Faulting Related to the 1915 Earthquakes in Pleasant Valley, Nevada

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By ROBERT E. WALLACE

Exploratory Trench Across the Pleasant Valley Fault, Nevada

By M. G. BONILLA, H. A. VILLALOBOS, *and* R. E. WALLACE

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FAULT SCARPS FORMED DURING THE EARTHQUAKES OF OCTOBER 2, 1915, IN PLEASANT VALLEY, NEVADA, AND SOME TECTONIC IMPLICATIONS

By Robert E. Wallace

ABSTRACT

A set of fault scarps was formed during the earthquakes of October 2, 1915, in Pleasant Valley, Nevada. Four main scarps developed in a right-stepping en echelon pattern. From northeast to southwest, they are the China Mountain, Tobin, Pearce, and Sou Hills scarps. A fifth scarp, which formed at the crest of the Stillwater Range, may be of nontectonic origin. The combined length of the scarps is 59 km, the average vertical displacement is 2 m, and the maximum displacement, which occurs on the Pearce scarp, is 5.8 m. Several northwest-striking segments of the scarps have a right-lateral component of displacement, generally less than 1 m but 2 m in one place. Only one instance of a left-lateral component of displacement has been found. The fault plane, exposed in only a few places, dips at angles between 45° and 80° west and northwest. The axis of extension is oriented about N. 65° W.

At many places the 1915 scarps formed along an older scarp, and in some places older scarps represent more than one previous event. When displacement events occurred prior to 1915 is not known with certainty because the evidence is ambiguous, but the average recurrence interval for large events is likely measured in thousands of years and probably is less than about 12,000 years.

Seismic moment, derived from the scarp dimensions, is 61×10^{25} dyne/cm, which corresponds to a local magnitude (M_L) of 7.2. This estimate is about half a magnitude unit smaller than the one derived from analysis of seismic data.

The four scarps lie on the west flanks of four mountain blocks which have tilted to the east. Other mountain blocks, east and west of the 1915 scarps, also have tilted to the east. This pattern raises questions about the mechanism responsible for the faults. At least some may be listric faults. The four scarps lie in a belt 6 km wide and 59 km long that trends N. 25° E. The belt may relate to a deep zone of extension.

INTRODUCTION

The fault scarps that formed during the earthquakes of October 2, 1915, in Pleasant Valley, Nevada, are the northernmost of a set of scarps that have formed along the central Nevada seismic belt in historical time. The 1915 scarps have been studied previously by Jones (1915), Page (1934), Muller and others (1951), Burke (1967), and Glass and Slemmons (1969). Other scarps along this belt formed in 1954 in Dixie Valley (Slemmons, 1957; Slemmons and others, 1969), in 1954 at Rainbow Mountain (Tocher, 1956; Slemmons, 1956), in 1934 at Excelsior Mountain (Callaghan and Gianella, 1935), in 1932 at Cedar Mountain (Gianella and Callaghan, 1934a, b), in 1903 at Wonder (Slemmons and others, 1959), in 1872 in Owens Valley (Carver and others, 1969; Hill, 1972; Slemmons and others, 1968), and in 1869 at Olinghouse in the Truckee River valley (Slemmons, 1969).

This report on the 1915 scarps is part of a study using the forms and sizes of scarps developed during prehistorical earthquakes (Wallace, 1977a, b) to define paleoseismicity in this part of the the Great Basin province. Fault scarps, the relief of which results from one or only a few displacements events, are referred to here as "young" fault scarps. In the Great Basin province, young fault scarps that are prehistoric are believed to be related to earthquakes, because they are similar to scarps known to have formed during earthquakes and because displacement by tectonic creep has not been identified. Young faults in the region may be as old as a few hundred thousand years; the ages of most are poorly known (Wallace, 1977a, 1980).

The 1915 scarps are a set of scarps which formed in historical time that can be compared to older, prehistorical scarps. A more exact estimate of fault length and average displacement than previously obtained now provides a basis for comparing seismic moment derived from rupture dimensions with that derived from seismic-wave analysis. The physical features of different types of faults, for example, the ways they branch, the arrangements of multiple strands, and the variations of displacement along strike, are becoming more significant as land-use measures are instituted in urban areas to reduce the hazards of earthquakes.

The fault scarps were formed during the earthquakes of 1915 (pl. 1) in four main en echelon segments along the traces of normal faults that lie at the west base of four mountain blocks, for which the scarps are named. The China Mountain, Tobin, and Pearce blocks are all parts of what is generally termed the Tobin Range, and the Sou Hills block is most properly considered either an entirely separate block or a part of the Stillwater Range. A fifth fault segment, which may be related to gravitational spreading rather than to fundamental tectonic processes, is near the crest of the Stillwater Range and is referred to as the Stillwater scarp.

Each of the four scarp segments is a complex set of branching and discontinuous scarps and scarplets, rather than a single continuous scarp (pl. 1). The strike of each scarp changes abruptly at several points, and gaps of a few hundred meters are not uncommon along each of the major scarp segments.

Pleasant Valley, the area from which the earthquake and the scarps obtained their most commonly used name, is adjacent only to the Tobin and Pearce scarps. Pumpernickel Valley borders the west flank of China Mountain, and an unnamed valley separates the Sou Hills from the main Stillwater Range. The scarps are between 50 km southeast of and 100 km south of Winnemucca (fig. 1); several points on the Pearce scarp are readily accessible by good gravel roads.

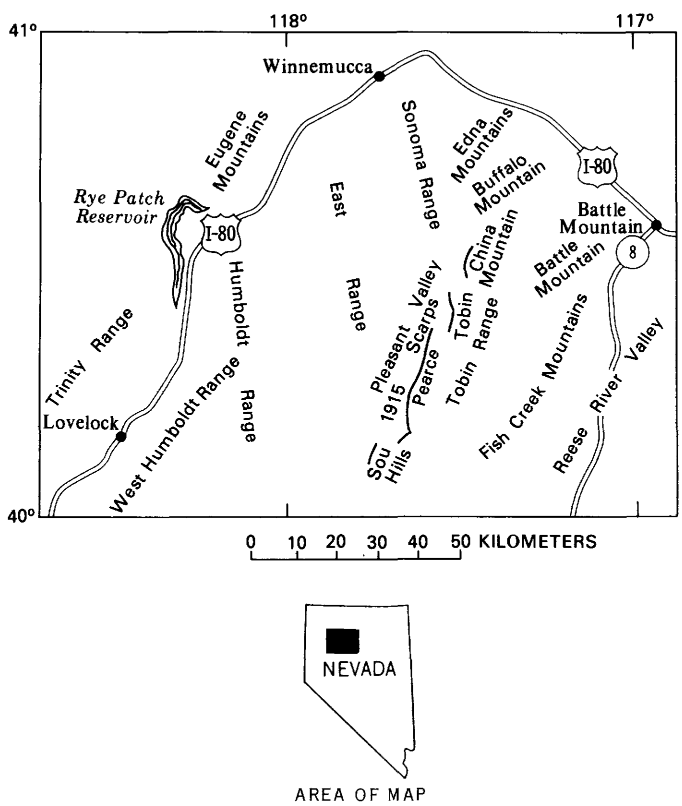

FIGURE 1.—Index map showing locations of 1915 scarps.

The scarps are especially well preserved because of the desert climate of the region. Annual precipitation in the valleys generally is less than 15 cm, although in the high parts of the Tobin Range precipitation probably is several times that amount. I first visited the scarps in 1957 and photographed a few sites then, but my major fieldwork was carried on intermittently during 1972-1979.

The main shock of the earthquake series had the following parameters:

Time:	2253 P.s.t., October 2, 1915, or 0653 u.t., October 3, 1915 (Coffman and von Hake, 1973, p. 152).
Epicenter:	40½° N., 117½° W. (Coffman and von Hake, 1973, p. 152).
Intensity:	X (Coffman and von Hake, 1973, p. 152).
Richter magnitude:	7¾ (Coffman and von Hake, 1973, p. 152).
Duration:	40–45 seconds (Jones, 1915, p. 195).

The main shock was felt over an area of approximately 1,300,000 km², from Oregon and Washington to the Mexican border and from the Pacific coast to Montana, Wyoming, Colorado, and Arizona. Two strong foreshocks occurred at 1541 and 1750 P.s.t on October 2. Numerous aftershocks occurred for months afterward (Slemmons and others, 1965; Townley and Allen, 1939). The 7¾ magnitude (above) by Coffman and von Hake is based on records from the seismographic stations of the University of California, Berkeley, and at Lick Observatory. Other estimates of magnitude are 7.6 (Richter, 1958) and 7.5 to 7.8 (Alan S. Ryall, written commun., 1974).

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D. B. Slemmons kindly provided aerial photographs, and the many discussions with him were extremely valuable. A preliminary photogeologic analysis by C. E. Glass was very helpful. Discussions with Robert and Caesar Siard and B. M. Page about historical facts provided otherwise unavailable data. A. R. Wallace assisted in some of the fieldwork. T. C. Hanks advised about seismic moment and magnitude, and discussions with R. C. Speed and M. G. Bonilla are especially appreciated.

FORMATION OF THE FAULT SCARPS

Whether the four scarps formed simultaneously during the main earthquake or whether one or more formed during the large foreshocks or aftershocks is not known. Seismic records obtained at the nearest seismic stations—the University of California, Berkeley, and the Lick Observatory—have not been examined to determine whether the locations of the main shock can be distinguished from the locations of the large foreshocks and aftershocks (T. McEvilly, oral commun., 1978). That the foreshocks at 1541 and 1750 P.s.t. were themselves relatively large earthquakes and that conceivably ground rupture could have accompanied them is attested to by the following account of Roylance (1915).

