Profiles and ages of young fault scarps, north-central Nevada

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ABSTRACT

The geomorphic characteristics of young fault scarps can be used as a key to the ages of fault displacements.

The principal features of scarps younger than a few thousand years are a steep free face, a debris slope standing at about 35°, and a sharp break in slope at the crest of the scarp. The principal slope of older scarps declines with age, so that scarps of about 12,000 yr of age have maximum slope angles of 20° to 25°, and slopes as low as 8° to 9° represent ages much older than about 12,000 yr. The crestal break in slope broadens with age.

The material in the scarp face, whether loose fanglomerate or indurated bedrock, controls to a large extent the rate of scarp degradation.

Where more than one displacement has occurred along a fault, a composite or multiple scarp develops. Composite or multiple scarps suggest mean recurrence intervals on individual faults measured in thousands of years.

INTRODUCTION

The identification of faults that may generate earthquakes has become an important task in assessing the hazard and risk of earthquakes and in developing hazard-reduction procedures. Faults are important both because they are the sources of energy for earthquakes and because of the hazard of ground-surface displacements along them.

Faults that can be expected to have displacements within the lifetime of a structure or engineering project have been termed "active faults." The criteria for "active" have included both historic seismicity and geologic evidence of displacement in the recent geologic past, generally late Quaternary. For this paper I have chosen to use the term "young faults," which is intended to be less specific in that an older age limit for the most recent displacement is not defined.

In many places young faults are first recognized by their geomorphic expression. In the Basin and Range province most young faults have a vertical component of displacement, so that conspicuous fault scarps throughout the province form steps in the alluvium or colluvium at the base of the typical block-faulted ranges.

The intent of this study is to bring about a better understanding of the geometry and mechanics of the block faulting, the history and habits of recurrence of fault displacements (both along individual faults and in the province as a whole), and the patterns of migration of seismic and tectonic activity.

Given more than 10,000 km of total length of major young faults in the Great Basin, analysis of geomorphic characteristics of fault scarps provides one of the most important methods of studying the recent tectonic history of the region. Within this context the present study attempts to quantify, as far as possible, some characteristics of scarp morphology and to relate the change in morphology to the aging or degradation process. I am hopeful that a useful and easily applied key to the ages of scarps will evolve. To date, only moderate success has been achieved, primarily because independent evidence of the ages of scarps is sparse. However, the characteristics of scarp morphology, particularly scarp profiles, and some further evidence and thoughts on the degradation process are presented here as an aid in interpreting any scarp.

Most of the scarps discussed are in poorly indurated fan gravels, alluvium, or colluvium. Scarps represented by major faceted spurs on mountain fronts, linear mountain fronts, and other lineaments in bed rock are generally not treated here. Although such mountain-front features commonly reflect faulting, they may be older than several hundred thousand years and may involve parallel retreat of mountain fronts and other processes beyond the scope of this paper.

An important assumption in this study is that the displacements on those faults analyzed occurred principally as sudden offsets were accompanied by earthquakes, rather than as slow tectonic creep. I know of no examples of tectonic creep on faults within the Great Basin.

Among many significant earlier studies of Basin and Range faulting are those by Le Conte (1889), Spurr (1901), Davis (1903), Louderback (1904), Gilbert (1928), and Nolan (1943). D. B. Slemmons (1967) and his students analyzed aerial photographs of the entire Basin and Range province to interpret the history of young faulting. A paper by Thompson and Burke (1974) provides an excellent review of current geophysical data on faulting in the province.

The present study attempts to establish a more quantitative basis for the further analysis of young faults in the Basin and Range province. A pilot study area was selected in north-central Nevada, between lat 40° and 41°N and long 117° and 118.5°W (Fig. 1) where many young faults are located, including the scarp produced during the Pleasant Valley earthquake in 1915, and where shorelines of glacial Lake Lahontan provide an important key to the age of faulting. Topographic maps of the Winnemucca, Reno, and Lovelock 2-degree sheets in the U.S. Geological Survey series (scale 1:250,000) can be used as a guide to the locations given in this paper.

NOMENCLATURE

Terms used in this paper that refer to different parts of a fault scarp are taken primarily from Wood (1942), Young (1972), and Cooke and Warren (1973). These authors deal with the general problems of slopes and slope processes rather than with fault scarps specifically. The terms that are used here for different parts of fault scarps are shown in Figures 2 and 3.

The *upper* and *lower original surfaces* are the segments of the original surface that have been separated by faulting. The *toe* or *base* of the scarp and the *crest* of the scarp are, respectively, the lower and upper extremes of the fault scarp; *free face* is the exposed surface resulting from faulting or succeeding gravity spalling; *debris slope* is the talus slope accumulated below the free face; and *wash slope* is any part of the scarp controlled by fluvial erosion or deposition.

The terms *wash-controlled slopes, debris-controlled slopes,* and *gravity-controlled slopes* are defined by Cooke and Warren (1973) and are useful in discussing the process control of slopes. The term *slope replacement* refers to the process of

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Geological Society of America Bulletin, v. 88, p. 1267–1281, 20 figs., September 1977, Doc. no. 70905.

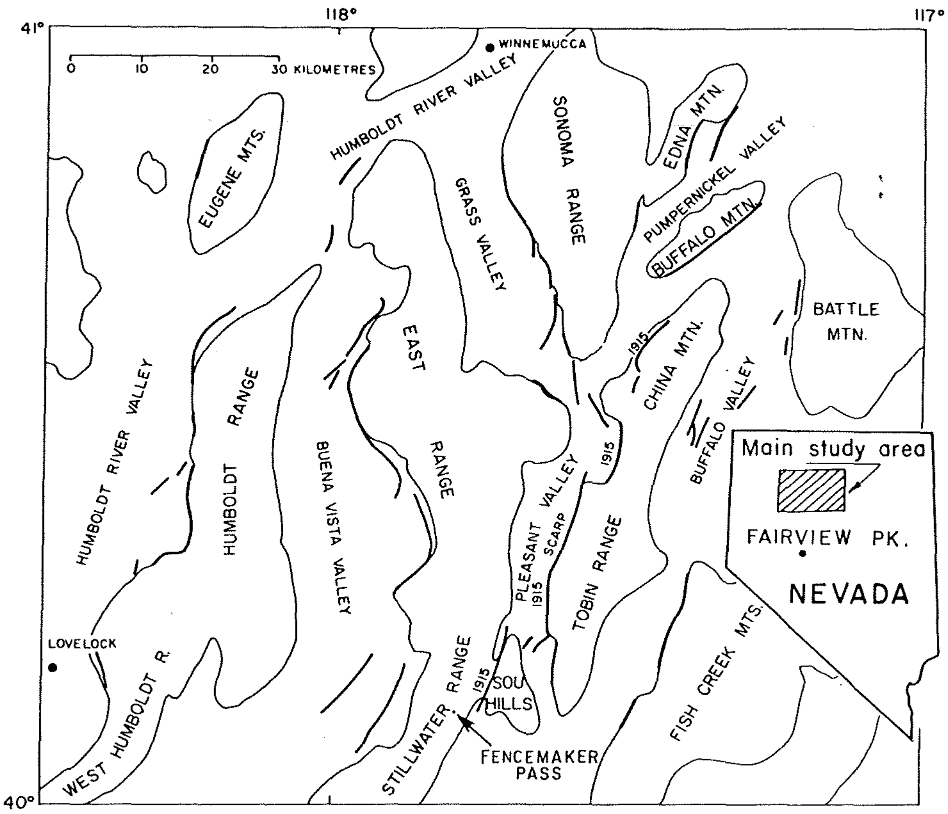

Figure 1. Index map. Heavy lines are scarps along young faults.

changing the original fault surface to a surface controlled by erosion (Young, 1972). *Slope decline* is the decrease in slope angle with age (Young, 1972).

I have chosen throughout this paper to use the term *fault scarp* or *scarp* for all of the scarps described, although in some places the term *fault-line scarp* might be more applicable. For most of the scarps studied, the original fault displacement still is the principal origin of the relief feature referred to, although erosion has greatly modified some segments of the scarps.

CHARACTERISTICS OF INITIAL SCARPS

The characteristics of scarps immediately after inception are well represented by those developed during the earthquakes of 1954 at Fallon-Stillwater (Slemmons, 1959; Tocher, 1959). Photographs taken by Karl Steinbrugge (Figs. 4A, 5A) and D. B. Slemmons shortly after the earthquakes were made available to me, but I did not see the scarps until 1957.

The initial scarps or fault planes generally dip away from the upthrown block at angles ranging between 50° and vertical, but in places the scarp overhangs, that is, dips steeply toward the upthrown block. The overhang does not represent thrusting but merely irregularities in the response to extension in the upper several metres of alluvium or colluvium. Sixty degrees approximates the angle of rupture to be expected for normal faults from laboratory and theoretical considerations and approximates the angle commonly found in underground exposures of range-front faults. Steeper fault surfaces, as much as 90° or more, generally represent response of surficial materials to tensional fracturing.

Very commonly an open crack or graben at the base of the scarp accompanies this type of faulting. The crack may be from a metre to more than 5 m deep and a metre wide. Grabens, in places complex, range in width from a metre to a few tens of metres wide and are 1 to 2 m deep. Open cracks soon become filled with debris, although Page (1934, p. 703, Fig. 11) found that deep cracks persisted at least until the 1930s after the Pleasant Valley earthquake of 1915.

Bed rock is exposed in only a few places in the scarp face, although the scarp may develop at the base of a mountain front only a few metres from bed-rock outcrops. Generally, the new scarp is faced with alluvium or colluvium.

The crest of the scarp commonly overhangs where roots of vegetation support the upper soil units. Clumps of vegetation may slide off the crest and come to rest at the base of the scarp or at intermediate points.

In places the faulting is distributed over widths of several metres so that no single scarp more than 0.3 m high is developed, and the fault may grade into monoclinal warping. Vegetation is only partially disturbed and continues to grow.

PROCESS OF SCARP MODIFICATION

A review of the literature about slopes is not possible here, but a few references can serve to introduce the reader to the range of processes recognized and the problems remaining. Books by Carson and Kirkby (1972), Young (1972), and Cooke and Warren (1973) provide excellent reviews. Papers that are particularly pertinent include Ahnert (1971), Carson (1971), Cooke and Reeves (1972), Cotton (1952), Davis (1892, 1954), Fair (1947, 1948), Gilbert (1877), Horton (1909), Kirkby (1971), Lawson (1915), Leopold and others (1966), Melton (1965a, 1965b), Meyer and Kramer (1969), Penck (1924), Schumm (1956), Strahler (1956), and Wood (1942).

A fault scarp, once it has been formed, immediately begins to change through the processes of erosion. Loose clasts fall from the face under the influence of gravity, and rain washes material from the face and distributes it below the scarp. Frost heaving and other processes contribute to the degradation.

The shape and configuration of the original scarp are controlled by the processes of faulting or fracture mechanics and properties of the faulted materials. Two phases in the succeeding changes of the scarp can conveniently be referred to as "slope replacement" and "slope decline" (Fig. 3; Young, 1972).

In the process of change, the slope of the original fault plane or scarp (Fig. 3A) is replaced by one controlled by erosional processes. In the early stages of slope replacement, the dominant erosional process is gravity spalling from the free face (Wood, 1942; Young, 1972) and accompanying accumulation of debris at the scarp base (Fig. 3B). As time passes, water erosion or wash becomes the dominant process, and the slope changes in angle (slope decline) as well as configuration (Figs. 3D and 3E). Cooke and Warren (1973) classified slopes in categories according to the dominant process as "gravity-controlled slopes," "debris-controlled slopes," and "wash-controlled slopes."

