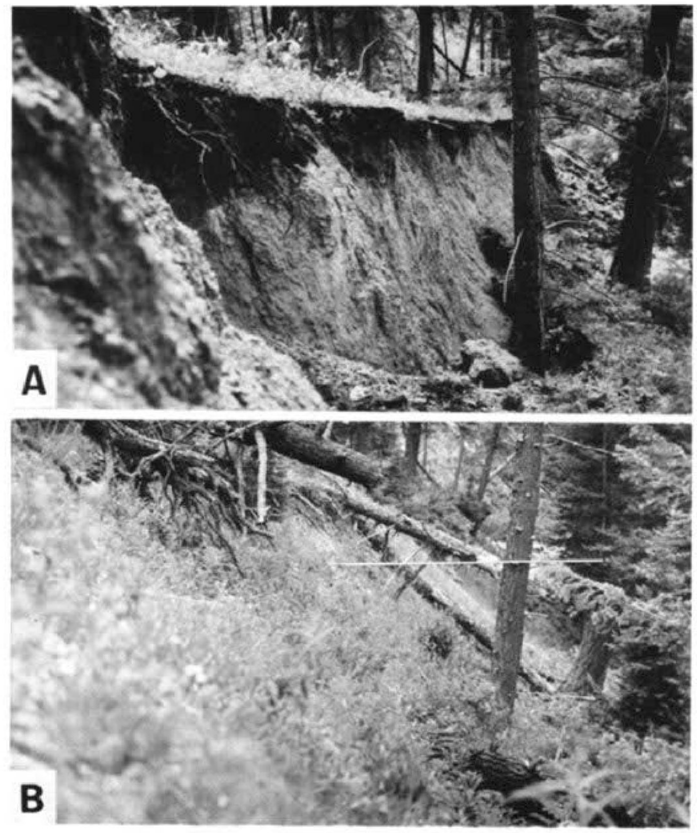

Figure 4. Red Canyon fault scarp 60 m west of Red Canyon Creek in (A) 1959 (photo by I. J. Witkind, see Witkind, 1964, Fig. 18) and (B) 1978.

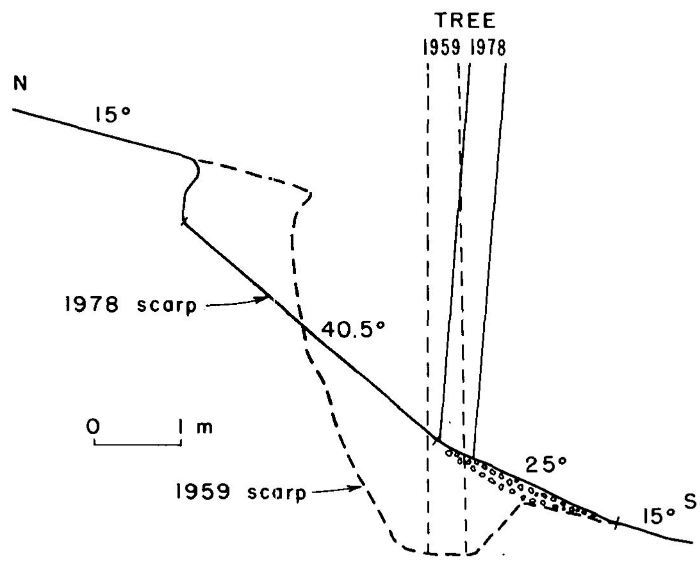

Figure 5. Profile of Red Canyon fault scarp 60 m west of Red Canyon Creek. Solid line measured in 1978; dashed line estimated from photographs taken in 1959.

readily dislodged unless bonded to the slope by the fines. In the upper part of the scarp where slope angles as steep as 45° were common, relative stability is apparently a result of the fines which provide bonding, whereas toward the toe of the scarp, loose coarse clasts were progressively more dominant, the fines were scarce at the surface, and the slope angle was more nearly an angle of repose for loose clastic materials.