> The first indication of disturbance was felt at exactly 3:40 p.m. Saturday, 2nd inst., when with a terrific report, similar to a large dynamite blast, the mountain side of Kennedy gave a lurch due north and then vibrated for about five seconds in a manner which I would say was rather violent, considering the California disturbances. This shock had hardly subsided when another deep rumble was heard, followed by a swaying motion, which appeared to be in a northerly direction. From this time on it was one continual disturbance; one quake hardly died before a rumble announced another. This state of affairs occurred continuously until 5:45 p.m. when the only indication that conditions were not right was a sort of subdued rumble, such as might be experienced were there a great cauldron boiling and bubbling under foot, just beneath the earth's surface. About this time the inhabitants at Kennedy apparently became accustomed to this condition and settled down satisfied that the disturbance had spent itself and was a thing of the past, when all of a sudden without the slightest warning a great roar was heard and the earth's surface began to roll and sway up and down, evidently in all directions. Really the earth's surface appeared to be some great monster in the throes of convulsions, which sent quivers in all directions. This convulsion continued without stop for fully one and one-half minutes. This disturbance was in my estimation about twice as violent as that experienced in San Francisco in 1906.
>
> During this performance of the earth it was next to impossible for a person to stand erect. From this disturbance on, it was an incessant continued disturbance, the earth never appearing quiet. About 9 p.m. we retired for the night and as near as I can describe the situation, one could shut his eyes and imagine he was occupying a berth in a moving Pullman car, accompanied with creakings and rattling of windows, to be abruptly awakened by outbreaks at intervals of twenty to thirty minutes, lasting from five to ten seconds. At 10:55 things had quieted, or perhaps we were unconscious in sleep, when without the slightest warning a great roar and rumbling was heard and we were thrown violently out of bed and buffeted in all directions continuously for not less than fifteen minutes. During this disturbance it would appear to tire itself and would hesitate for an instant as if it were changing hands and fumbling in trying to get a good grip and would then shake violently with the other hand until tired; then it would change hands and repeat the operation. This shake started at 10:55 p.m. Western Union time, as recorded. I did not note the time of starting, but when the disturbance subsided sufficiently to allow one to enter the house in quest of sufficient apparel, as it was next to freezing outside, I noted the time was 11:10 p.m.

Most of the scarps shown in plate 1 are believed to be of tectonic origin, but some fractures must have occurred as a result of lurching, liquefaction, or differential settlement. Roylance (1915), for example, states that "the road in places shows cracks and is flooded with water." He also quotes Mr. W. L. Pearce, who was camped at Mud Springs: "At each great lurch of the ground the water of the spring spurted up in the air." No fractures are identified that cross or are near the present roads, so the location of the cracks to which Roylance refers is unknown.

That some movement took place on the Pearce scarp during the foreshock at 1541 is suggested by the following account of Roylance (1915):

> About 4:30 p.m. Saturday Mr. Berry and myself went up the hill at the back of the Roylance Reduction Co. mill to observe if possible whether there was any indication of volcanic eruption. We noted that just above the mountains skirting the east side of the valley, from about Mount Tobin south and Pearce ranch, there appeared a long slim cloud of a light reddish brown color, which hung just over the location of the break or fissure described above. On using a glass we were able to discern that it was dust and not smoke, and which was forced up by the rush of air through the fissure as the ground in that vicinity was sinking.

The dust may have been related only to landslides and rockfalls, but clearly Roylance believed that the dust was related to the fault, even though on Saturday afternoon he apparently had not yet realized that a scarp had formed. Apparently he left Kennedy for Winnemucca late Saturday night, passing Mud Springs about 2:30 a.m., Sunday. He states:

> As we passed over this road at night, we were unable to see much of the condition and evidences of the quake, but I have been informed that along the mountain sides or foothills at the left, or east, commencing about opposite the Siard ranch and running south past the Pearce ranch, the line of a break or fissure caused by the earthquake can be seen. Along this break the earth sunk from six to twelve feet, the appearance from a distance being as if a new roadway had been cut or graded along the foothills.

DIMENSIONS OF THE SCARPS

The map distance from the north end of the China Mountain scarp to the south end of the Sou Hills scarp is approximately 59 km. The lengths of the scarps are China Mountain, 10 km; Tobin, 8.5 km; Pearce, 30 km; and Sou Hills, 10.5 km. The Stillwater segment is 1.5 km long. The sum of the four individual lengths, excluding the Stillwater scarp, is approximately equal to the overall length of the set of scarps, even though there are large gaps between the en echelon segments.

The original slopes of the scarps, which in most places are in colluvium or fan gravels, apparently were steep—between 70° W. and vertical (Jones, 1915; Page, 1934). The scarps produced in 1954 in the Dixie Valley-Fairview Peak area, 40–100 km southwest of the 1915 scarps, had similarly steep slopes (Slemmons, 1957). In the few places that the fault surface on bedrock is exposed, the dip of the fault plane ranges from 45° to 80° west and northwest. On the piedmont slope at the south end of Pleasant Valley near Wood Canyon, some scarps generally less than 1 m high face east or southeast in opposition to the main scarp, thus bounding broad graben blocks. Grabens only a few meters wide occur along at least half of the total length of the scarp (see fig. 22).

Displacement is predominantly dip slip. The maximum vertical component of displacement, which occurred along the middle part of the Pearce scarp (fig. 2), is approximately 5.8 m. The average vertical component of displacement, derived from measurements at 80 sites, is approximately 2 m. The averages for each of the four segments are: China Mountain scarp, 0.9 m; Tobin scarp, 1.9 m; Pearce scarp, 2.8 m; Sou Hills scarp, 0.9 m.

Many scarp heights very nearly represent the original vertical component of displacement, but at some localities erosion has enlarged the scarp height and a correction must be made to determine the actual fault displacement. A method for making such corrections is described by Wallace (1980). Inasmuch as scarp heights were usually measured at the more conspicuous localities, where the heights are greater than 1 m, the average height obtained is probably exaggerated by a few percent.

Although displacement was predominantly dip slip, some oblique slip occurred (Glass and Slemmons, 1969). A fence that crosses the fault just east of the buildings at the Pearce ranch (near

FIGURE 2.—Scarp near Pearce ranch. Maximum scarp heights occur along this segment of the fault.

center of west edge, sec. 33, T. 29 N., R. 39 E.) appeared in 1974 to be misalined in a right-lateral sense by about 50 cm. According to Jones (1915, p. 203), however, the fence was not "laterally displaced * * * as closely as can be determined by eye." Perhaps the 50 cm of displacement occurred after Jones examined the scarp in 1915, but that is unlikely because the vertical displacement was the same, within measurement error, in 1974 and in 1915, so I infer that no movement has occurred there since 1915. Jones (1915, p. 203) does report that striations incline "less than five degrees to the north from the vertical." Given 3.8 m of vertical displacement, an 85° pitch to the north could account for more than 40 cm of lateral slip. Another fence, about 1,400 m south of the first fence, crosses a segment of the fault that strikes northwest, and at that fence the right-lateral component of displacement is approximately 2 m (fig. 3). A third fence, which crosses the Tobin scarp near the major bend in its trace (SE1/4 SE1/4 sec. 19, T. 30 N., R. 40 E.), is shifted approximately 0.9 m in a right-lateral sense. Several sets of en echelon fractures, particularly along the south half of the Pearce scarp, also suggest a component of right-lateral slip (figs. 4, 10). In addition, numerous small gulches appear to be misalined in a right-lateral sense, but the irregularities of such channels commonly do not permit a definite conclusion or accurate measurement. The scarp, because it represents the surface of a dipping plane, forms V patterns at many points where it crosses channels, and the relative width of the scarp on the legs of the V's can be used as an indicator of lateral slip. Most such V's are symmetrical, but a few suggest some right-lateral slip. One example of a left-lateral component of offset was found approximately 1 km southwest of the mouth of Cottonwood Creek along a segment of the Pearce scarp that strikes northeast. There, slickensides plunge almost due west, but four other sets of slickensides range between N. 43° W. and N. 65° W. Regional extension is oriented N. 65° W., as is discussed in the section "Characteristics of Faulting and Some Tectonic Implications." Any fault segment trending perpendicular to this direction has dip slip only. Fault segments having other orientations can be expected to have a component of strike slip.

FIGURE 3.—Pearce scarp, 1,400 m south of Pearce ranch, showing right offset of fence line by approximately 2 m (photograph taken July 1975).

DESCRIPTION OF SCARPS

CHINA MOUNTAIN SCARP

The China Mountain scarp (fig. 5) breaks the west flank of the northeasternmost part of the Tobin Range. Unlike the three other scarp segments which lie generally at the base of a mountain front, this segment lies within the range block, about 200 to 300 m above the valley margin. It crosses spurs that extend westward from the main mountain mass toward Pumpernickel Valley. The scarp is generally between 1,800 and 2,100 m in elevation, higher than most of the rest of the scarps.

The China Mountain scarp is more degraded than the other scarp segments. A sharp scarp crest persists, but a free face is preserved in only a few places; generally a debris slope predominates. The scarp is conspicuous because it forms a band predominantly covered by grass or open soil passing through brush-covered terrain. Larger shrubs, common adjacent to the scarp, have not been reestablished on the scarp, though some have been transported onto the band when the blocks in which they were already rooted slid down the scarp.

FIGURE 4.—Scarp near Siard ranch showing right-stepping en echelon pattern suggestive of left-lateral slip.