Parallel slope retreat, which in some places is a major element of slope development (see review by Young, 1972), does not appear to be an important factor here for scarps less than a few tens of thousands of years old. Repeated faulting, within periods of a few thousands of years at least, has occurred on the same scarp line, thus little slope retreat is indicated. On a longer time scale, however, linear mountain fronts appear to be kilometres away from the causative fault line, indicating large-scale slope

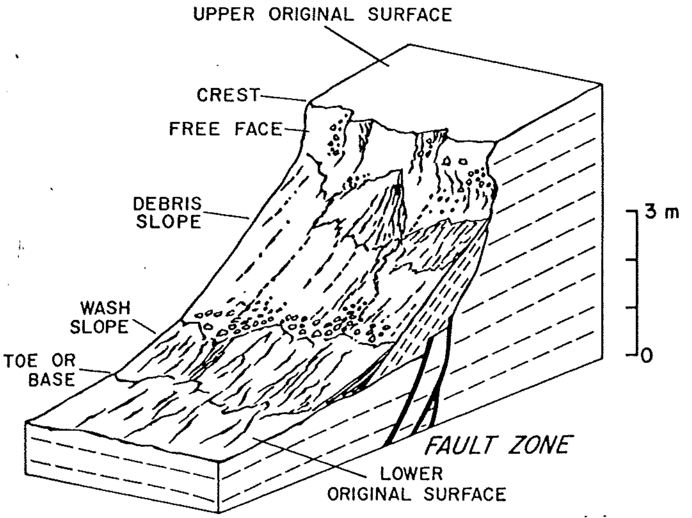

Figure 2. Block diagram of a fault scarp showing terminology used in this study.

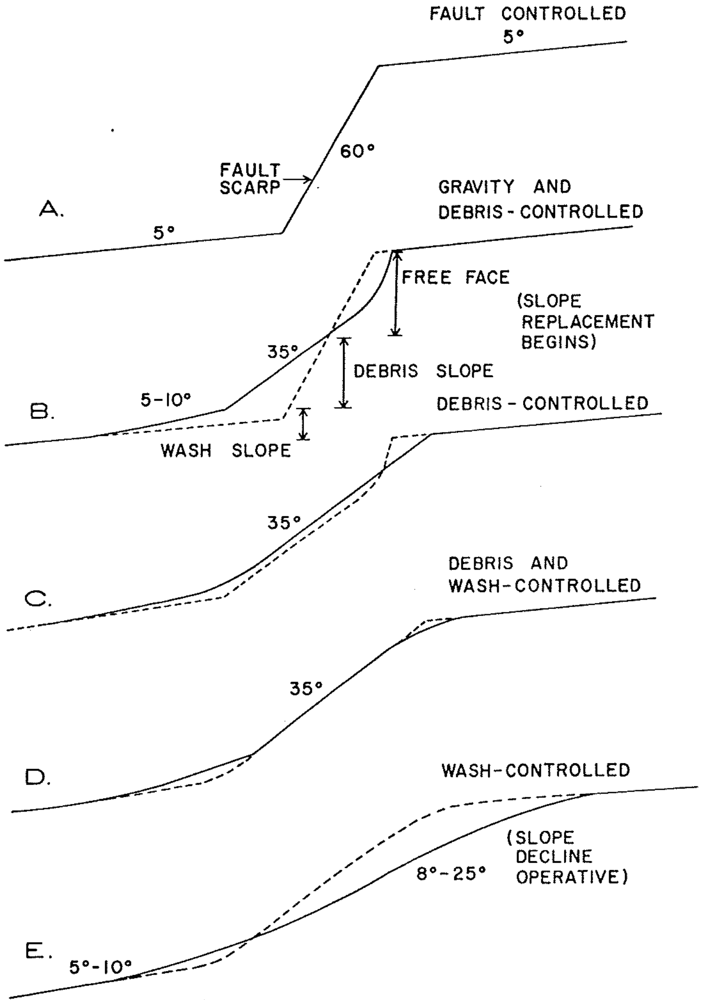

Figure 3. Sequence of fault-scarp degradation. To show incremental change, dotted line represents solid line of previous profile.

retreat. An example of this can be found along the east side of the Humboldt Range (see profile on Unionville quadrangle map, Wallace and others, 1969). The time involved for this amount of retreat can only be poorly assessed but may be millions of years for kilometres of retreat.

Free Face

The initial fault scarp is a free face in which the original rock (here most commonly fanglomerate or colluvium) is exposed. The face immediately begins to spall. Pebbles, cobbles, and boulders, as well as finer clasts, break loose and fall from the face. Larger blocks of indurated material several metres in size break away and fall to the base of the free face where they begin to disintegrate. Within a few months or years, the original face may have retreated many centimetres. Comparison of photographs of a part of the scarp developed during the earthquake of December 1954 (Figs. 4 and 5) taken in 1974 and 1954 shows that the free face in places retreated more than 2 m in the 20-yr period. That particular part of the scarp is in poorly indurated fanglomerate that is characteristic of many of the faulted fans studied. In contrast, a scarp in well-indurated colluvium displaced by the 1915 fault shows almost no spalling in 60 yr.

The slope of the free face is generally between 45° and overhanging. The top of the free face overhangs the lower slopes very commonly, because the upper few centimetres or metres of the near-surface materials are better bonded either by plant roots or by induration related to soil development. Erosion of the looser material below undermines the overlying material, which then breaks off and falls to the base of the slope, temporarily leaving sizable irregularities in the otherwise relatively smooth debris and wash slopes that are developing.

Surface runoff flows over the crest of the scarp and down the free face. Rills notch the crest and channel the free face. The lower part of the free face generally joins the debris slope below at a sharp discontinuity in slope. As the debris slope advances up the free face, however, areas are created near the junction that are sometimes difficult to assign to one or the other. In Figure 3B, the free face is illustrated as composed entirely of a spalled surface, and the lower part is shown to grade evenly into the debris wedge below. Typically, the lower part of the original scarp is rapidly covered by debris, preserving the original 60° to 90° scarp angle, whereas the upper part becomes buried only after some lowering of the angle of the free face by spalling. The buried surface of the free face thus is convex upward (Wood, 1942).

At some places the scarp is gullied, but as the scarp ages the smaller gullies are subdued, and only the throughgoing channels are conspicuous. The lower the slope angle, the less sensitive is the scarp to the various intensities of gully wash and deposition, so that some degree of stabilization is reached. Slopes between 18° and 22° are a modal concentration that may represent some form of stability in the erosional process, but an explanation for this has not been determined. Perhaps the modal grouping of slope angles represents an accident of sampling. On many scarp surfaces, cobbles or boulders are residually concentrated as fine material is removed, leaving armored slopes that are more stable than before.

Crest

The crest or crestal break in slope is between the free face and the original upper surface. Initially, the crest is a sharp break, and it persists as a sharp break in slope as long as the free face exists. The crest migrates away from the original scarp as spalling proceeds on the free face. After the free face has disappeared, the crest becomes more and more rounded. The profile of the rounded crest is convex upward, and the highest part of the curved surface approaches the slope of the upper original surface asymptotically. A typical set of slope angles at 4-m intervals downslope from the upper original surface might be 3°, 3.5°, 4°, 5°, 6.5°, 9°, 12°. Theory for the development of such a curve is incomplete. Rain splash has been suggested by Mosley (1973) as an important factor in developing the convexity of badland divides. Gilbert (1909) and Jerusalem (1973) proposed other theories for the development of convex hillslopes.

Debris Slope

The debris slope is directly below the free face and is composed of loose material that has fallen and come to rest at an angle of repose of about 34° to 37°. For the more common materials derived from fan gravels and colluvium in this region, 35° is a common angle of repose, although smaller and larger angles are found. Melton (1965b) considered that angles in the 34° to 37° range represent the angle of static friction but that angles of about 26° represent angles of sliding friction. In this study few slopes as low as 26° could be demonstrated to be debris slopes controlled by gravity. The debris slopes on the 1915 and 1954 scarps stand at about 35° and are mostly unstable, so that when one attempts to climb the slopes the debris gives away underfoot and becomes redistributed on the lower slopes at only slightly lower angles. In the Sou Hills (sec. 5, T. 26 N., R. 38 E.), a rock train of basalt blocks is intersected by the 1915 fault. The original slope of the train of blocks is between 25° and 27°, but after their disruption the blocks assumed a slope of 30° to 32°. Processes other than gravity alone, possibly frost heaving, must have been active to develop the 25° to 27° slope angles.

Several older scarp features, such as major faceted spurs on the east flank of the Stillwater Range, have slopes between 30° and 35°. The angles possibly are controlled by the angle of stability for debris coating the bed-rock surfaces (Cooke and Warren, 1973, p. 156–157), although large segments are cliffs or free faces.

Coarser blocks and boulders roll to and accumulate at the base of the debris slope and grade upward into finer materials. The finer materials are more susceptible to rill wash, and debris containing a high content of fine material also tends to develop a crust at the surface. In some places fine material

Figure 4A. View looking south along scarp near Fairview Peak as photographed in 1954 by Karl Steinbrugge.

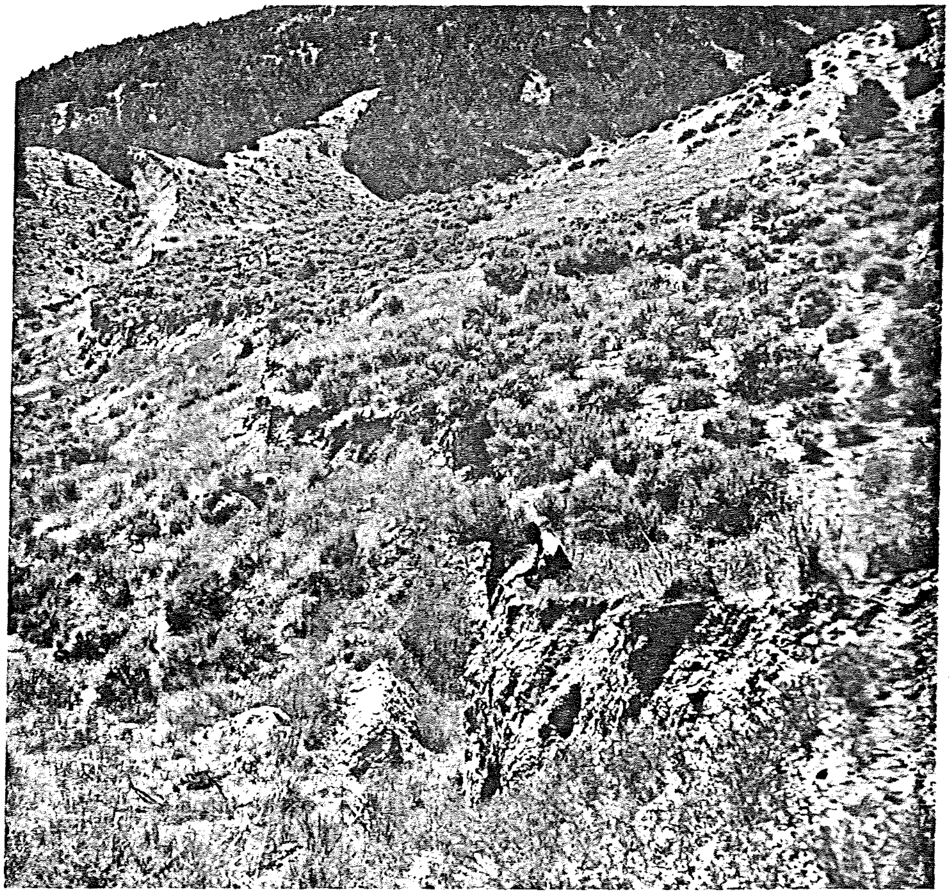

Figure 4B. Same locality as shown in Figure 4A photographed in 1957.