Small scarplets that faced the main scarp and defined the

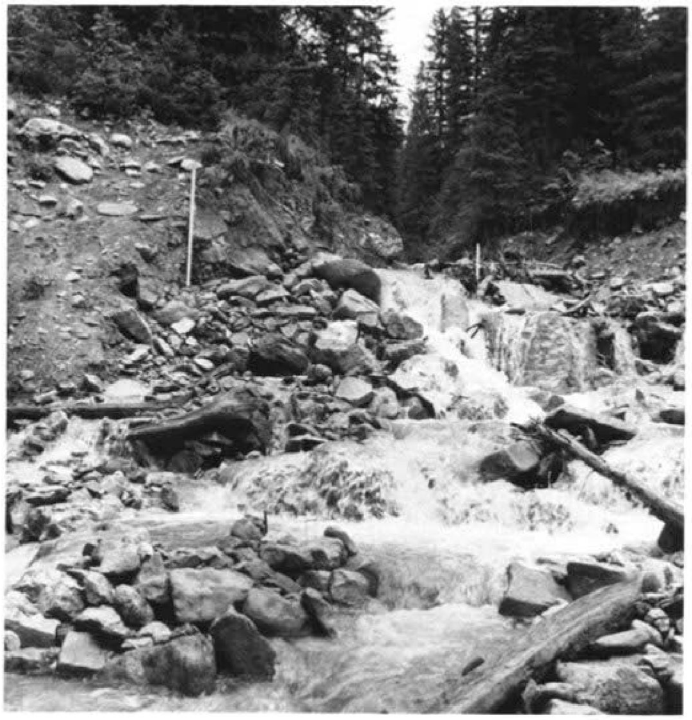

Figure 6. Red canyon fault scarp where crossed by Red Canyon Creek. Large boulders in creek have impeded retreat of knickpoint. Stadia rod is 1.5 m long.

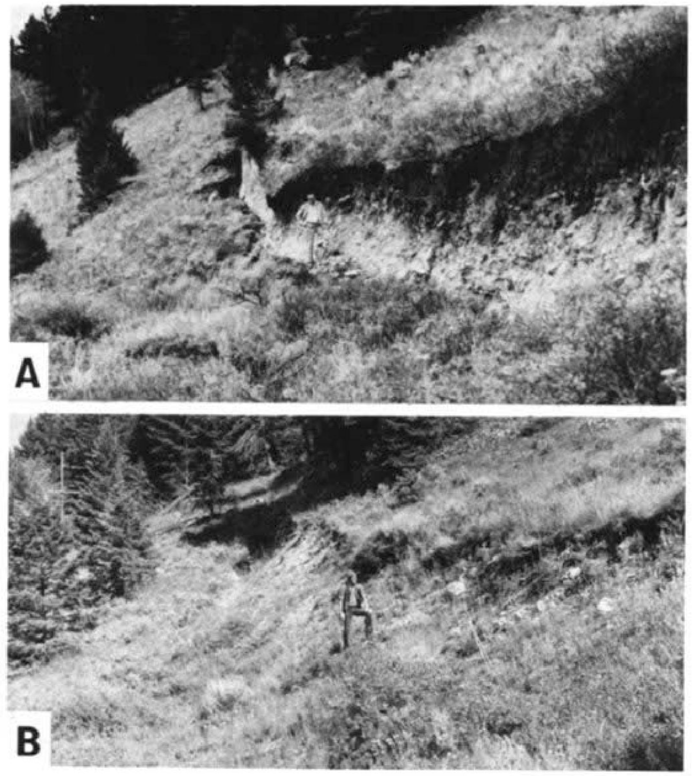

Figure 7. View to west along Hebgen fault scarp 5 km southeast of Hebgen Dam in (A) 1959 (photo by J. R. Stacy) and (B) 1978.