FIGURE 5.—China Mountain scarp (see arrow) on west flank of China Mountain.

The relatively greater degree of degradation of this scarp may be due to its higher elevation, where rainfall is greater and thus erosion is faster. I had wondered whether the China Mountain scarp could represent a seismic event earlier than 1915, but B. M. Page (oral commun., 1976) reports that he saw the scarp from a distance in 1933 and was told by ranchers that the scarp formed in 1915, although it was neither mapped by him in 1933 (Page, 1934) nor reported in 1915 (Jones, 1915).

The 1915 scarp clearly follows an older, subdued scarplet over much of its length, although, in a part that jogs sharply southeast (see pl. 1, sec. 16, T. 31 N., R. 40 E.), the scarp slopes southwest into a steep northeast-facing hillside that has no apparent older topographic expression of young faulting. The southeast-trending segment thus appears to be a relatively new, perhaps a totally new fracture that has joined two previously established segments.

TOBIN SCARP

The Tobin scarp (figs. 6, 7, 8) lies along the west base of a part of the Tobin Range, a horst block of the Basin and Range province. Spurs extending from the range crest are truncated or faceted at their western or basinward ends as a result of repeated block faulting during late Tertiary time. The 1915 rupture lies at the base of these faceted spurs and extends across intervening valleys, creating steps in the valley bottoms. The geomorphology of this fault-generated range front is discussed by Wallace (1978).

A notable feature of the Tobin scarp is the sharp change in strike at its midpoint. The north half strikes N. 25° W., whereas the south half strikes N. 25° E.; each half parallels a regional trend.

The northern half of the scarp is only 4 km long and dies out to the northwest, even though very conspicuous older fault scarps continue with more or less constant strike to the northwest for tens of kilometers. Why the 1915 rupture did not propagate farther northwest along these older lines of weakness is of interest and is discussed in the section, "Characteristics of Faulting and Some Tectonic Implications."

The piedmont slope that flanks the Tobin scarp on the west appears to have been oversteepened by warping. Slopes at the head of the piedmont slope are as great as 14°, and those parts that are steeper than 5.5° are deeply dissected. Contours on the piedmont slope trend N. 30° E., and the Tobin scarp cuts across this trend. The piedmont slope forms a ramp rising to the east and southeast, bridging the Tobin and Pearce blocks; these relations suggest that part of the block movement is accommodated by warping in addition to faulting.

The southern part of the 1915 scarp dies out at about the junction of the Tobin and Pearce blocks, but older subdued scarps along the same line continue a few kilometers still farther south. These older scarps also lie along a major break in topography between the Tobin and Pearce blocks, a break which follows a bedrock fault shown on the geologic map by Muller and others (1951).

PEARCE SCARP

The Pearce scarp (figs. 9-17), 30 km long, is the longest segment of the 1915 set of scarps, and its displacements, as large as 5.8 m, are the greatest found on any part of the set. Over most of its length, either colluvium or alluvium forms the face of the scarp; in only a very few places is bedrock exposed in the scarp face, even though at almost every point, the scarp is only a few meters to a few tens of meters from bedrock (fig. 15).

Wherever the scarp is formed in alluvium or colluvium that is only slightly indurated, it displays a free face over much of its surface and a debris slope covers only 10 to 40 percent of the scarp face (figs. 14, 16). Some large blocks have tilted away from the main scarp under the influence of gravity, and many have fallen and broken into smaller blocks which disintegrate more rapidly than the rocks in the free face itself. Grabens are common along the base of much of the scarp. Where alluvium or colluvium is moderately indurated, little or no spalling from the original scarp face has occurred since 1915. In the least indurated materials, especially in fine, loesslike materials, the scarps have degraded relatively rapidly into a slope controlled by wash and solifluction processes, and so a free face is generally absent. Where the original scarp was less than 0.3 m high, degradation is especially noticeable; the smaller the height of the scarp, the more rapidly it has become obscured. Bucknam and Anderson (1979) have demonstrated a relation between scarp height and scarp slope, and Nash (1980) has developed a model to explain why the slope of small scarps declines most rapidly.

The closeness of the scarp to the bedrock-gravel contact in most places suggests that the principal plane of displacement followed that contact closely at depth and departed from it only in the upper few tens of meters, where it propagated at a steeper angle, possibly almost vertically, to the surface through the gravels. This more nearly vertical propagation of the fault from the bedrock-gravel contact would account for the sharp westward convexity of the trace where it crosses several alluvium-filled channels, as at the mouth of Miller Basin (fig. 13*A*). According to this interpretation, the westward convexity is a trace of the gravel-bedrock interface at the base of the channel fill, projected upward at a steep angle onto the relatively horizontal ground surface (fig. 13*B*).

Some scarps that seem to represent fault activity tens of meters above the base of the range front but still in colluvium, very likely represent secondary landslidelike movement of colluvium over the bedrock surface. Examples of such scarps can be found in the Pearce ranch area. Landslides had disturbed the range front prior to 1915 in a few places, and the 1915 scarp broke across these slide blocks. This relation is observed in sec. 18, T. 28 N., R. 39 E. A precise age for the landslide-derived scarps cannot yet be established.

FIGURE 6.—Tobin scarp. View southeast along west flank of the Tobin Range.

The Pearce scarp is complex in detail, with branches and discontinuities at various places. Left-stepping patterns of en echelon fractures (fig. 10), particularly along the southern half of the scarp, suggest a component of right-lateral displacement, but scarplets branch both to the west and east in the northern part of the scarp. Gaps in the scarp are difficult to explain. One gap, at the mouth of Cottonwood Creek, is 0.6 km long, although adjacent segments show displacements of 2 m or more. Bonilla (1970, p. 58) cites this location as one of several examples of "absorption" of faulting in soil and rock.

Geomorphic evidence of older scarps can be found at many places along the 1915 scarp. One of the localities where the 1915 scarp follows the base of an older scarp most clearly (figs. 11, 12, 24) is at the mouth of Siard Canyon. There, a compound scarp represents multiple offsets of alluvial gravels supporting a well-developed terrace on the north side of the canyon. The 1915 scarp forms the lower part of the compound scarp, and above the

FIGURE 7.—Tobin scarp. View east at south edge of sec. 19, T. 30 N., R. 30 E., showing junction of segments that strike N. 25° W. and N. 25° E. Spring emerges in thicket of brush at right of photograph.

FIGURE 8.—View northwest along Tobin scarp near north edge of sec. 19, T. 30 N., R. 40 E. Scarp is more subdued here than along much of Pearce segment, although a free face persists.

FIGURE 9.—Pearce scarp in vicinity of Little Miller Basin (sharp canyon at right edge of photograph). The V-shaped pattern of the scarp is developed wherever the scarp crosses small gulches.

FIGURE 10.—Oblique aerial view of Pearce scarp where it crosses Wood Canyon at the south end of the Tobin Range. Note left stepping en echelon pattern of fractures to right of Wood Canyon, offset of alluvial flat in Wood Canyon (close view shown in fig. 16), and progress of entrenchment of post–1915 drainage headward from scarp. Fault scarp in upper right of photograph apparently was not reactivated in 1915.

free face and sharp crest of the 1915 scarp the slopes range from 6.5° to 21°. Relatively sharp breaks in slope between 10° and 8° and between 19° and 16° suggest that more than one event is recorded in the slopes of this upper part of the scarp (fig. 24). Wallace (1977a) discusses the origin of such compound scarps.

The close correlation between age and slope angle for scarps of similar heights permits correlation between certain fault scarps in the area and wave-cut cliffs of the last high stand of Lake Lahontan. This stand has been dated at about 12,000 yr B. P. (Morrison and Frye, 1965). Fault scarps and wave-cut cliffs a few meters high have slopes of about 20°; slopes of 8° are considered to be several times as old. Truncation relations confirm that some of the fault scarps are at least as old as the Lake Lahontan cliffs. Inasmuch as the original height of the scarps represented by these remnants on the existing scarp can only be approximated, the method of relating slope, height, and age developed by Bucknam and Anderson (1979) cannot be used to determine a more accurate age.

About 500 m north of Golconda Canyon, a compound scarp includes a fresh 1915 scarp at its base, above which are facets sloping 23° and 18°; above

FIGURE 11.—Oblique aerial view of Pearce scarp where it crosses Siard Canyon. Main part of Tobin Range in background. Repeated movement along the fault is demonstrated by the compound scarp just left of Siard Canyon. See also closeup taken at arrow (fig. 12).

the compound scarp original colluvium slopes are 7° to 8°. All of these facets represent scarps of different ages and are separated by sharp breaks in slope. At least three major events are represented.

Similarly, along the northernmost part of the Pearce scarp, where the 1915 offset is only about 0.5 m (fig. 17), an older, subdued scarp is preserved above the 1915 scarp. The maximum slopes of the older scarp are approximately 12° to 13°, whereas the original fan slopes are approximately 4°. Bonilla and others (this volume) dug an exploratory trench across this part of the fault and found ambiguous evidence of the age of two previous displacement events. Their evidence suggests that the events occurred during the past 5,000 yr.

At the south end of the Pearce block, the 1915 scarp changes strike sharply from south to southwest. Just west of this southern part of the scarp, in an area 5 km north-south by 2 km east-west, is a set of many scarplets only a fraction of a meter high and striking generally southwest. Scarplets face both southeast and northwest and define two broad grabens, oriented S. 30° W. The trend of these grabens suggests that regional extension is about N. 60° W., normal to the graben axes, an orientation similar to the direction N. 65° W. estimated from the overall pattern of the scarps (see section, "Characteristics of Faulting and Some Tectonic Implications").