Figure 4C. Same locality as shown in Figures 4A and 4B photographed in 1974. Note retreat of scarp where man knelt in 1957 view.

washed off the free face is deposited as a miniature alluvial fan coating the debris slope immediately below the free face. The principal secondary fans, however, are part of the wash slope described below.

Many of the smaller secondary features are caused by events of low-energy transport, such as light rainfall and frost heave, in contrast to the more energetic cloudburst events that determine the major changes and rates of change.

Wash Slope

Below the debris slope on young scarps a wedge of alluvium commonly develops that overlaps the debris slope and the original fan slope (Fig. 3B). These deposits range in slope from that of the original fan, commonly 3° to 7°, to as much as 10° or 15°. On many older scarps it is difficult to identify the most significant break in slope at the base of the scarp within about 2 m normal to the scarp.

Although in Figure 3 an alluvial deposit is portrayed at the base of the scarp, such a deposit cannot be identified everywhere. Instead, small gullies may cut the base or toe of the scarp and continue down the fan slope to merge with the original distributaries of the fan. At places the gullying is pronounced, especially where the original fan stands at angles greater than about 5.5°. Secondary fans develop at the downhill ends of the newly formed gullies. Angles

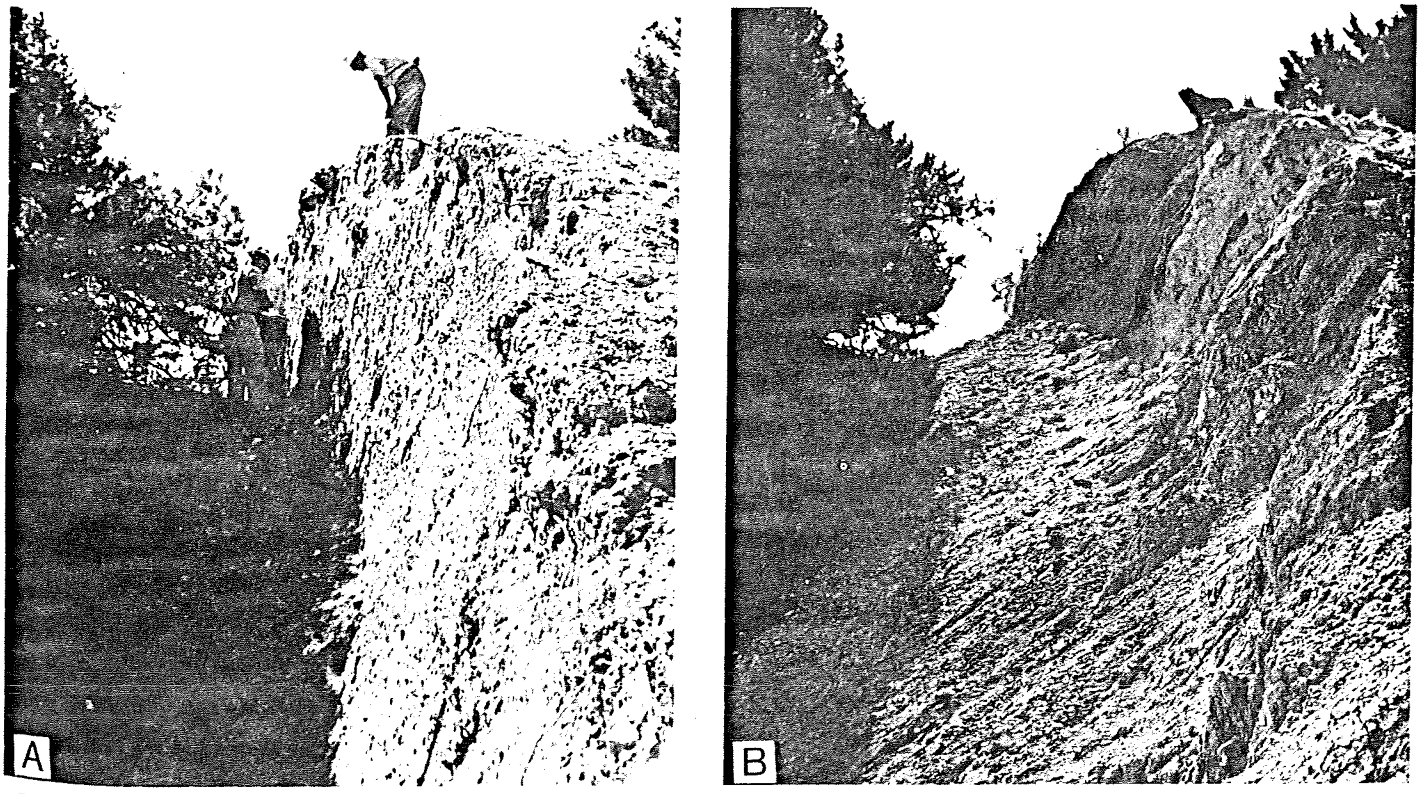

Figure 5. A. Scarp near Fairview Peak produced in December 1954. Photograph taken by Karl Steinbrugge shortly after event. B. Same scarp in 1974. Note debris slope and modified original scarp face.

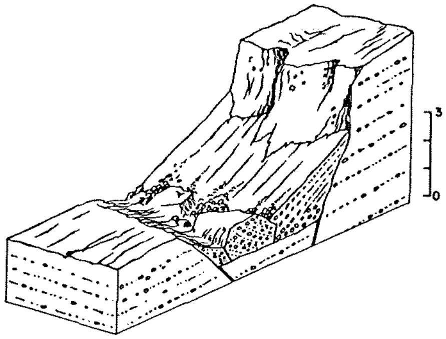

Figure 6. Graben at base of scarp.

steeper than about 7° may be remnants of earlier fault scarps, but in some places the surfaces are undoubtedly warped tectonically.

Wash control implies both erosion and deposition by water. To determine whether a given surface is principally erosional or depositional is often difficult, particularly where dealing with materials that were originally water-laid deposits (such as fan gravels) or partially water-laid (such as colluvium). As a scarp grows older, erosion far outweighs deposition in controlling the shape and slope of fault scarps (Fig. 3E). Evidence that supports erosional control includes (1) rounding and gullying of the scarp crest, (2) gullying of the main scarp face, (3) residual concentration of coarse material on the scarp face after fine sediments are washed away, and (4) gullying at the base of the scarp and farther down the fan slope.

Toe, Original Fan Surface, and Graben

The toe of the scarp may be indeterminate, because the wash slope grades almost imperceptibly into the original alluvial fan and in many places is absent. Where a wash slope is absent below the debris slope, the base of the debris slope may be referred to as the toe of the scarp.

Where the original fan slopes more than about 5.5°, both the wash slope and the fan itself are dissected during periods of heavy runoff. During lighter runoff and during the ebbing phase of larger runoff events, the wash slopes are an environment of deposition.

Major fan slopes steeper than about 5.5° are believed in many places to have resulted from tectonic warping or tilting rather than from deposition. For example, major canyon and gully development dominates on the bajada in secs. 25, 26, 35, and 36, T. 30N., R. 39 E., on the west flank of the Tobin Range, where slopes are greater than 5.5°. At slopes between 3° and 5.5°, gullying is prominent but deposition is also present, so that a degree of balance exists. Below 3°, deposition clearly dominates except for deflation in the playa areas (Wallace, 1961). From these relations it seems likely that slopes between 8° and 14° on the upper reaches of the bajadas or fans must be warped from their initial depositional slopes.

A graben at the base of many scarps (Fig. 6) exerts an important control over the form and curvature of the toe or basal break in slope. The graben produces a sharp discontinuity in slope and thus in the balance between erosion and deposition. Drainage commonly is deflected along the graben so that the basal break in slope is perpetuated as a sharp break.

The toe of the scarp may be greatly modified if renewed faulting has occurred. The new break tends to be at the scarp base or in the midsection of the old scarp, although in places the new fault has broken uphill from the older scarp. The principle of parallel retreat of slopes would tend to require that newer breaks form near or downhill from the base of the older scarp. This concept may be significant in interpreting multiple movements on individual scarps.

Erosional Process Control and Age

Figure 7 suggests the relations between the dominant erosional process acting on scarps in unconsolidated alluvium and colluvium as they age. The shapes of the curves were derived largely by deduction, but the time element is estimated from the data presented throughout this paper. The graph is presented primarily to stimulate thought and observations about the interaction of several processes.

In brief, the arguments for the points on the curves are as follows: After 100 yr, the debris-controlled slope is dominant, but the free face or gravity-controlled slope is still prominent, and a wash-controlled slope also begins to be well developed. After about 1,000 to 2,000 yr, as extrapolated from degradation rates on the 1915 and 1954 scarps, the free face disappears; the slope is then a combination of debris slope and wash slope. After 10,000 yr, rounding of the scarp crest becomes significant. The rounding must start principally after the free face disappears. After 100,000 yr slope decline is in progress, thus slopes are wash-controlled, but the wash-controlled slope is superimposed on a debris slope. The semantic argument might be made that the debris control ceases as soon as the free face is removed and is unavailable to supply debris (see dashed line in Fig. 7). But the debris-slope angle seems to be a stable angle that persists in places for hundreds of thousands of years, so the solid debris-controlled curve is dropped to zero at a rate to suggest this. After 1 m.y. almost all scarps, even those in bed rock, have declined substantially in slope angle, so that wash and other processes are dominant.

Precipitation, Climate, and Erosion

The amount and types of precipitation and runoff are important factors in scarp erosion.

The region studied is considered arid, but annual precipitation varies widely as a function of local relief. In general, the broad intermountain basins at about 1,200 m elevation have between 12 and 20 cm of rainfall annually, whereas higher in the ranges, at elevations of 1,500 to 3,000 m, the rainfall may be 35 to 45 cm. On the average, between 10 and 20 thunderstorms occur annually at any point (Visher, 1954).

Snowfall accounts for a significant percentage of the annual precipitation. Freez-

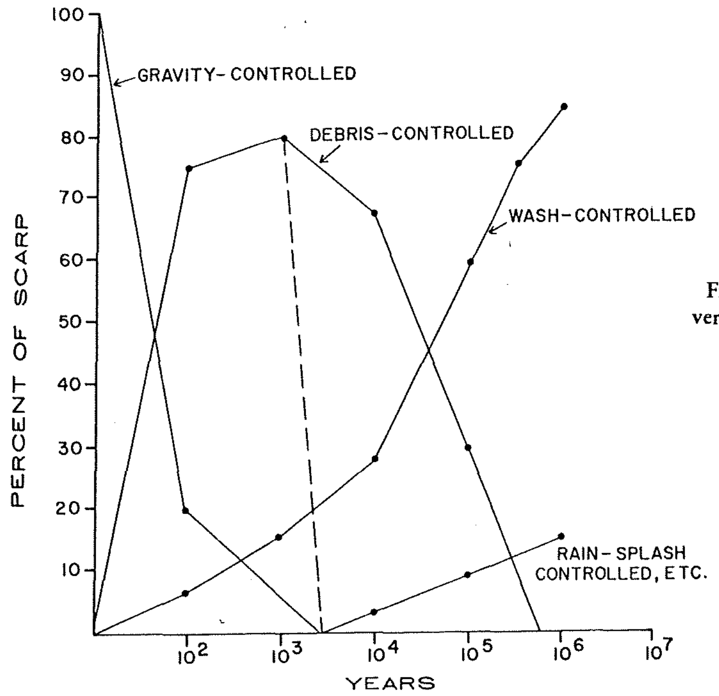

Figure 7. Process control versus age of scarp.