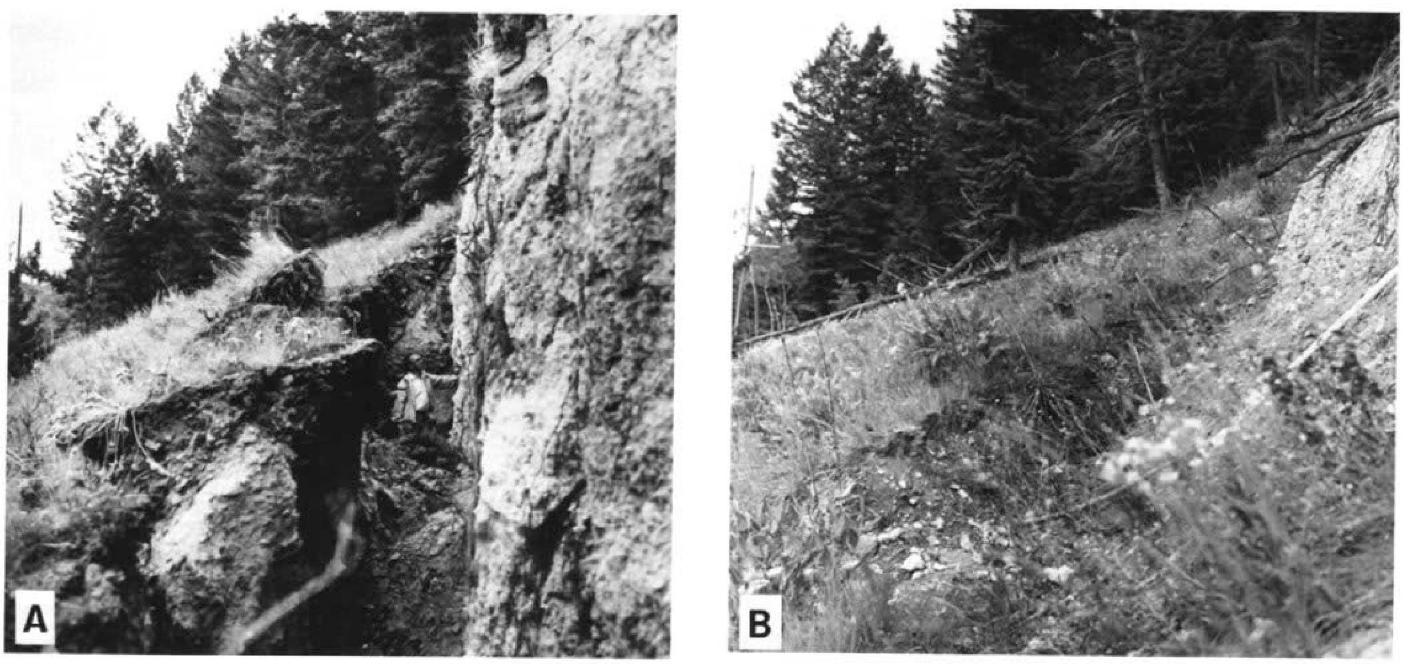

Figure 8. View to west along Hebgen fault scarp 5 km southeast of Hebgen Dam in (A) 1959 (photo by J. R. Stacy; see Witkind, 1964, Fig. 24) and (B) 1978. In 1959 just the tip of a root was exposed that in 1978 was bared for 1 m (upper right).

graben at its base had largely disappeared and were evident only as a gentle slope toward the main scarp. A few such scarplets between 0.5 and 1 m high still retained slopes as steep as 29°.

The fines eroded from the scarp had accumulated in the areas of the grabens at the scarp base, although where external drainage is present, some must have been carried far from the site of the scarp.

Scarp at Red Canyon Creek. Figure 4 shows the appearance of the Red Canyon fault scarp about 60 m west of Red Canyon Creek, and Figure 5 shows comparative profiles of the scarp at that locality. The scarp developed in predominately fine-grained colluvium and alluvium, although clasts of pebble and cobble size are imbedded in the fine-grained matrix.

In 1959 the scarp is estimated, by measuring dimensions from photographs, to have sloped southward between 65° and 90°; the material at the crest, which was supported by roots, overhung the main part of the scarp. A small graben lay at the base, and a tree had dropped with the graben block. By 1978 the slope of the scarp had declined to about 40°, and material from the upper half of the scarp filled the graben and spilled out to the south over the graben's lip. The lower metre of the scarp was dominated by loose angular clasts of pebble to cobble size that form slopes of about 25°. The main part of the scarp was supported primarily on relatively fine-grained material that contains a considerable fraction of clay, so that the material bonds and molds when wet and is stiff and brittle when dry.