In contrast to the more smoothly planar piedmont slope, or bajada, adjacent to the Tobin scarp, the piedmont slope flanking the Pearce scarp is made up of a set of distinct alluvial fans. The difference between these two slopes suggests differences in tilting or warping. Distinct fans may have formed on a base that had either a low slope away from the scarp or possibly a slope toward the fault. The piedmont slope adjacent to the Tobin scarp may have had a history of tilting to the west (Wallace, 1978).

The Pearce block is a secondary block to the main Tobin block and has tilted toward it. Muller and others (1951) show that faulting was initiated prior to eruption of the Tertiary lavas and that "faulting was accompanied by progressive eastward tilting of the range, shown by the fact that the dip of the rhyolite is steeper than that of the overlying andesite." This geometric relation

FIGURE 12.—View of 1915 scarp and older scarp at Siard Canyon (see location shown in fig. 11). The free face of the 1915 scarp is the nearly vertical slope in deep shadow, above which is an older scarp having a slope of 20° to 22°.

suggests rotation by gravity sliding off the main Tobin block (see "Characteristics of Faulting and Some Tectonic Implications").

The north end of the Pearce block grades into a ramplike piedmont slope of fan gravels; no clear fault trace bounds the block, although an older subdued fault scarp does extend N. 45°–50° E. from near the north end of the 1915 scarp toward the main Tobin block. Details of how movement was accommodated between the Pearce block and blocks to the north are unclear.

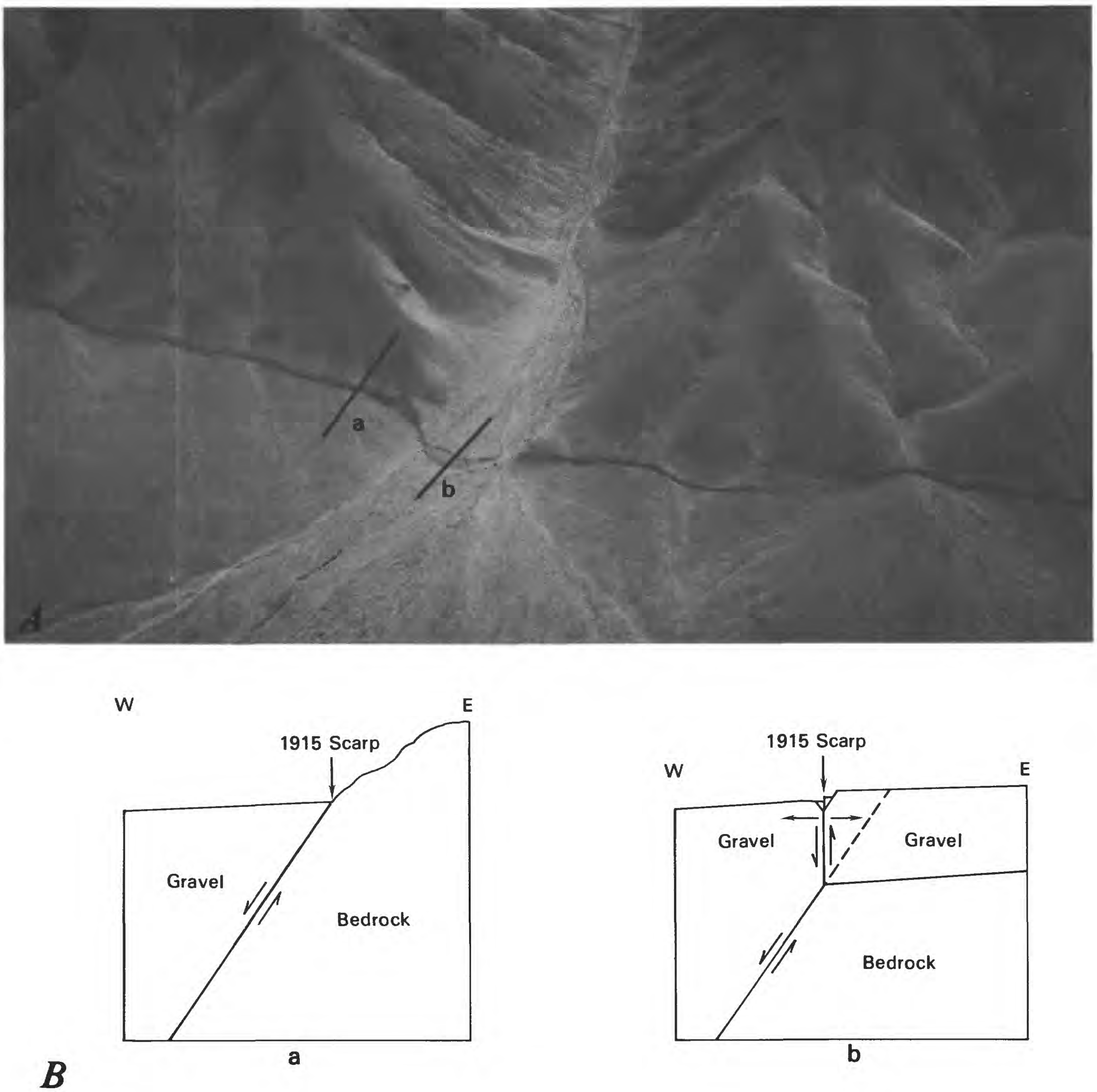

FIGURE 13.—Pearce scarp at mouth of Miller Basin. Downstream convexity is believed to be related to westward dip of fault and to configuration of gravel-bedrock contact under the channel. *A*, photograph showing location of cross sections a and b diagrammed in *B*.

SOU HILLS SCARP

The Sou Hills scarp, the southwesternmost segment of the 1915 scarps, lies on the west flank of the Sou Hills. Older west-facing subdued scarps in late Quaternary gravels continue along the same general trend for 8 km north of the north end of the 1915 Sou Hills scarp. The south end of the 1915 scarp dies out approximately at the south end of the Sou Hills block, where the Sou Hills abut Dixie Valley.

The scarp is discontinuous, and in some sections two scarps parallel each other about 400 to 500 m apart. The longest strand is 1.4 km long. Scarp heights range from less than 0.1 m to about 2.7 m; the average height is about 0.9 m.

Volcanic rocks, including basalt, rhyolite, rhyolitic tuff, and lake beds underlie the Sou Hills. The scarp is generally in colluvium and alluvium derived from these rock types. Where the scarp crosses talus composed of boulder-size blocks derived from basalt or rhyolite, the boulders seem to have merely readjusted during packing to stand at the angle of repose, approximately 30° to 35°, without developing a free face. Where scarps less than 1 m high are in lake beds or fine-grained alluvium, no free face is preserved and the scarp crest is rounded. One such small scarplet 100 m north of the McKinney Pass-Dixie Valley road would be difficult to recognize as a fault scarp if it did not face into the hillslope.

The south edge of the Sou Hills coincides with a major east-trending line or zone which marks a change in the direction the ranges tilt (Stewart, 1980). South of this latitude, approximately 40° N., a predominance of young faults on the west flanks

FIGURE 14.—View south along Pearce scarp just north of mouth of Miller Basin, showing prominent free face above a debris slope which occupies 20 to 40 percent of the height of the scarp. Note large block in center spalling and tilting to the right.

of mountains gives way to a predominance of east-facing young faults, among them the 1954 scarp on the east flank of the Stillwater Range. The west-facing Sou Hills scarp is almost alined with the east-facing scarps on the east flank of the Stillwater Range.

STILLWATER SCARP

A west-facing scarp approximately 1.5 km long formed in 1915 near the crest of the Stillwater Range, 3 km south of Fencemaker Pass, at an elevation of 2,200 m. When B. M. Page (oral commun., 1975) visited the site in 1933, he was told by a rancher that the scarp was formed in 1915. The scarp was reactivated in the early 1950's, probably during the earthquake of 1954, during which scarps formed in Dixie Valley along the southeast flank of the Stillwater Range. The north end of this 1954 scarp, as mapped by Slemmons (1957), is approximately 40 km south of Fencemaker Pass. Tree-ring dating of small piñon pine trees growing on the scarp gives evidence that there was movement there in 1954; in 1974, the trees that showed no evidence of disturbance were less than 20 yr

FIGURE 15.—Pearce scarp at mouth of Little Miller Basin. The scarp is generally near the contact of colluvium or alluvium with bedrock, but seldom is bedrock exposed in the scarp face. One example of such a bedrock exposure is left of center of this view, just out of sight (see closeup in figures 26 and 27).

old, whereas the few trees that were either sharply bowed or showed other evidence of disturbance, such as bared roots, were all more than 20 yr old.

The scarp is as much as 1.8 m high, but when the effects of headward erosion are considered, the maximum vertical component of displacement is estimated to be no more than 1.2 m. A graben as deep as 0.3 m is present in some places at the foot of the scarp. Only small remnants of a free face remain; most of the scarp is best classified as debris slope. A short segment of an opposing east-facing scarplet lies 100 m west of the north end of the main scarp. It represents the northwest margin of a small graben which forms a nearly closed drainage basin near the crest of the range.

Although the Stillwater scarp appears to have been activated both in 1915 and 1954, it is questionable whether it is related to tectonic faulting.

FIGURE 16.—Prominent free face of Pearce scarp at mouth of Wood Canyon, sec. 12, T. 27 N., R. 38 E. Here the scarp displays a prominent free face and little debris at its base, although the scarp is in gravels, only slightly indurated, that formed the floor of Wood Canyon prior to 1915. Rod is 1.52 m (5 ft long).