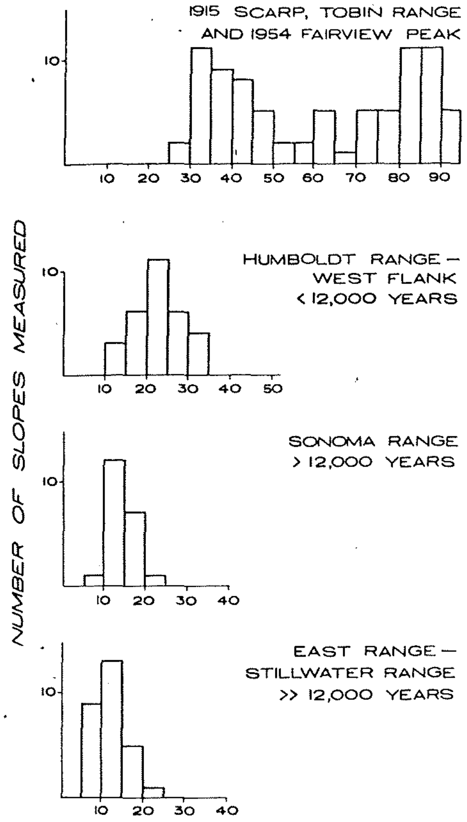

Figure 8. Histograms of principal slope angles on fault scarps, north-central Nevada.

ing temperatures are common from November through March. The average annual number of times of freeze and thaw is between 120 and 130 (Visher, 1954). Frost heave, solifluction, and mudflows are enhanced during the freeze-thaw cycles and are believed to be important in modifying slopes, but no quantitative evaluation of these processes was made during this study.

The rates and processes of scarp degradation must have changed with climate, and the climate surely has changed many times since some of the fault scarps were formed. Morrison (1964, 1965) and Morrison and Frye (1965) described the variations in the level of Lake Lahontan and computed the mean annual temperature and precipitation during the three main late Quaternary weathering optima. I suggested (Wallace, 1961) that more material is leaving the basins by deflation under present-day climatic conditions than is being brought in from the surrounding ranges by fluvial action. Yet at least since late Miocene time, more than 2,000 m of unconsolidated materials has accumulated in the basins by fluvial action.

I have not attempted to evaluate the effects of changing climates and know of no adequate basis for doing so. When more quantitative data are available on fault-scarp erosion in different climates, an adjustment factor possibly can be introduced. For the present, the rates of processes are assumed to be averaged over the past few tens of thousands of years.

MEASURING PROFILES

Several methods were used to measure scarp profiles. The most satisfactory for recording detail and for simple data reduction involved using a telescoping fiberglass stadia rod and Abney level. The stadia rod, either at 3 or 4 m length, was placed on the ground and the slope angle read directly with the Abney level.

Selection of the site for measuring a profile is critical in order to avoid as many complicating factors as possible. For example, if modern or young drainage channels are near and parallel to the scarp base, erosion of the scarp is greatly accelerated, and scarp height may be greatly exaggerated.

CHARACTERISTICS OF SCARPS OF VARIOUS AGES

The primary purpose of this study has been to identify, and quantify as far as possible, characteristics of fault-scarp profiles that would be useful in determining the ages of scarps. The sequence of changes in scarp profiles described above and illustrated in Figure 3 can provide a key to relative ages of scarps. The maximum angles of the principal slope or slopes of younger scarps can be used as a general key to age. The angularity or curvature of the break in slope at the crest of the scarp is also a useful indicator of age. Gross dissection of the scarp is evidence of antiquity, but the main emphasis in this paper is on profiles.

Angles of Principal Slope or Slopes

On most profiles between the crest and base of a scarp are one or two relatively straight segments or "principal slopes." Figure 8 summarizes the principal-slope angles found on about 125 scarp profiles. Each histogram represents a group of range-front or near range-front faults that have continuity or appear to constitute an integrated fault set.

The historic scarps of 1915 and 1954 display two principal sets of slopes. The angles greater than 55° represent the free face and the angles between 34° and 37° represent the stable-debris slope. Angles between these sets represent unstable transitional slopes.

The free face is, geologically speaking, very short lived, so that slope angles steeper than 37° disappear within a few hundred or, at most, a few thousand years. Only a few segments of scarps from 1954 have lost their free faces, whereas many from 1915 have. But a few scarps from 1915 still have very little debris slope, and the free face is still dominant.

The 1915 scarp, 68 km long and cutting a variety of fanglomerates and colluviums, displays a free face over approximately 70% of its length. On the main scarp, near the Pearce School, 80% to 90% of the scarp length retains a free face. At the rate of disappearance of 20% of the free face in 60 yr, at least 300 yr would be required for the free face to be removed entirely, if all scarps were developed in poorly indurated fanglomerate. Well-indurated material very likely can support a free face for a much longer time, possibly for as long as a few thousand years, if the small change since 1915 in some scarp segments is a measure.

The histogram of slopes of the scarps on the west flank of the Humboldt Range represents scarp ages less than 12,000 yr but greater than a few thousand years. Faults of this set cut the high shoreline of Lake Lahontan (age 12,000 yr), but because no free face survives, the scarps are probably more than 2,000 yr old. The measurements are principally from the central part of the range front between Rochester and Sacramento Canyons. Scarps of more than one

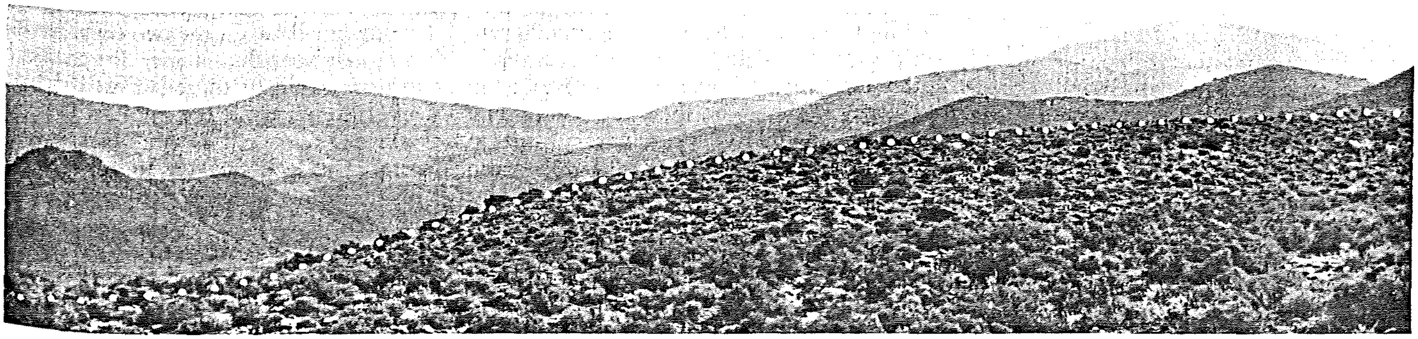

Figure 9. Profile (white dotted line) of scarp at mouth of Rawhide Canyon, northwest flank of Granite Mountain. View northeast. Scarp is believed to be much older than 12,000 yr.

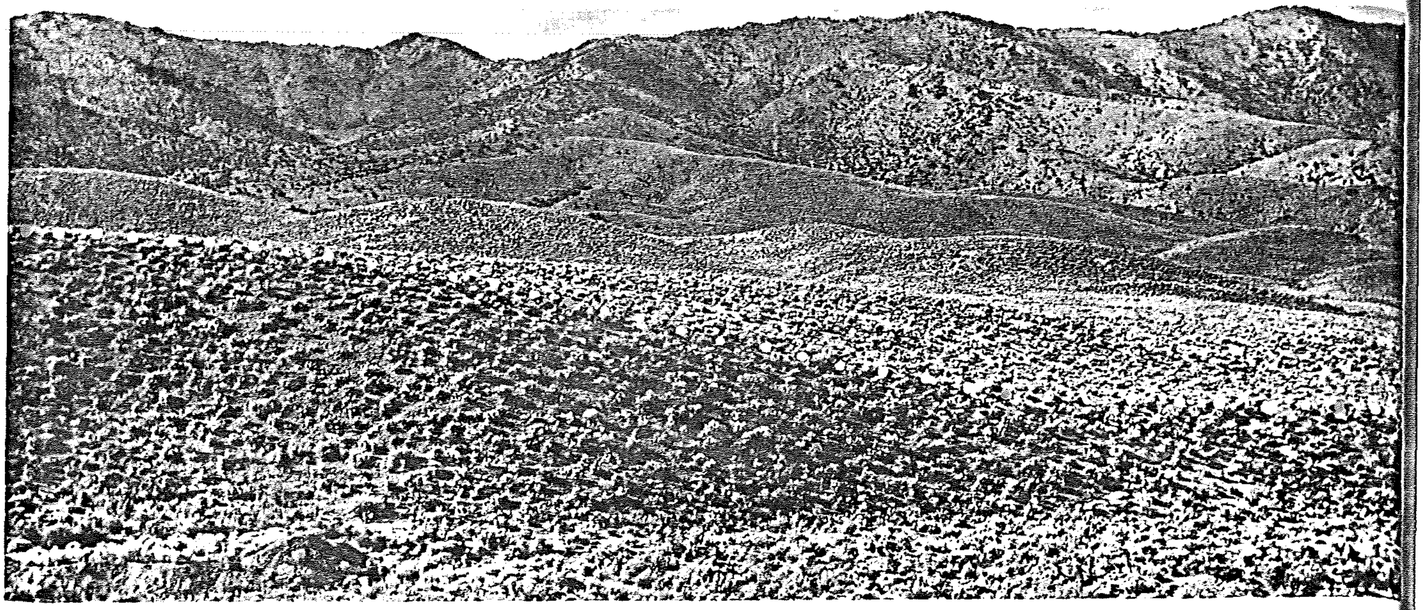

Figure 10. Profile (white dotted line) of scarp at mouth of Rockhill Canyon, East Range. View south. Scarp is believed to be much older than 12,000 yr

age are known to exist there but have not yet been adequately sorted out. The principal characteristics of this age group are a modal peak of slopes in the range of 20° to 25° and a sharp break in slope at the crest. A few slopes steeper than 30° are found, but none are as steep as 35°. The stable debris-slope phase thus may have been largely replaced by the wash-slope phase. The sharp break at the scarp crest is less than 1 m wide in several places.

A group of scarps along the west flank of the Sonoma Range is characterized by principal slopes in the 10° to 20° range. I have no direct evidence yet of the age of these scarps, but by comparison to wave-cut cliffs of Lake Lahontan which have a modal concentration near 20°, I assume they are somewhat older, although since a few slopes are 20° or even greater, they may not be greatly older than 12,000 yr.