The large boulders underlying the valley floor of Red Canyon Creek have resisted erosion and "stabilized" the knickpoint in this creek. In contrast, the knickpoint in Cabin Creek eroded very rapidly and permitted Cabin Creek to achieve grade within a year (Morisawa, 1975, p. 204). At Red Canyon Creek, the knickpoint in the stream profile produced by the fault scarp had retreated differentially. The principal break in slope in 1978 was supported by several boulders more than 1 m in diameter which lay about 15 to 16 m upstream from the scarp base (Fig. 6). This break in slope, or knickpoint, was between 1.5 and 2 m below the general level of the lowest part of the old valley floor upstream from the scarp. More nearly at the level of the lowest part of the valley floor and 65 m upstream from the scarp base was a secondary knickpoint supported by a large log. In 1978 a very indistinct knickpoint was questionably identified about 170 m upstream from the fault scarp at Cabin Creek.

Scarp on North Side of Hebgen Lake. Figures 7 and 8 picture the Hebgen fault scarp about 5 km southeast of Hebgen Dam in sec. 31, T. 11 S., R. 4 E. A characteristic profile at this locality is shown in Figure 9. The scarp is developed in poorly sorted colluvium ranging from fractions of clay size to boulders 0.5 m in diameter.

In 1959 the scarp stood as steeply as 90°, and the upper part, where held together by roots, overhung the rest of the scarp. A graben more than 3 m deep in places lay at the base (Fig. 8A). In 1978 parts of the scarp still constituted a free face and stood at angles of between 70° and 80° (Fig. 8B), but in general the slope had declined to about 40° in the upper, steeper parts and to about 35° in the lower parts where the angle of repose of pebble- and cobble-sized clasts exerted the principal control. Small scarplets—a few metres from the base of the main scarp and less than 0.5 m high—could still be identified, and some still stood at angles above 30° in 1978.

Scarp at Cabin Creek. Profiles of the Hebgen fault scarp near Cabin Creek (SE¼ sec. 15, T. 11 S., R. 3 E.) are shown in Figures 10 and 11. The profile in Figure 10 was measured across the scarp about 10 m east of the eastern margin of the flood plain of Cabin Creek. Here the scarp in 1959 was about 4.9 m high and had slopes ranging between 70° and 90°. In 1978 the scarp crest had retreated at least 1 m, as estimated by the exposure of tree roots which were bared to about 1 m in 1959 and to between 2 and 2.5 m in 1978. Under the tree roots, colluvium of flat, angular clasts of pebble size stood vertically or overhung in 1978. Below this steep segment, the slope had declined to a quasi-stable angle of slightly more than 40°, a common slope angle of the scarps. At the toe, angular clasts had accumulated to stand at slope angles between 20° and 30°.

Figure 11 is a profile measured across the scarp about 10 m west of the eastern margin of the flood plain of Cabin Creek. Slope angles of as much as 62° in the upper part of the profile suggest that those segments should be termed free faces; however, material not only falls from those steep parts of the scarp to lower parts, but it also slumps and moves by processes of flow.

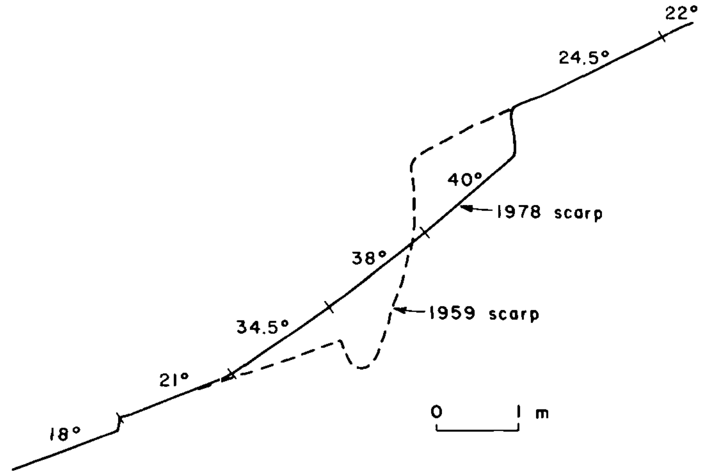

Figure 9. Profile of Hebgen fault scarp 5 km southeast of Hebgen Dam. Solid line measured in 1978. Dashed line estimated from photographs taken in 1959 (see Fig. 8A).