The Stillwater scarp lies 10 km south of the south end of the Sou Hills scarp, which itself appears to die out to the southwest, and approximately 40 km northeast of the northeast end of the Dixie Valley scarp of 1954 as mapped by Slemmons (1957). The scarp at one point is less than 50 m from the head of a precipitous scarp (27° to 30° slope), 1 km high, on the east face of the Stillwater Range, and it parallels an older Cenozoic fault of large throw (Speed, 1976). The association of the fault with such great and steep relief suggests that the graben bounded by the main scarp represents extension toward the open face of the mountain front, and thus that it could be a secondary structure related to lateral spreading (fig. 18). Zischinsky (1969) suggests the name "sackungen" for such

FIGURE 17.—Pearce scarp near its north end. Here, the 1915 scarp is approximately 0.5 m high and lies at the base of an older, subdued scarp above the tape reel. (The tape is extended 0.7 m for scale.)

structures related to lateral spreading, and Radbruch-Hall and others (1977) describe similar extensional structures in Colorado.

PROFILES OF THE SCARPS

Determining topographic profiles across the scarps are helpful in describing the scarps, in comparing the amounts of degradation on various segments, in comparing the ages of scarps, in identifying multiple movements, and in adjusting scarp-height measurements to ascertain the true vertical component of displacement.

The terms used in referring to parts of the scarp are shown in figure 19 and are discussed in Wallace (1977a). The free face is that part of the scarp that is steeper than the angle of repose for loose material; when first formed it represents the fault surface, but it soon changes to a steep slope from which material spalls to produce the debris slope. The debris slope is composed principally of loose material spalled from the free face and generally stands at the angle of repose. The wash slope is composed primarily of material washed by fluvial action from the free face and debris slope and deposited at the base of the scarp. Examples of profiles are shown in figures 20–23.

Most commonly, the scarp is composed of a free face and a debris slope. A free face tends to remain more prominent on scarps several meters high than on those less than one meter high. Compare, for example, the profiles of the Pearce scarp (figs. 21, 22) with those on the Tobin scarp (fig. 20) and Sou Hills scarp (fig. 23). Even where most of the scarp is composed of debris slope and wash slope, however, small remnants of free faces are protected and preserved at the base of bushes or larger boulders. Bucknam and Anderson (1979) find that along a scarp of a single age, the relation between the scarp's height and its slope angle can be approximated by a logarithmic curve and that

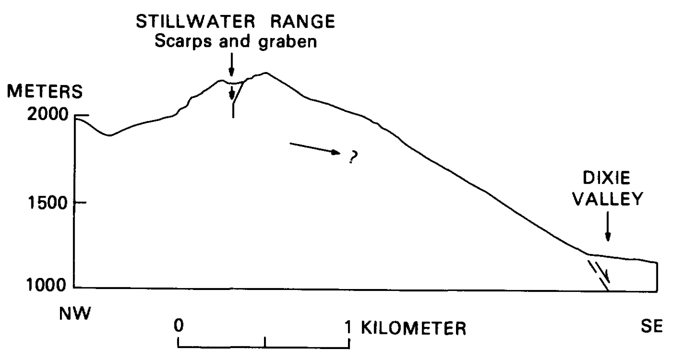

FIGURE 18.—Diagrammatic cross section, equal vertical and horizontal scales, showing relation of graben and related scarps at crest of Stillwater Range. Lateral spreading of range and origin of the faulting as "sackungen" is suggested.

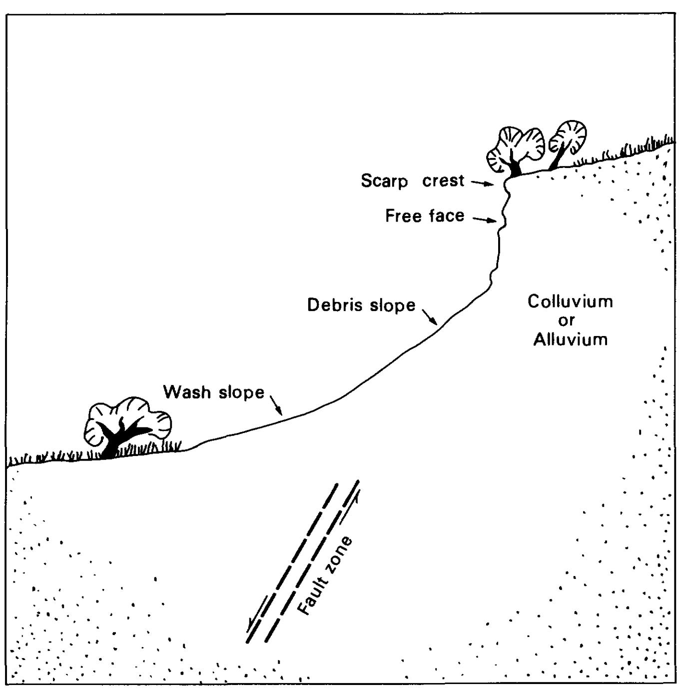

FIGURE 19.—Diagram showing terms for parts of scarp.

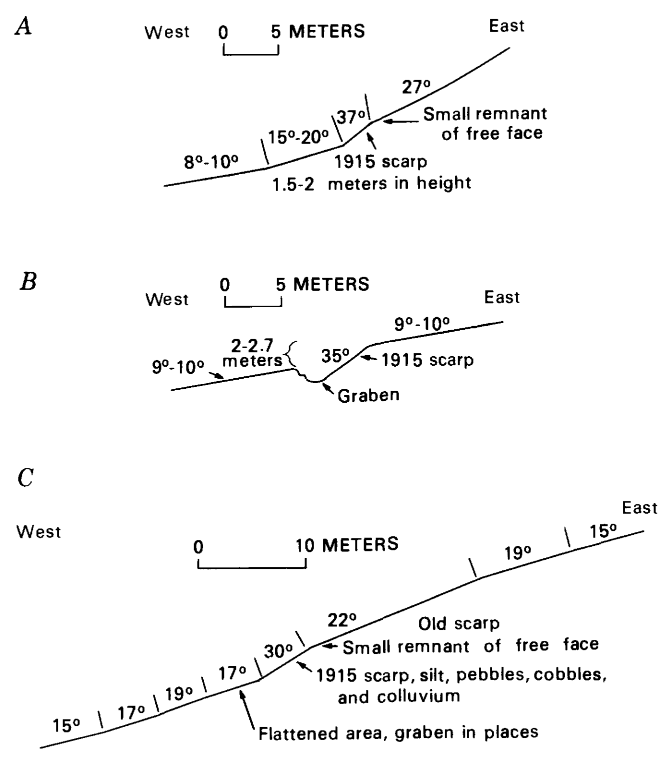

FIGURE 20.—Profiles across Tobin scarp. *A*, West center sec. 31, T. 30 N., R. 40 E., *B*, SW 1/4 sec. 31, T. 30 N., R. 40 E., *C*, North edge sec. 19, T. 30 N., R. 40 E.

for a scarp of a given height, the older the scarp, the smaller the slope angle. Nash (1980) describes a diffusion mechanism to explain this relation.

Below the scarp the original surface commonly has a lower slope than does the original surface above the scarp, in part because in many places the 1915 scarp developed along the base of an older scarp. The presence of a graben at the base of the older scarp also may account for a lower slope. Where the slope of the original surface below the scarp is steeper than that above the scarp, either the surface has been warped or the 1915 break may have developed uphill from the zone of a major previous movement. Slemmons (1957) describes warping or tilting of blocks away from the main scarp during the 1954 earthquake in Dixie Valley.

Grabens, which commonly develop at the base of the scarp, can be seen in figures 21*B* and 22*B* and *C*; a complex graben and multiple scarps are illustrated in figure 22*A*.

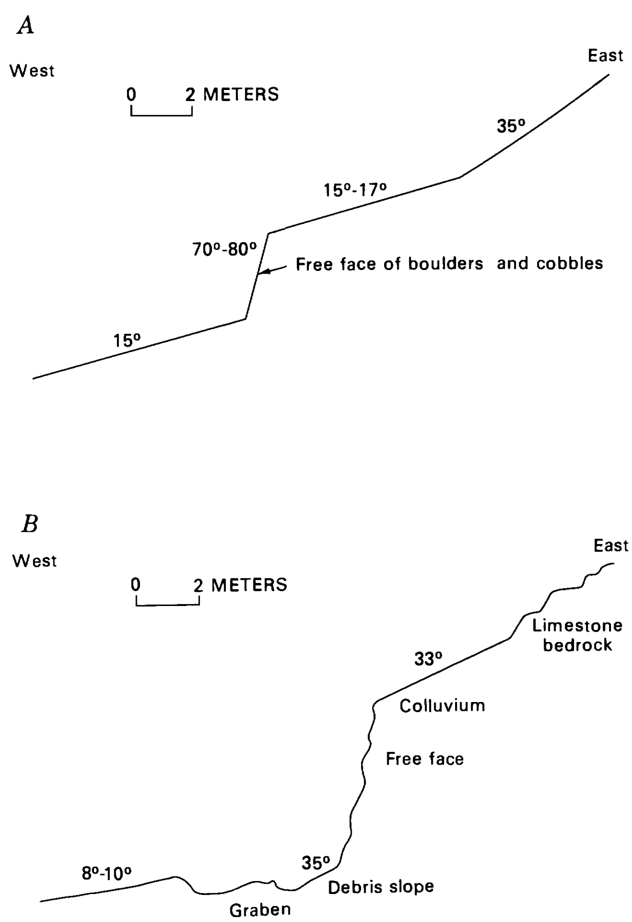

FIGURE 21.—Profiles across the Pearce scarp. *A*, One kilometer north of Cottonwood Canyon, *B*, Miller mine area.