The slope angles of scarps along the west side of the East Range (Figs. 9, 10) and the north end of the Stillwater Range are considerably lower, on the average, than those of the other three sets of fault scarps. Most are in the 10° to 15° range, and many are only 8° or 9°. At several points scarps of this set are truncated and beveled by Lake Lahontan so that they clearly are older than about 12,000 yr. If slope angle is a valid criterion and slopes decline as postulated, these scarps must be considerably older than the high stand of Lake Lahontan.

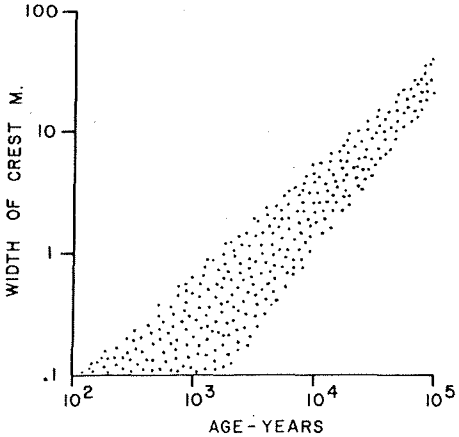

Figure 11. Graph showing width of crestal break in slope versus age of scarp.

In addition, the crestal break in slope of the scarps along the East and Stillwater Ranges is commonly many metres wide as compared to widths of 3 m or less for the crestal break of wave-cut cliffs, along Lake Lahontan and widths of less than a metre for younger scarps.

Effects of Materials

The type of material in which the scarp is produced greatly affects the rate of degradation. In Figure 11, I have postulated curves for principal slope angles against age of fault scarp. The curves are intended to circumscribe the major field of scarp slopes of various ages and in various materials. The curves are interpolated between very few control points and are based on several assumptions.

Initial slopes of between 50° and 90° are characteristic of fault scarps. Scarps in fractured bed rock are essentially unchanged in 100 yr, as shown on the upper curve (Fig. 12 ~~11~~). Fractured bed-rock mountain fronts in this region commonly have slopes between 30° and 35°, and these slopes persist for hundreds of metres vertically. This amount of relief represents a million or more years. Thus a plateau in the fractured bed rock curve seems to be necessary to represent the stable slope of faceted mountain fronts. Mountain fronts believed to be 10 m. y. old have slopes of approximately 15°, thus setting the oldest point on the upper curve.

The lower curve, which characterize scarps in fanglomerate, indicates that debris slopes commonly become dominant in 100 yr or less. Slopes of Lake Lahontan (about 12,000 yr old) are approximately 20°. Slopes of fans more than 1 m. y. old are approximately 3° to 5°, thus setting the oldest point on the lower curve. The dashed excursion from the lower curve shows a plateau representing a modal peak in the 18° to 22° range, which may represent a relatively stable angle, but the genetic significance, if any, of this stable angle is not yet understood.

Break in Slope at Scarp Crest

The break in slope at the crest of a scarp appears to be sensitive to degradation and may be useful as an indicator of age. As discussed above, in the early phases of a scarp the break in slope is sharp and angular, representing the break in slope between th free face and the original upper surfac Later it becomes subdued, and on olde scarps the change between the principa slope and the original upper surface is s gradual that one has difficulty identifying dividing line between the two (Figs. 9, 10) it is more a zone than a line. The change i curvature could be more precisely define than I have yet done, but for a simple measurement I refer to it as the "width" of th crestal zone.

Figure 12 illustrates in a crude way the relation between age and degree of roundin of the crestal break in slope. The two assumed points that control the graph are a origin point of approximately 100 to 2,00 yr, the time when the free face disappea and the crestal break is very narrow, and width of the crestal zone of 1 to 5 m for scarps about 10,000 yr old. The later point is based primarily on the width of the break in slope at the crest of wave-cut cliffs in fanglomerate cut during the high stand of Lake Lahontan.

Break in Slope at Base of Scarp

Previous discussion indicates that the curvature of the basal break in slope results from rather different processes than the crestal break in slope. The result is that as the crestal break in slope becomes very subdued and broad, the basal break in slope seems to reach a relatively stable curvature. Thus, on scarps considerably older than 12,000 yr, an asymmetry develops in which the basal break in slope is much sharper than the crestal break in slope (Figs. 9, 10). Generally, I had little difficulty in identifying a break in slope at the base of the scarp within 2 m, whereas the break in slope at the crest of the scarp in places was difficult to identify within 10 m.

Profiles of Dissecting Channels

Fault scarps produce an instant change in the gradient of any channel they intersect. The dominant effect is an increase in gradient, because the uphill block generally has risen, but, locally, grabens or horsts and grabens develop, producing temporary local dams or diversions across the drainage.

Considering only the effect of uplift of the uphill block, streams from rivulet to major wash size very soon begin to erode the lip of the escarpment. This lip or knickpoint then migrates upstream during the process of channel regrading.

Along the 1915 scarp, knickpoint retreat in 59 yr ranged from less than 0.3 m to more than 400 m. The distance of 400 m was measured on a wash in sec. 12, T. 27 N., R. 38 E., which drains approximately 12 km² of the west flank of the Tobin Range. In 1957, the knickpoint was 335 m from the scarp. At Golconda Canyon, also on the west flank of the Tobin Range which drains more than 26 km², the knickpoint could not be identified with certainty, as grade apparently had been fully reestablished.

Where washes are of small or intermediate size, that is, having drainage basins less than 1.3 km², knickpoints may be preserved. Indeed, multiple knickpoints may survive to provide evidence of multiple displacements on the scarp. Figure 13B illustrates a long profile of a channel that dissects a scarp in the SW¼ sec. 17, T. 31 N., R. 33 E. Several breaks in slope suggest knickpoints, possibly as many as seven, but such breaks in slope may have other origins. For example, change in induration or coarseness of sediments in the beds being dissected could produce such steps. In the example illustrated, the breaks in slope in the channel are not reflected in the general relief of the surrounding hillslopes, so that they may indeed represent the retreat of multiple knickpoints.

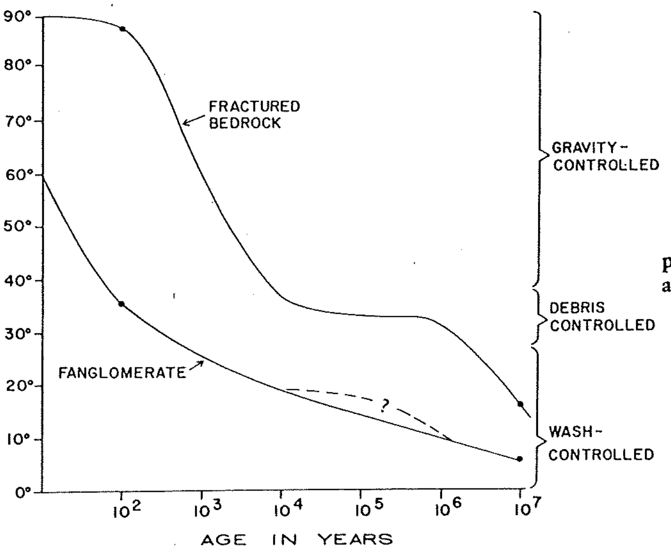

Figure 12. Limits of principal slope angle versus age of fault scarp.

Small benches or terraces on the flanks of dissecting channels are more useful in some places than knickpoints in suggesting the past history of scarps, particularly when they are preserved near the scarp. The profile of a scarp near Leach Hot Springs is shown in Figure 13D. There two small terraces are preserved in a small gulch that dissects the fault scarp. At least three faulting events must have occurred during the total displacement of about 10 m. Significantly, these three events are not reflected as steps or identifiable breaks in slope on nearby segments of the scarp.

Even if benches or terraces are not pronounced, profiles measured across dissecting channels may reveal subtle benches or breaks in slope.

Variables To Be Considered

The importance of underlying materials in causing variations in the rate of slope degradation cannot be overemphasized (Fig. 12). Other important variables include the original height of the scarp, the angle between the fault plane and the slope displaced, the width of the fault zone, and vegetation.

Along a scarp of a given age the taller (higher) segments generally display steeper slopes than lower segments, even though both are in the same materials. One reason is that lower scarps may have a small ratio of scarp height to fault-zone width, so that the scarp originates as a composite scarp, in some places approaching a monocline. But the slopes actually appear to decline more rapidly on scarps 0.3 m high than on those 3 m or more high. The processes of scarp erosion, for example, rivulet and solifluction processes, appear to operate more rapidly at the smaller scale.

Where colluvium or other surfaces standing at slope angles of 25° to 35° are cut by faults dipping 50° to 60°, the result may not be a single fault surface. When the colluvium standing at these angles is loose and unindurated, the loose material adjusts itself to an angle of repose of about 35° after faulting, rather than preserving an exposed fault plane.

Vegetation may hold surface materials together so that they drape over a fault rather than being displaced. The last relic of a free face is commonly found under a bush or tussock of grass where spalling is slower.

Consideration of the variables emphasizes that the characteristics should be noted over a considerable length of a given fault. Almost every scarp more than a few kilometres long cuts a variety of materials. Although the variables may seem to complicate the interpretation, opportunities are also provided. A free face may survive in well-indurated material, whereas fault history might be less well recorded in soft, poorly indurated materials.

DATING SCARPS

Evidence of scarp ages has been sparse. The high stand of Lake Lahontan (about 12,000 yr ago) is an important datum. Some faults clearly cut the high beach line, whereas other fault scarps were truncated and beveled by wave action during the high stand of the lake. Isotopic dates of carbon found in deposits related to the scarps are useful, as are the dates of Mazama ash (about 6,600 yr in age). Ages of trees growing on or near fault scarps provide keys to the past few hundred years. Comparison of old and new photographs taken from the same point provides a means of estimating