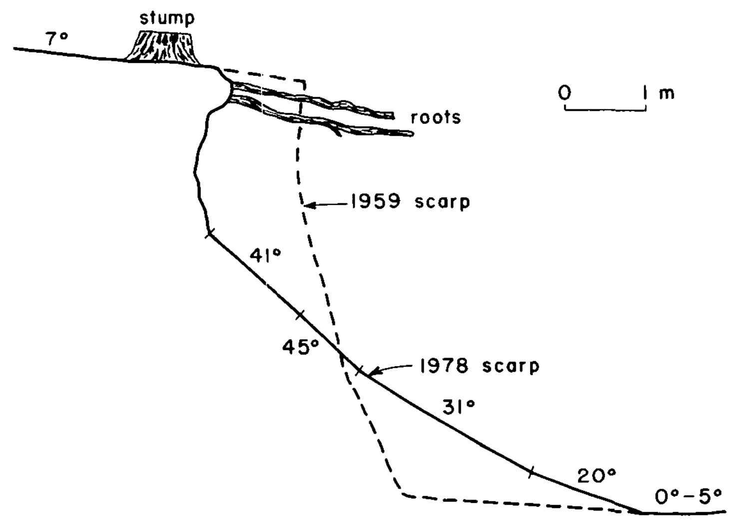

Figure 10. Profile of Hebgen fault scarp about 10 m east of eastern margin of flood plain of Cabin Creek. Solid line measured in 1978. Dashed line estimated from photographs taken in 1959.

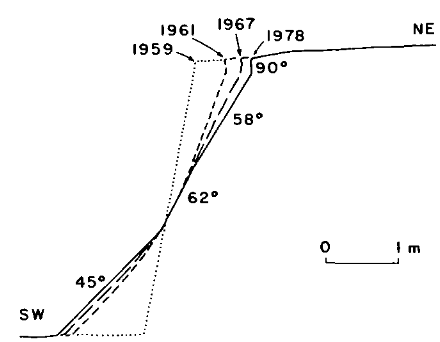

Figure 11. Profiles of Hebgen scarp about 10 m west of eastern margin of flood plain of Cabin Creek. Solid line measured in 1978. Profiles of 1959 and 1961 estimated from photos by Morisawa (1975); profile of 1967 estimated from photo by M. G. Bonilla.

Madison Range Scarp. The Madison Range scarp described by Pardee (1950) was reactivated in 1959, and displacements of as much as 1 m were recorded along a segment of the old scarp south of the Madison River (Myers and Hamilton, 1964; Witkind, 1964). The old scarp ranges in height from 10 to 30 m; thus the 1959 scarp represents only a small segment of the total height of the scarp. The small scarp created in 1959, nevertheless, was still conspicuous in 1978, and slopes of 45° to 60° still existed even where the scarp was only 0.2 m high. Clearly, however,