At some locations the scarp is compound and remnants of older scarps appear as elongate facets or bevels roughly parallel to the crest and base of the scarp and generally lying above the part of the scarp developed in 1915. Profiles display breaks in

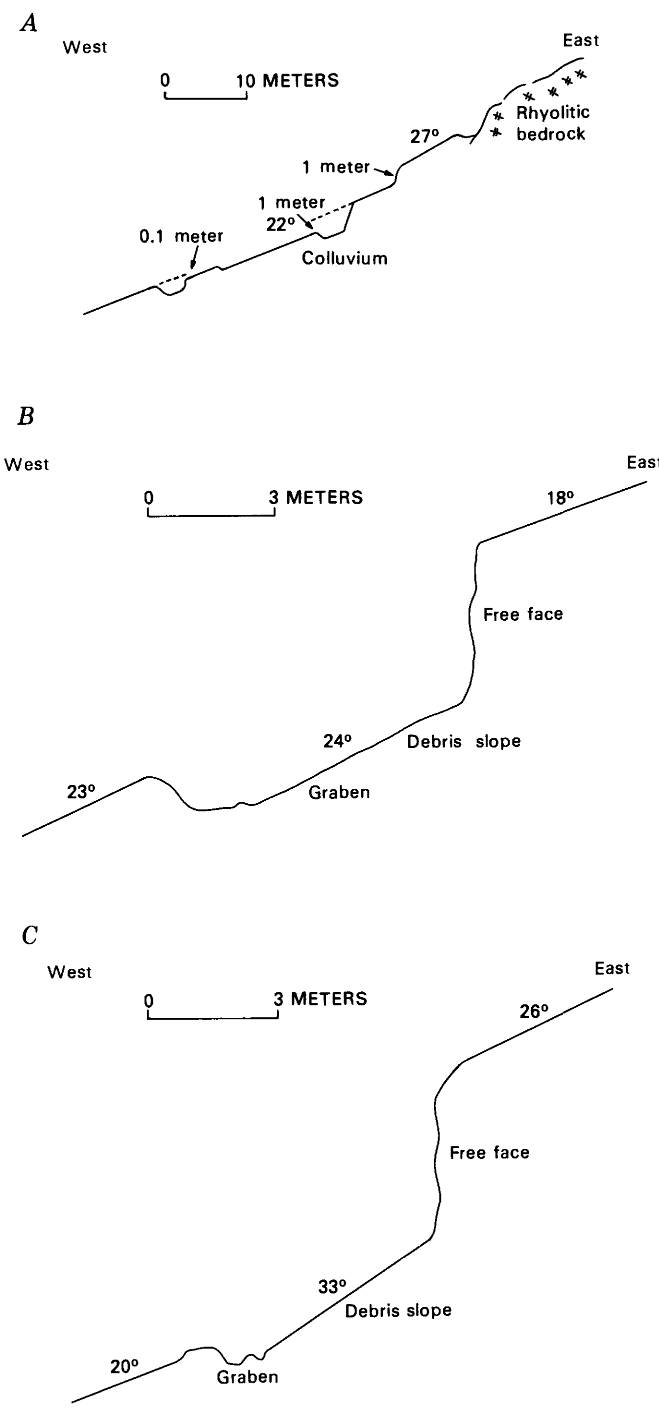

FIGURE 22.—Profiles across the Pearce scarp at and near south edge of sec. 21, T. 29 N., R. 39 E. *A*, 0.45 km south of section line, *B*, 0.4 km south of section line, *C*, 0.5 km south of section line.

slope between the facets (fig. 24). Each significant break in slope above the crest of the 1915 scarp may separate one older scarp from the remnant of another.

Commonly, the breaks in slope can be discriminated by eye without measuring slope angles. The breaks tend to have linear continuity along the slope, and scarp facets separated by the break in slope may differ in microrelief or erosional texture. Angular differences as small as 2° may produce the appearance of facets, but generally angular differences greater than 3° are required to clearly differentiate facets. Not everywhere are the remnants of older scarps clearly preserved as facets. Where slopes are underlain by materials of different degrees of induration, microtopography may be dominated by the effects of differential erosion.

To determine the vertical component of fault displacement from heights of scarps in various stages of degradation requires reconstruction of the original slopes and an estimate of how far the free face has retreated. As the material spalls from the free face, the crest migrates uphill, and the scarp height is exaggerated. At the same time, the toe of the scarp becomes covered by debris, and the apparent toe of the scarp is extended downhill. The dip of the fault plane must also be considered in the reconstruction. Despite these complications, fairly accurate vertical components of displacement can be estimated for the 1915 scarps. Wallace (1980) provides nomographs to assist in estimating the vertical component of displacement on the basis of the apparent height of a scarp.

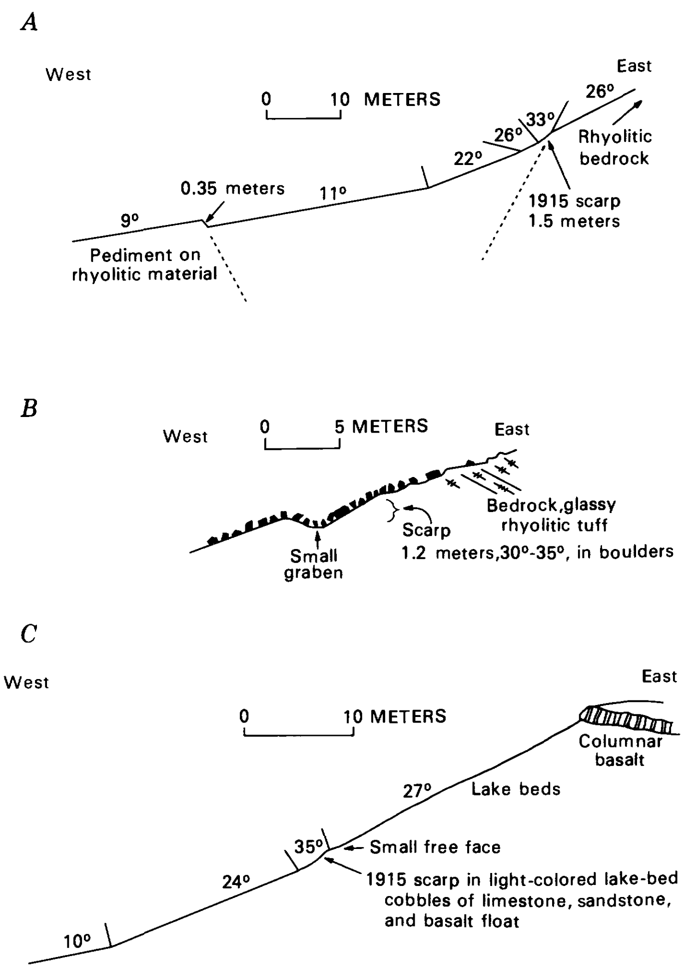

FIGURE 23.—Profiles across Sou Hills scarp. *A*, Approximately 0.3 km north of south edge of T. 27 N., R. 38 E., *B*, near north end of main scarp, *C*, center, sec. 5, T. 26 N., R. 38 E.

RECURRENCE OF FAULTING

That many previous displacements have occurred along the faults that produced the 1915 scarps are evidenced by the height of the range fronts, the presence of faceted spurs (fig. 25), and other features characteristic of fault-generated range fronts (Wallace, 1978). Of particular interest in regard to the seismic history of this area is the frequency with which earthquakes have been generated by displacement along these faults. A history of large earthquakes accompanied by surface displacement can be inferred from the presence of older scarps preserved along or in close proximity to the 1915 scarps and by a determination of the ages of these older scarps. The technique of dating fault scarps by scarp geomorphology, especially angle of slope, is discussed in papers by Wallace (1977a), Bucknam and Anderson (1979), and Nash (1980), and comments about the application of this technique to the 1915 and related scarps are included in the sections "Profiles of the Scarps" and "Description of the Scarps." Some remnants of older scarps, preserved immediately above the 1915 Pearce scarp, are similar in slope to the wave-cut cliffs of Lake Lahontan, although the heights of the older scarps are not known. From such evidence it appears that at least one large displacement event occurred within the past 12,000 yr B.P. Other scarp remnants above the 12,000-yr-old scarp are even more subdued and suggest individual displacement events prior to 12,000 yr B.P.

In addition to evidence provided by the morphology of pre–1915 scarps, other relations suggest earthquakes and fault-displacement events before 1915. Only the relatively large earthquakes were likely accompanied by fault scarps larger than a meter high. Smaller displacements related to smaller earthquakes would be unlikely to leave a clear record for long periods of time.

At least two stages of fault displacement are apparent along the Pearce scarp 100 m north of the mouth of Little Miller Basin. Two prominent bands, one above the other, are preserved on a planar surface of limestone in the scarp face (fig. 26). The lower band represents that part of the limestone surface that was exposed in 1915 when the colluvium in the hanging wall of the fault moved downward about 3 m. The 3–m-wide band is smooth, has pronounced slickensides, and has only a few patches of lichens on its surface. In contrast, the upper band, exposed during an earlier displacement, is very rough and pockmarked by solution pits, and lichens are well developed over 30 percent of the surface. The upper band is about 4 m wide, and its planarity and uniformity of texture suggest a single displacement event. Evidence of more than one event, of course, may have been eroded in the process of solution pitting.