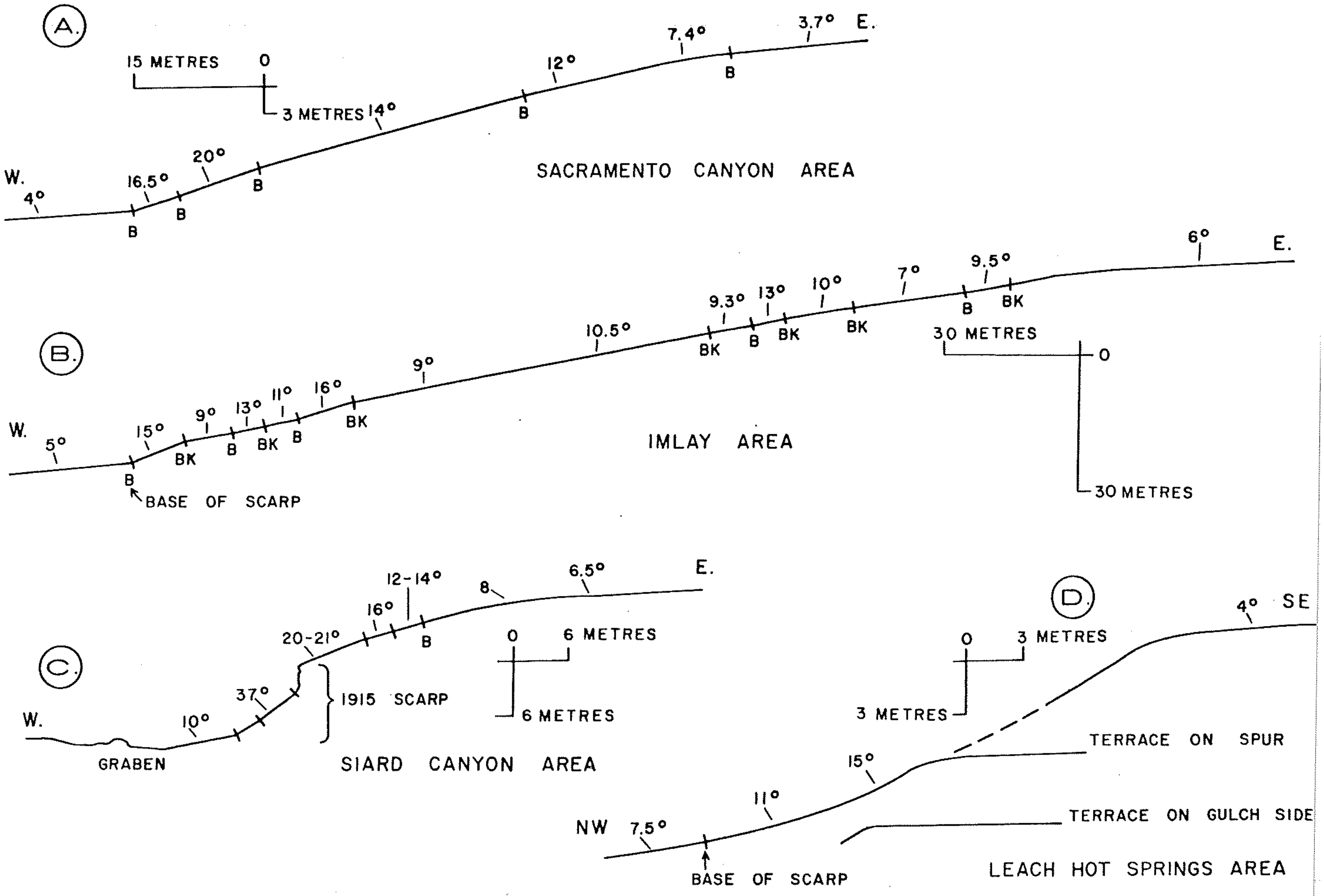

Figure 13. Evidence of multiple displacements on faults as shown by breaks in slope (B) on scarps and dissecting gulches, knickpoints (BK) on dissecting gulches, and terraces on dissecting gulches. A. Scarp profile at mouth of Sacramento Canyon. B. Long profile of gulch near Imlay. C. Scarp profile of 1915 and older surfaces at mouth of Siard Canyon. D. Scarp profile and nearby terraces on dissecting gulch, Leech Hot Springs area.

changes of scarps over a short period. Other methods such as paleomagnetism undoubtedly would prove useful, if suitable material were found and collected for dating, and datable soils, if found in strategic localities, would also help.

Lake Lahontan Beach Lines

A good example of a fault scarp that is truncated at the high beach line of Lake Lahontan is shown in Figure 14. Here, the fault displaces the alluvial fan surface about 6 km (4 mi) north-northwest of the mouth of Fencemaker Canyon on the northwest flank of the Stillwater Range. The fault scarp is preserved where it is above the high stand of Lake Lahontan (1,332 4370 ft. m elevation), but scarps at lower elevations have been obliterated by wave action in the lake. Clearly this scarp is older than the high stand of the lake.

A comparison of the profiles of the fault scarp with the wave-cut cliff (Fig. 15) is instructive, because they are cut in the same material at the same locality. The fault scarp has a maximum slope of 13.5°, whereas the wave-cut cliff has a maximum slope of 20°. The crest of the wave-cut cliff changes abruptly, within 1.5 m horizontally, from 19° to 5°. The fault scarp gradually changes from 13° to 4.5° over a horizontal distance of more than 10.7 m. The lower angle of slope and the more gentle curvature of the crest of the fault scarp suggest that it is not only older but considerably older than the wave-cut cliff.

Radiocarbon Dates

Some carbonized wood was found near the 1915 scarp (NE¼ sec. 3, T. 29 N., R. 39 E.; Fig. 16). The dates determined by Meyer Rubin (1974, written commun.) were 480 ± 200 and 670 ± 200 yr. The carbon was in layers of gravel within 2 m of the surface of the fan and within 10 m of the apex of the fan, which had been graded across the frontal fault zone of the Tobin Range prior to the 1915 faulting. These dates can be used to interpret when the most recent earthquake and faulting prior to 1915 must have occurred, but certain assumptions about processes and rates of processes must be made.

The scarp from the most recent earthquake and faulting before 1915 had been completely obliterated from this segment of the mountain front by 1915. Only the break in slope between bed rock and the alluvial fan remained. The gravels of the fan apex in which the wood was found must have been deposited in the very late stages of the cycle of erosion in which the scarp was obliterated and the fan developed. The age of the wood, therefore, must represent a small fraction of the total time elapsed since the most recent faulting before 1915.

On the basis of radiocarbon dates of tufa, Broecker and Kaufman (1964) postulated that the highest stand of Lake Lahontan occurred twice, about 12,000 and 9,500 yr ago, but Morrison and Frye (1965) expressed the opinion that such dates are 6,000 to 8,000 yr too young. Specimens of tufa and gastropods from an elevation of 1,296 m (about 36 m below the high stand) were analyzed by Meyer Rubin (1975, written commun.) and gave the following ages: (W-3126) gastropods — 10,810 ± 300 yr B.P.; (W-3128) tufa — 11,720 ± 350 yr B.P.

In this paper the age of the high stand is referred to as about 12,000 yr, although the

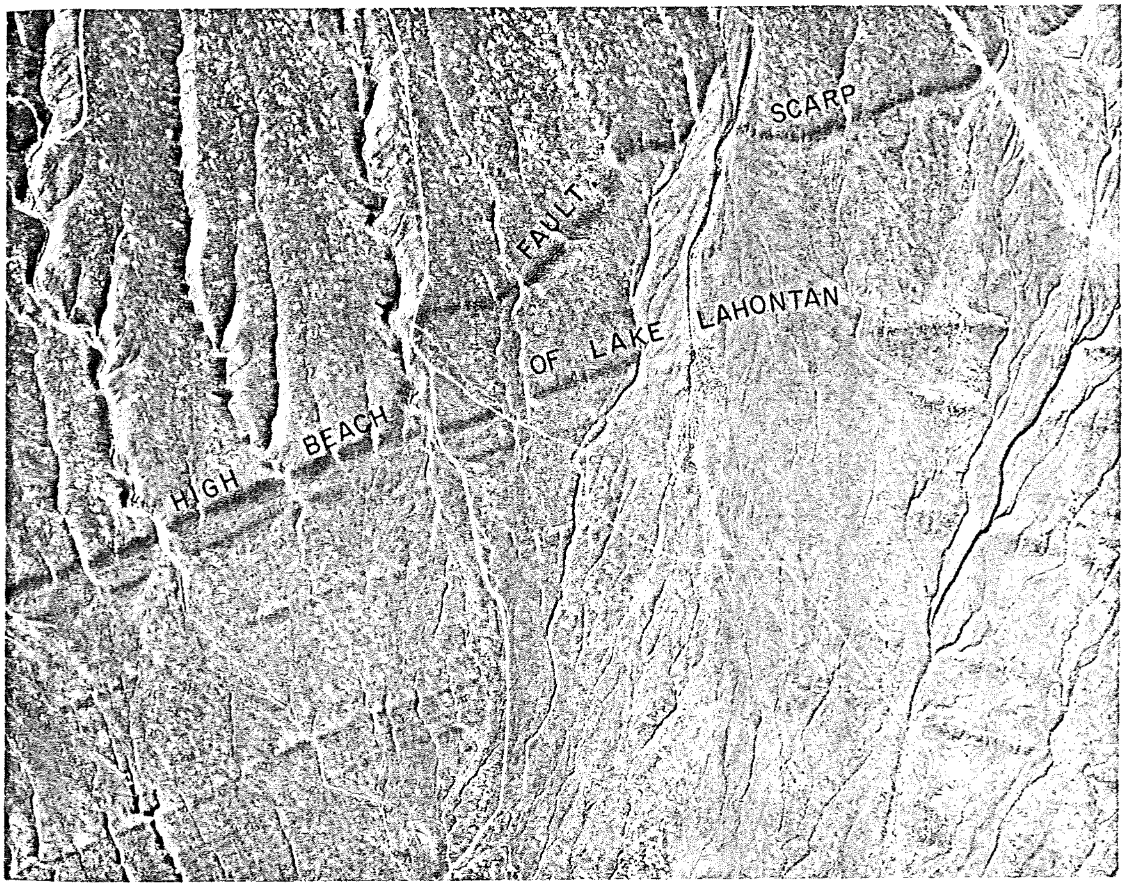

Figure 14. Fault scarp truncated by wave-cut cliff at high stand of Lake Lahontan (about 12,000 yr old). Near Fencemaker Canyon, Stillwater Range.

error may amount to several thousand years.

Mazama Ash

A sample of ash collected from the face of the 1915 scarp where it cut colluvium in the NW¼ sec. 19, T. 30 N., R. 40 E. has been identified by R. E. Wilcox (1974, written commun.) as Mazama ash and dated at 6,600 yr B.P. (Powers and Wilcox, 1964). The ash is well layered and interfingers with gravel in a small irregular pocket a metre across. The pod of ash is in such a precarious position on a steep free face that it surely will be removed within a few tens of years as the 1915 scarp erodes. If any previous scarp had developed along the same line as 1915 between 6,600 yr B.P. and 1915, the ash pod probably would not have been preserved. Even if a scarp had developed downhill several tens of metres, headward erosion that had produced a graded surface prior to 1915 could be expected to have removed the pocket of ash. The tentative conclusion is that no major scarp comparable to that of 1915 was formed since sometime before 6,600 yr B.P.

Tree Rings

The study of tree rings (dendrochronology) can provide useful data about the past few hundred years, but few trees are present in this arid region where most of the scarps studied are near bases of ranges. As an example, however, in the gulch just north of the Miller mine (east center edge, sec. 7, T. 28 N., R. 39 E.), a large juniper tree stands about 30 m east of the 1915 scarp. The main root of the tree is exposed for 6 m, apparently having been bared as a result of erosion of terrace material after the last faulting before 1915. Tree rings show the tree to be at least 230 yr old, thus the faulting event must have occurred between about 1744 and 1915. Significantly, this is the only suggestion of faulting prior to the 1915 event as recently as 1744, and the interpretation is questioned.

To say the least.

or flash flood.