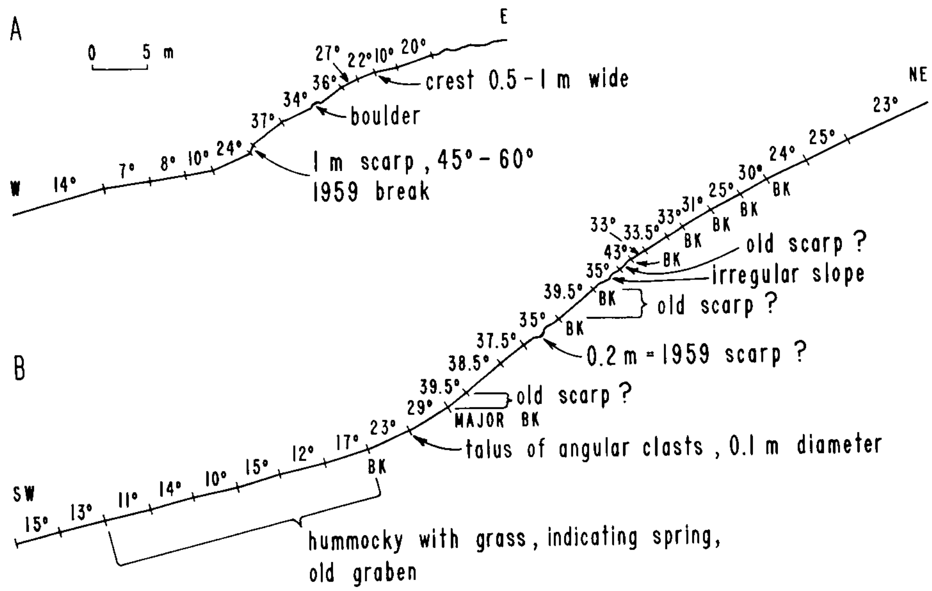

Figure 12. Examples of profiles of Madison scarp where reactivated in 1959; (A) 300 m south of Little Mile Creek, north edge sec. 25, T. 12 S., R. 2 E.; (B) 800 m north of Madison River, east edge sec. 34, T. 11 S., R. 2 E. BK indicates break in slope. Steep segments and sharp breaks in slope may represent old displacements accompanying earthquakes.

at sites where the scarp lies along a hillside hundreds of metres high—on which slopes of 30° to 35° are characteristic—the wash and downhill movement of colluvium will soon obscure the 1959 scarp, possibly within a century. Where the fault crosses rock trains, rocks have been rotated or rolled by the 1959 displacement, and these may be identifiable for several centuries by a study of lichen development or lack of it on the rocks. Pardee (1950, p. 373) noted a tree about 150 yr old on the scarp and concluded that "the scarp has existed in its present form since about 1770." The implication that the last displacement on the scarp was before 1770 is not necessarily correct. For example, most trees on the scarp were not killed by the development of a 1-m-high scarp in 1959, and if the total height of the scarp is a result of repeated displacements of a few metres each, many trees could survive on parts of the scarp not directly affected by the more recent scarplets.

The profiles in Figure 12 suggest multiple displacements. In the profile shown in Figure 12B, the slope of 39.5° near the base of the scarp above which are slopes of between 37.5° and 38.5° may represent an increment of older fault displacement. Similarly, the segment having a slope of 43° about two-thirds of the way up the scarp may represent an even more recent increment of displacement. Near the crest of the scarp, the segments between which breaks in slope are recorded possibly represent facets of an older part of the scarp that have degraded by different amounts. The implications of such complex scarps are discussed by Wallace (1977b).

In summary, the Madison scarp probably was produced by the cumulative displacement of many events of one or a few metres each, similar to what happened in 1959. Slope angles of 39° or more on some parts of the scarp, angles very similar to those developed on the main Hebgen scarps in only 19 yr, suggest displacements not more than a few hundred years old.

Comparison with Fault Scarps in Nevada. The sequence of forms accompanying the degradation of scarps in the different climates and materials of Montana and Nevada is similar, but the rate of degradation in Montana is much more rapid. Faces clearly identifiable as "free faces" were beginning to disappear on the Hebgen scarp after only 19 yr, whereas about 80% of the length of the 1915 Pleasant Valley, Nevada, scarp still displays a free face. Many of the slopes that might be considered to be debris slopes along the Hebgen scarp stand at angles of 35° to 45° and appear to be quasi-stable. Along the Nevada faults, the debris slopes almost universally stand at angles less than 37°, generally at 30° to 35°. The difference appears to be attributable to a greater abundance of fines including clay along the Hebgen Lake scarps. These fines bond the material and make it relatively plastic and able to flow when wet, but stiff when dry. In Nevada the colluvium and alluvium contain clasts dominantly sand sized or coarser so that materials on the debris slopes are mostly loose and unbonded. In the two regions, both the types and rates of erosion processes differ markedly between summer and winter.

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