Many of the solution pits are crudely circular in plan, 1–2 cm wide and 0.5 cm deep. Rill-like troughs many centimeters long, 1–2 cm wide, and 0.5 cm deep also are present (fig. 27). Between the two bands is a less conspicuous transition band a

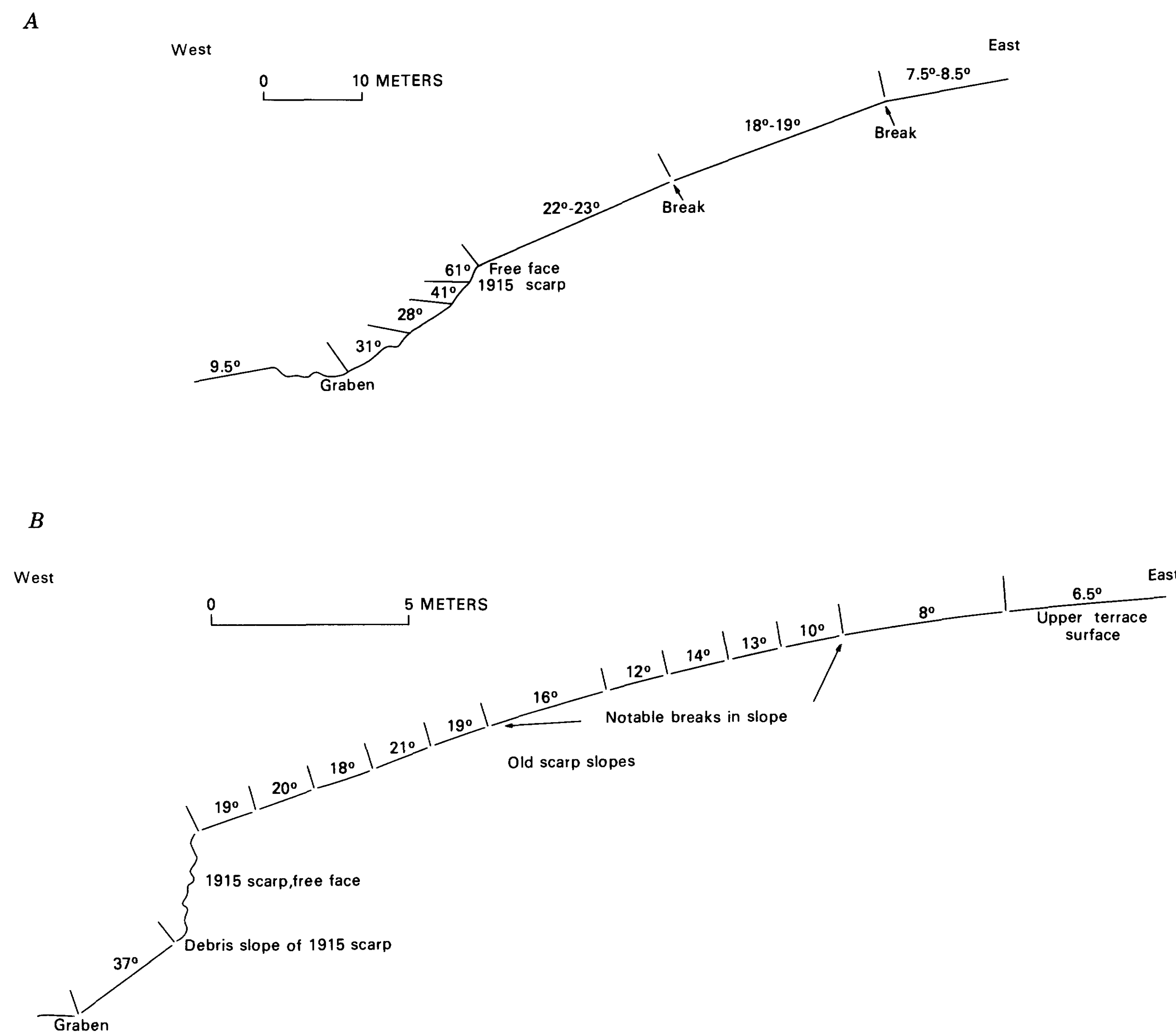

FIGURE 24.—Pearce scarp, showing evidence of more than one displacement. *A*, Pearce scarp near Pearce ranch. *B*, Pearce scarp at mouth of Siard Canyon.

few centimeters wide. Whether this transition band represents an increment of fault displacement is unknown; perhaps it represents weathering under the imperfect cover that would have been provided by the upper few centimeters of loose colluvium of coarse clasts that lay against the limestone surface before 1915 but after earlier displacements.

The degree of solution pitting on the upper band should provide a measure of the length of time that that surface has been exposed and, thus, a time constraint as to the date of a large displacement event prior to 1915. A cursory search of the literature about rates of solution pitting on limestone, however, produced little information that was directly applicable. The most useful evidence thus far has come from an examination of solution-pitted surfaces of cobbles and pebbles that coat the old beaches and beach bars of glacial Lake Lahontan. The beaches of the last high stand of the lake have been dated at approximately 12,000 yr B.P. (Morrison and Frye, 1965), and beaches and bars that developed at lower elevations as the lake evaporated are younger.

Many deeply pitted cobbles and pebbles of the same lithology exposed in the scarp face were found on the beaches and bars of Lake Lahontan in Buena Vista Valley, approximately 15–20 km west of the Pearce scarp. On the beaches formed during the high stand of the lake, the exposed upper surfaces of cobbles and pebbles are deeply pitted. Their lower, buried surfaces are smooth and well rounded, as would be expected of beach gravels, and many of the bottom surfaces are coated with caliche. A centimeter or more of limestone clearly has been removed by solution from the upper surfaces of some of the cobbles. Given such a rate of solution, the pitting observed on the limestone surface in the Pearce scarp could have been formed in 12,000 yr, so this may be an upper limit for the age of that surface. But cobbles on beaches and beach bars 30–50 m lower in elevation than the high stand are similarly pitted, so significant pitting can occur in some undetermined period of time less than 12,000 yr. Furthermore, many of the beaches and bars have a cover of loess as thick as 20 cm that was deposited over the original lake-washed gravel surface. Gravel under that loess cover still retains the rounded surfaces characteristic of wave-washed gravel. Only where deflation has removed the loess and exposed the gravel, or where the gravel was never covered, are the clasts deeply pitted by solution. A history of loess deposition, then removal, thus occurred within the past 12,000 yr before solution pitting occurred; it follows that considerably less time than 12,000 yr was sufficient for deep pitting to develop on this limestone. On the other hand, the

FIGURE 25.—Pearce scarp and faceted spurs near Miller Basin. Note that upper parts of facets have lower angle of slope than lower parts.

absence of solution pitting on the lower band, which has been exposed for more than 65 yr, suggests that a period of exposure much longer than 65 yr was required for the pitting in the upper band to develop.

In the People's Republic of China in 1978, I examined several objects of limestone and limestone marble which are said to have remained exposed to the weather for about 1,200 yr. At Sian, where some of the objects were examined, the an-

FIGURE 26.—Limestone bedrock exposed in face of Pearce scarp. Lower band, 3 m wide, was exposed in 1915. Upper band, about 4 m wide, probably was exposed during similar previous earthquake. Lower band is characterized by well-preserved slickensides (light streaks) and very sparse cover of lichens. Upper band is characterized by solution pitting and well developed coating of lichens (see detail in fig. 27).

nual rainfall is between 60 and 70 cm, approximately three times that in Pleasant Valley, Nevada. The degradation by weathering and solution of the surfaces on the objects at Sian ranged from negligible to fairly severe, but none was even a small fraction as degraded or pitted as the limestone surface in the upper band on the fault at Pleasant Valley. Despite the cursoriness of the examination and the number of unknown factors, such as composition of the limestones and relative acidity of the rains, the comparison suggests that the pitted surface of the fault scarp in Nevada is considerably older than the eighth-century objects in China.

In summary, the pitted surface on the fault scarp apparently was exposed by one or more events more than a few thousand years ago, but less than 12,000 yr B.P. The 4–m width of the pitted band, similar to the width of the 1915 displacement, and the absence of obvious subbands within it, suggest that a single large-displacement event

FIGURE 27.—Detail of older surface of scarp shown in figure 26. Solution pits and channels are as much as 1 cm deep and 2 cm wide. Lichens are well developed. Scale in centimeters.

occurred several thousand years before the 1915 event.

A small lenticular body of volcanic ash is exposed in the free face of the 1915 scarp near the north end of the Tobin scarp (near the north edge of sec. 19, T. 30 N., R. 40 E.). The ash was identified by R. E. Wilcox (written commun., 1974) as ash thrown out 6,600 yr B. P. from Mount Mazama, at the site of the present Crater Lake in the Cascade Range of Oregon (Powers and Wilcox, 1964). The section of the lens of ash is 0.3 m thick and 0.4 m wide, and it is interbedded with colluvium and alluvium approximately 0.3 m below the ground surface. Sand and gravel beds interfinger with the ash.

The geomorphic setting of the sediments containing the ash suggests that they are near the head of an alluvial fan where slope wash and stream deposits interfinger. The head of the fan lies upstream of the 1915 scarp, and the fan had been deeply incised prior to 1915. No conspicuous older scarp is preserved on the surface of the fan or in colluvium in the vicinity of the ash lens, so the 6,600–yr-old ash would seem to establish a minimum age for the most recent major faulting event before 1915.

Although some degree of transport of the ash is implied by the interbedding of ash, sand, and gravel, the small size of the body and the uncontaminated nature of much of it suggest no more than local movement over a short period of time. Fault displacement events of only a few centimeters might not have been preserved and could be easily overlooked.