Other Criteria

In any area, special criteria may be useful. Small scarplets in alluvium and loess near

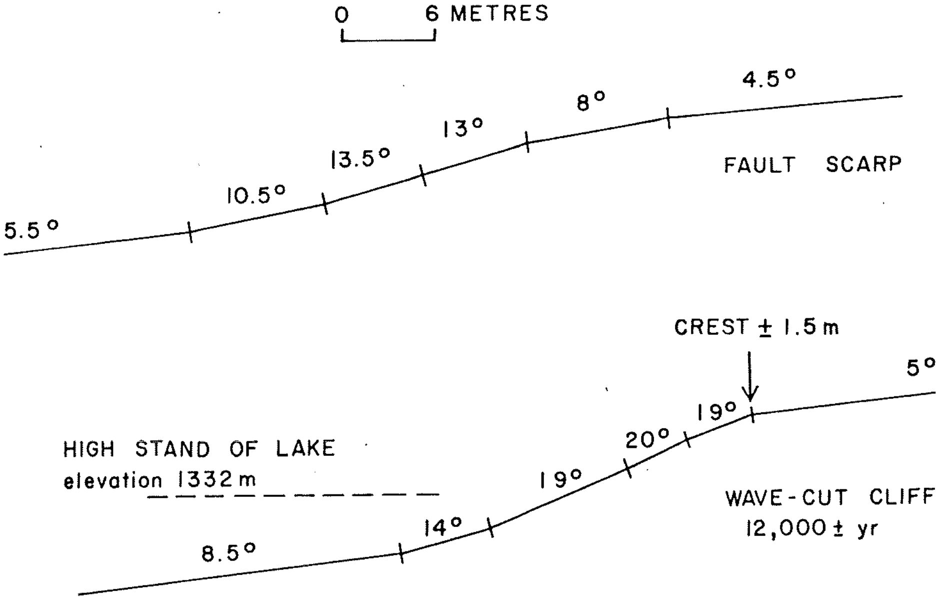

Figure 15. Comparison of profiles of fault scarp and wave-cut cliff of Lake Lahontan measured near the point of junction (see Fig. 14).

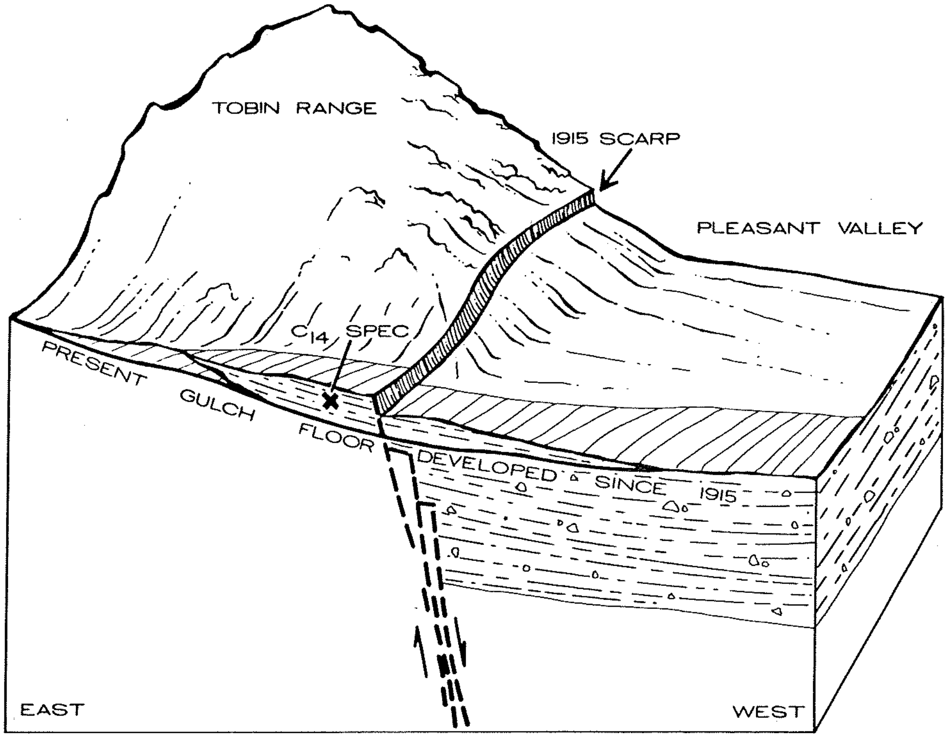

Figure 16. Setting of carbonized wood found near 1915 scarp on Siard Ranch, Tobin Range. Age of wood about 500 to 600 yr B.P.

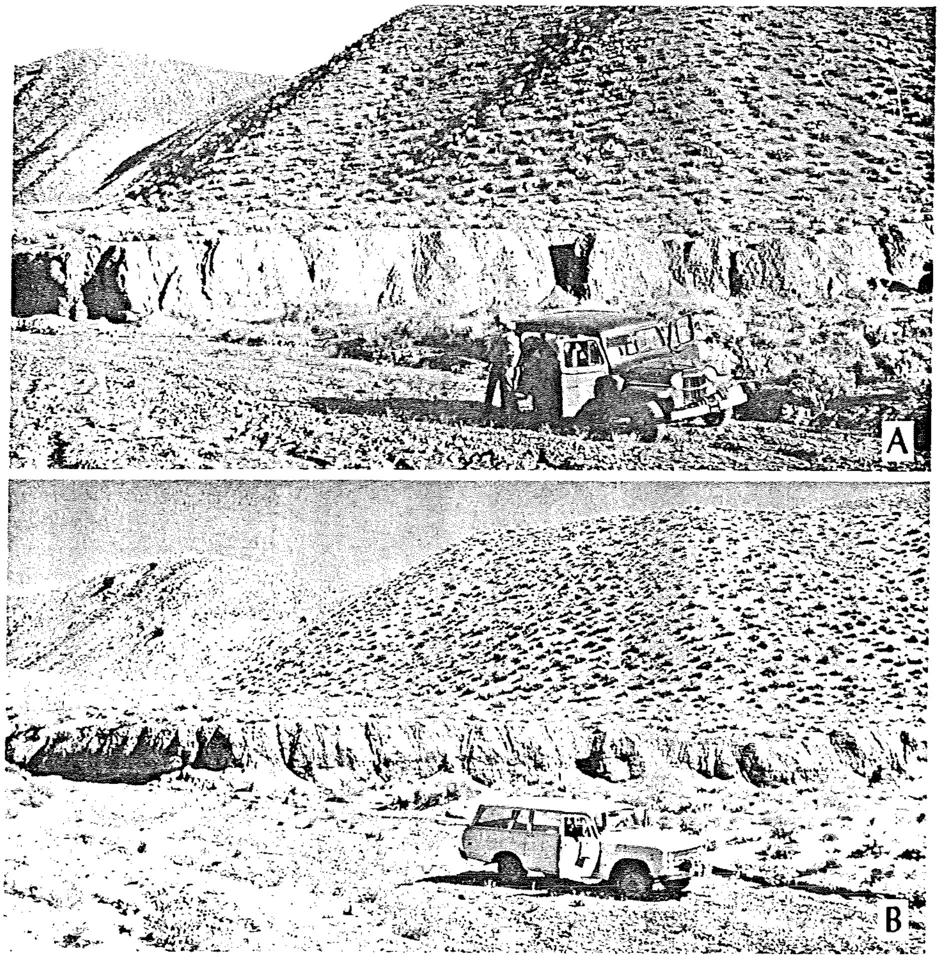

Figure 17. Comparison of 1915 scarp on Paris Ranch, Tobin Range, in 1956 (A) and 1974 (B) showing only slight changes in 17 yr.

and along the 1915 scarps were assigned either to the 1915 event or to older events according to the presence or absence of desert pavement or of a lichen-moss crust coating the face of the scarplet. Scarplets with a well-developed coating of either kind are believed to be older than 1915.

Historic Changes

Although the historic record of scarp morphology is incomplete, even for the 1954 Fairview Peak–Dixie Valley scarps, many photographs were taken a few days after the earthquakes as well as early in 1955. During the same period photographs were taken of the 1915 scarp in Pleasant Valley. Earlier photographs were taken by Jones (1915) and by Page (1934), but none of these localities has been rephotographed. I took photographs in 1957 of both the 1954 and 1915 scarps. The sites of my photographs, as well as sites at which Karl Steinbrugge took photographs in 1954 and 1955, were reoccupied in 1974. For the 1954 scarp, the effects of the first 20 yr of erosion can be seen, and for the 1915 scarp, the effects of the latest 20 yr can be seen.

The 1954 scarp on the east flank of Fairview Peak has retreated about 2 m (Figs. 4A, 4B, 4C), and the debris slope has come into being and enlarged. Figure 5 shows the development of a debris slope at the base of the 1954 scarp at the most distant point on the scarp shown in Figure 4.

The 1915 scarp on the Paris Ranch (sec. 33, T. 29 N., R. 39 E.) was photographed in 1957 and in 1974 (Figs. 17A, 17B). Although some changes have occurred, the scarp has not retreated more than 0.3 m, even in the relatively poorly indurated alluvial gravel shown. Measurements of this sort strongly suggest that a free face may survive on scarps in this region for hundreds or even thousands of years. In 1974 rock cairns were placed on the alluvial surface above this scarp and were measured and photographed to aid in future measurements of scarp retreat.

MULTIPLE DISPLACEMENTS

Evidence of multiple displacements on a single fault may be obtained from (1) pronounced breaks in slope on scarp profile, (2) benches or terraces along channels that dissect the scarp, (3) multiple knickpoints on channels that dissect the scarp, (4) scarp heights exceeding the maximum recorded for a single event, (5) complex erosion-sedimentation records, and (6) displacement of older deposits by greater amounts than younger deposits.

The profile of the fault scarp at the mouth of Siard Canyon, sec. 10, T. 29 N., R. 39 E. (Figs. 13C, 18), exemplifies the multiple scarp profile. Here, the 1915 scarp breaks

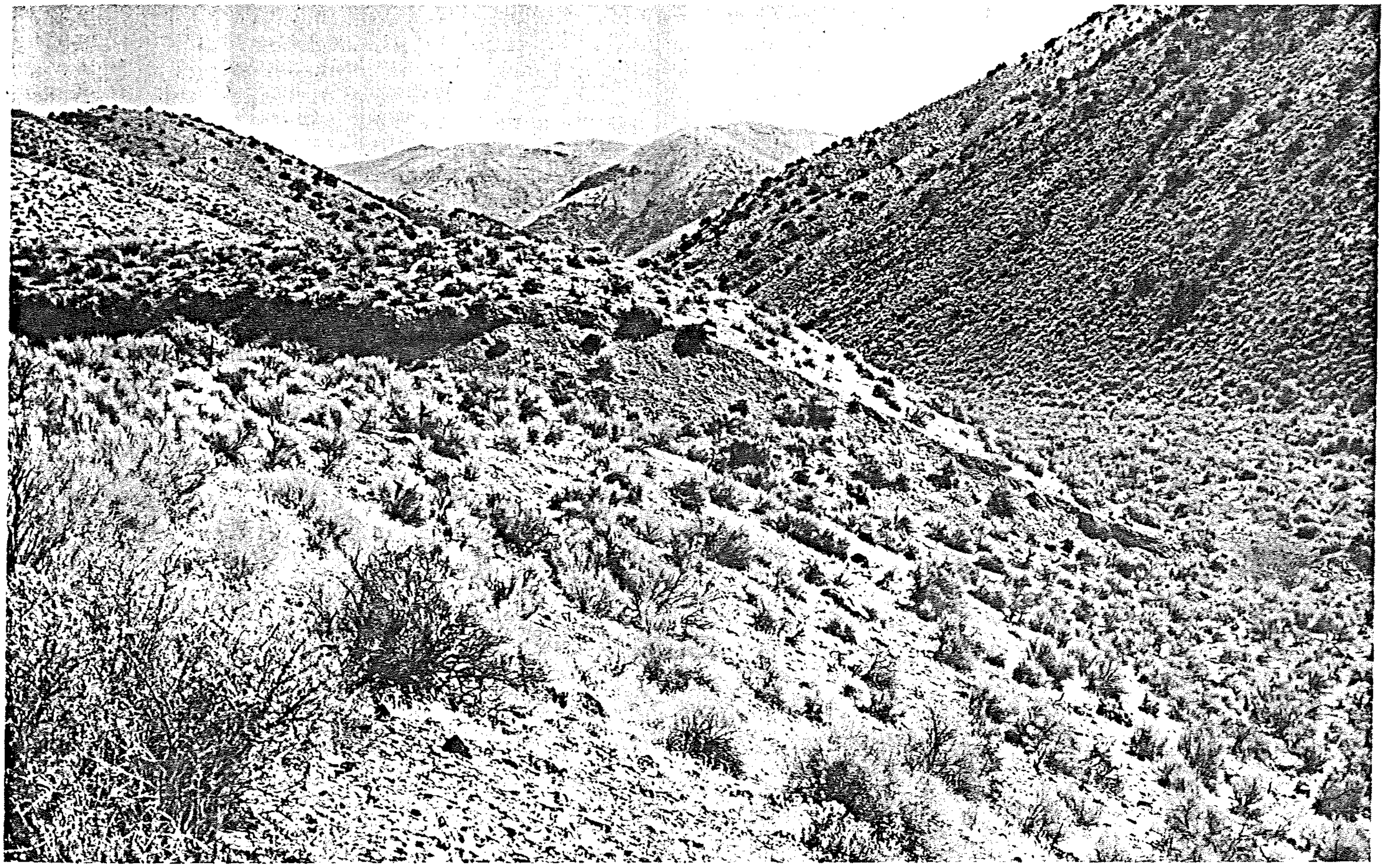

Figure 18. Photograph of multiple scarp at mouth of Siard Canyon. See Figure 13C for profile of scarp.

an older scarp. The original alluvial-fan surface slopes 4° below the scarp and 6.5° above the scarp. The 1915 scarp has a characteristic steep free face and a debris slope of 37°. The older scarp preserved above the 1915 scarp has a maximum slope of 21° and has multiple breaks in slope, between 20° and 16°, 16° and 12°, and possibly between 12° and 10°. The upper crestal break in slope is between 8° and 6.5° and is very broad. At least two displacements are clear, and possibly as many as three more displacements are represented. The youngest of the upper multiple breaks must be about 10,000 yr old, if the 21° slope is a gage.

The 1915 scarp just north of Golconda Canyon formed at the base of an older composite scarp (Fig. 19) that slopes 23° in its lower part. A break in slope separates the 23° slope from one above at 18° to 19°, and above that a major scarp crest forms the lower edge of a 7° to 8° slope that grades up to the main rocky slopes of the Tobin Range. Thus three or more displacements are recorded.

Benches, terraces, and knickpoints may provide clearer evidence of multiple offset than the breaks in slope of the scarp profile.

Several scarps have much greater heights than might be expected from one event. The maximum height of the 1915 scarp may have slightly exceeded 6 m, but the more

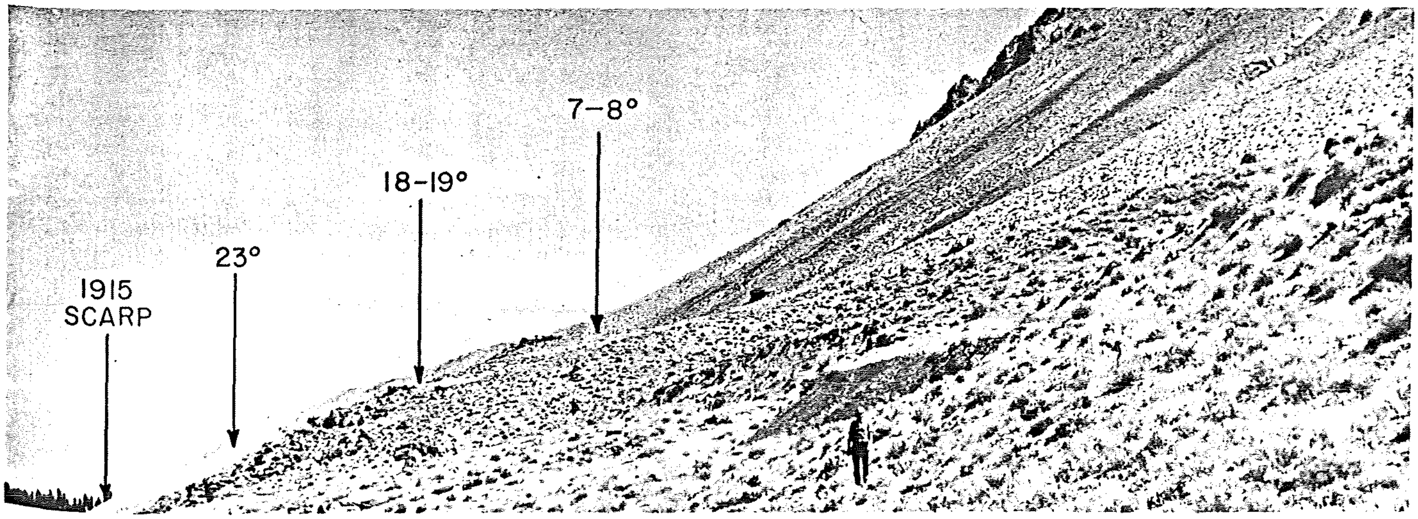

Figure 19. Multiple scarp on west flank of Tobin Range near mouth of Golconda Canyon. View north. Note 1915 scarp at left.

common modal high is about 3.5 m. I have not measured all of the scarps produced in 1954, but from reconnaissance I think they are of the same range of heights. The largest normal fault displacement recorded in the United States occurred during the Yakutat, Alaska, earthquake of 1899. The displacement was 13.1 m (Bonilla, 1970).

A scarp at the mouth of Willow Creek in the East Range, T. 32 N., R. 36 E., is approximately 46 m high. Another on the northwest flank of the Humboldt Range, T. 32 N., R. 34 E., is more than 43 m high (Fig. 20). Both scarps must have developed from several displacements, or very large displacements must be postulated during single earthquakes.

In the section "Dating Scarps," several lines of evidence are described that, in given situations, might provide evidence of multiple displacements. Few of these give unequivocal or precise answers to the age of prehistoric faulting, but when all are integrated some generalizations seem indicated. Many of the faults indeed have had multiple displacements. Repeated displacements very commonly occur along the same scarp line, although some scarps not directly a the range front may represent single events The mean recurrence of displacement along the faults in the study area appears to be o the order of thousands of years. At least one fault has been quiescent for 12,000 yr o more.

A flurry of events appears to have taken place up to the present along the Tobin Range, and a similar flurry of events is suggested along the west flank of the Hum- boldt Range, the latest displacement having

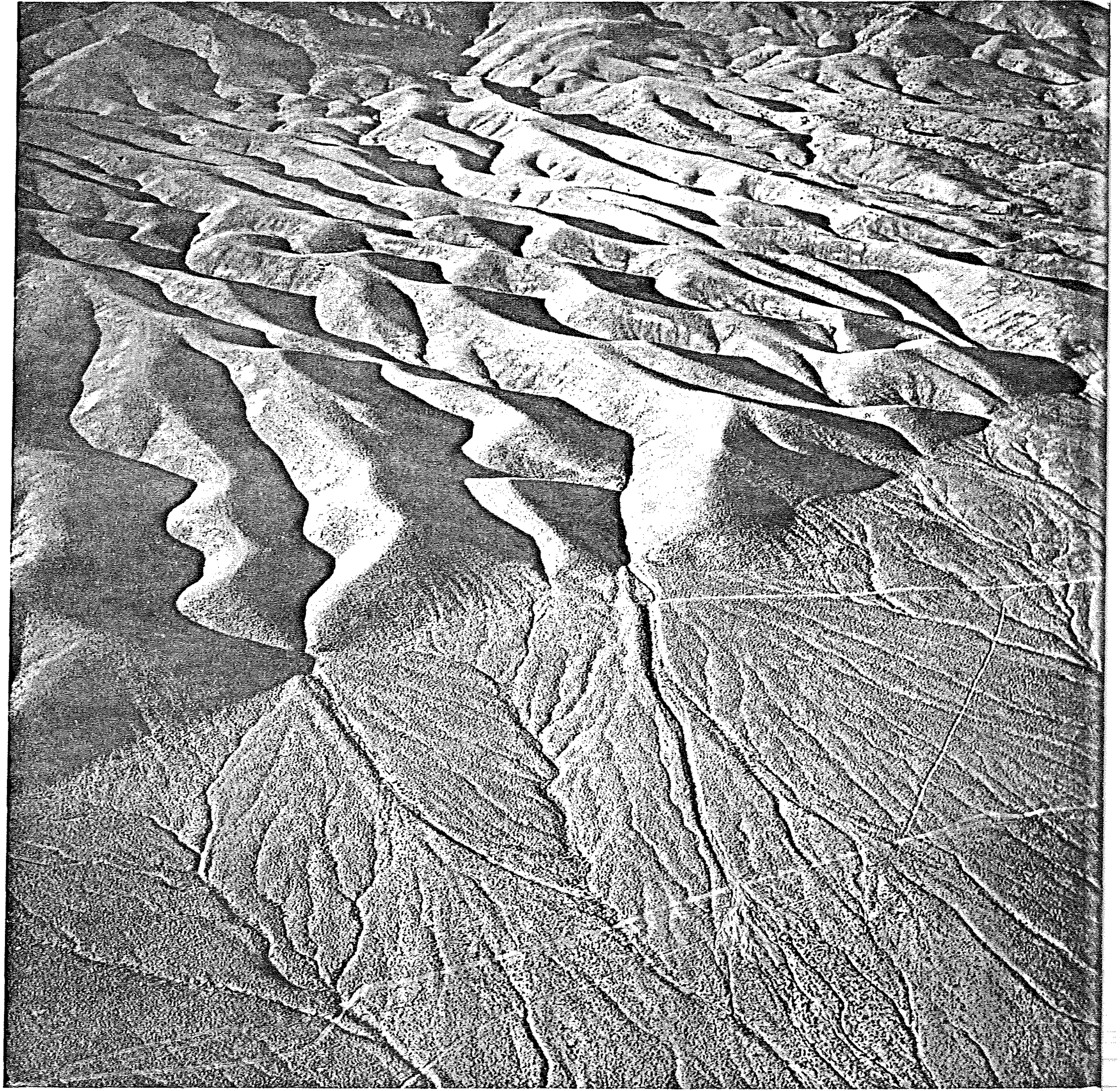

Figure 20. Scarp more than 45 m high on northwest flank of Humboldt Range. See profile of gulch in Figure 13B.

occurred since the high stand of Lake Lahontan. In contrast, along the northwest flank of the Stillwater Range, displacements have not occurred for considerably more than 12,000 yr. Thus, an areal pattern of activity is indicated in which the frontal faults of two ranges appear to be very active while the frontal fault of a range lying between them remains quiet, even though all three ranges have been tilting eastward since about 10 m.y. ago. Clustering of events both in time and space is indicated.

ACKNOWLEDGMENTS

Aerial photographs were supplied by D. B. Slemmons, the National Aeronautics and Space Administration, and the Lawrence Berkeley Laboratories of the University of California. Discussions with D. B. Slemmons, Harold Wollenberg, and Donald Noble were extremely helpful. Meyer Rubin provided the radiocarbon dates, and R. E. Wilcox identified the volcanic ash. Alan R. Wallace assisted in the field and with library research.

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MANUSCRIPT RECEIVED BY THE SOCIETY JANUARY 8, 1976
MANUSCRIPT ACCEPTED AUGUST 24, 1976