Bonilla and others (this volume) report that in a trench across the north end of the Pearce scarp faulted sediments show repeated displacements of probably less than a meter each. They infer that the last one prior to 1915 possibly occurred more than 2,000 yr but less than 5,000 yr B.P.

At a locality approximately 700 m south of the Siard Ranch, numerous pieces of carbonized wood, locally abundant enough to form a sedimentary layer, were found interbedded with gravel upstream from the 1915 scarp. The gravel is 0–4 m thick and wedges out a few tens of meters uphill from the scarp to form the apex of a pre–1915 alluvial fan. The wood occurs between depths of 1 and 2 m in the gravel. Two samples of the wood were dated by Meyer Rubin (written commun., 1974) at 670±200 yr and 480±200 yr B.P.; those ages correspond to any date between 1294 and 1504 A. D.

From present appearances, the surface of the pre–1915 alluvial fan has been smoothly graded across the site of the 1915 scarp; no conspicuous remnants of an older scarp remain. In light of the persistence of the scarps formed in 1915, a relatively long history must be postulated between 1915 and any large displacement event before 1915 to account for the obliteration of the older scarp and the headward buildup of a fan across the old scarp. The pattern of erosion since 1915 indicates that after a displacement event, erosion in the vicinity of a scarp is greatly accelerated because of the sharply increased gradient and the eroded material begins to deposit 100 m or more downstream from the scarp. That point of first deposition represents the apex of a new alluvial fan. As the fan gradually builds upward in height, the apex migrates headward, eventually crossing the trace of the fault. Given the absence of further tectonic disturbance, the uppermost beds of the fan, which include those near the fan's apex, will be the youngest beds of the fan. The age of the wood found near the old fan's apex thus must represent the most recent part of the fan's life; it follows that the age of the latest large pre–1915 displacement event at Pleasant Valley, later obscured by the fan, must be many times 600 yr.

Large boulders rolled off the range front in 1915, and rockfalls probably were triggered during earlier earthquakes. At a site between 0.5 and 1 km south of Golconda Canyon, a boulder field at the base of the mountain front contains at least three generations of boulders. The latest rockfall, believed to be related to the 1915 earthquake, has faces that appear freshly broken and are almost completely free of lichen cover. Boulders of the 1915 fall rest on the surface of the piedmont slope, their bases not embedded in the slope material. Older boulders, many of which are much larger than those believed to be of the 1915 generation, are all embedded to various depths in the piedmont slope materials, and lichens are far more extensively developed over their surfaces. Hoare (1982) suggests from a preliminary analysis of the lichens that a rockfall occurred about 300 to 500 yr B.P. On the basis of the rockfalls he witnessed in Yosemite Valley, California, during the 1872 earthquake that was centered in Owens Valley, Muir (1962) suggested that major rockfalls occurred during prehistoric earthquakes.

A major faulting event on the Pleasant Valley faults need not be postulated to account for the rockfall 300 to 500 yr B.P. Two fault scarps, perhaps as young as that rockfall, may identify nearby epicentral sites of earthquakes that could have triggered the rockfall. One set of scarps on the west flank of the north end of the Shoshone Range is about 65 km away, and another set of scarps on the west flank of the northeastern part of the Cortez Mountains is about 110 km away (see fig. 29). An earthquake as large as $M = 6.5$ may even have occurred on the 1915 fault and caused the rockfall 300 to 500 yr B.P. but left no conspicuous fault scarp. In historical time in the Great Basin province, conspicuous surface faulting has accompanied only earthquakes larger than about $M = 6.5$.

Lichens and moss also develop on soil and provide a means of distinguishing some small scarps formed in 1915 from those formed earlier. A combination of moss and lichens develops especially well on loess or fine silt to produce a very irregular surface referred to as "popcorn soil," because during dry periods the soil crunches when walked on. The surface is irregular because of closely spaced desiccation cracks between which blocks of ground, a few centimeters across, are capped by a growth of lichens and moss. The lichens and moss armor the surface and indurate the small blocks, thus protecting them from disintegration during rain. During subsequent drying periods, I hypothesize, the old desiccation cracks are reactivated and enlarged, so that the vertical dimensions of the blocks become as great or greater than their widths. Small scarps (that is, those less than 0.5 m high) believed to have formed in 1915 have no popcorn soil developed on their surfaces, whereas other scarps believed to be much older have well developed popcorn soil. Apparently, the popcorn soil requires considerably longer than 65 yr to begin to be noticeable, let alone to become fully developed.

The age of one faulting event before 1915 may be suggested by the age of a juniper tree growing near the Miller mine near the west edge of sec. 8, T. 28 N., R. 39 E. along the Pearce scarp. The tree is rooted in a crack in bedrock 4.5 m above a terrace of alluvial gravel and 35 m upstream from the 1915 scarp. By growth ring count, the tree is estimated to be between 250 and 300 yr old. A main root of the tree, instead of being enclosed in rock or soil, is entirely exposed over most of its length between the base of the tree and the terrace. The surface of a higher terrace remnant south of the present creek may project to about the base of the tree. This relation may indicate that the tree originally sprouted at the contact between bedrock and gravels underlying the higher terrace and that after an uplift event those gravels eroded away and the main, or lower, terrace was formed.

The uplift that instituted this cycle of downcutting could have been related to a fault-displacement event preceding that of 1915. Given the tree's age, the displacement event occurred between about 1674 and 1915. This entire line of argument would be negated if the root of this juniper tree behaved like the roots of some other conifers. For example, I have noted that the roots of some Monterey pine trees extrude from the ground as they age. Over a period of a few years, some Monterey pine roots, once buried, have moved upward out of the ground over a length of ten or more meters and have continued to enlarge in diameter in the newly exposed positions.

In summary, the times of displacement events prior to 1915 are very uncertain, but the average recurrence interval for large displacement events is likely measured in thousands of years, but probably less than 12,000 yr.

PATTERNS OF RECURRENT FAULTING

Although young fault scarps that formed prior to 1915 are conspicuous along many segments of the 1915 scarps, such sites constitute a small percentage of the total scarp length. Furthermore, other young scarps formed prior to 1915 are present near, but not directly on, the 1915 scarp trace. Near the south end of the Pearce scarp (secs. 11, 12 and 14, T. 27 N. R. 38 E.), for example, numerous small pre–1915 scarps, although arranged in the same general pattern as those formed in 1915, were not reactivated; these appear to represent greater total displacement than the 1915 scarps. Perhaps the earthquake during which they formed was of larger magnitude than that of 1915, or perhaps fault displacements during the pre–1915 event were less in this locality but greater elsewhere. The part of the Sou Hills scarp reactivated in 1915 is only about half the total length of the pre–1915 scarp, for the northern part of the old scarp remained unbroken in 1915. Splays northeast of the north end of the Pearce scarp also remained unbroken in 1915. As noted above, the northern part of the Tobin scarp is oriented parallel to prominent scarps to the northwest, but those scarps were inactive in 1915.

Although the faults appear to have a strong tendency to break again and again in the same place, during each displacement event some new breaks develop, and the amounts of displacement at given points may vary from event to event. The 1915 scarps generally, though not invariably, lie at the base of older scarps, but in places they are many meters uphill from the older scarp. In other places, 1915 scarps do not break the same segment at all, or they splay or diverge from the sites of previous scarps. The general longitudinal integrity of mountain blocks, however, attests to the fact that over long periods of time cumulative displacements along segments of faults many kilometers long will average out.

SIZES OF THE EARTHQUAKES AS DETERMINED FROM SCARP DIMENSIONS

The main 1915 earthquake has been assigned various magnitudes: 7¾ (Coffman and von Hake, 1973), 7.6 (Richter, 1958), and 7.5–7.8 (Alan S. Ryall, written commun., 1974). The size can also be expressed as seismic moment (Brune, 1968; Thatcher and Hanks, 1973; Hanks and others, 1975; Thatcher 1975; Kanamori, 1977a, b; Hanks and Kanamori, 1979), which in turn can be derived from fault dimensions and amount of slip (fig. 28, table 1). Seismic moment (M_o) is defined as

$$M_o = \mu DLh$$

where μ is shear modulus, D is average displacement, L is rupture length, and h is rupture dimension along the dip of the fault plane. The seismic moments of the cumulative rupture surfaces and of the individual rupture surfaces represented by the four main scarps are given in table 1; the displacements are depicted in figure 28. The rupture dimension along the dip of the fault plane is assumed in each case to be 17 km (15 km depth corrected for 60° dip), a depth consistent with maximum depth of hypocenters in Nevada; shear modulus is assumed to be 3×10^{11} dyne/cm^2, a common value for rocks.

Seismic moment can be translated into magnitude to enable comparison with other large earthquakes in the world. Hanks and Kanamori (1979) review the relations between seismic moment and the three expressions of magnitude, M_L, M_s, and M_w. The three forms nearly coincide and they imply a moment-magnitude scale $\boldsymbol{M}$ = 2/3 log M–10.7, which is uniformly valid for $3 \lesssim M_L \lesssim 7$, $5 \lesssim M_s \lesssim 7\frac{1}{2}$ and $M_w \gtrsim 7\frac{1}{2}$. Values of $\boldsymbol{M}$ calculated by this relation are given in table 1. Singh and Havskov (1980) suggest for intraplate events the relation $\boldsymbol{M} = 2/3 \log M_o–10.46$, from which a value of $M_w = 7.4$ would be obtained.

The values of magnitude derived from the surface expression of faulting and from moment-magnitude relations are approximately 1/2 $\boldsymbol{M}$

TABLE 1.—*Sizes of earthquakes, according to fault dimensions, magnitudes, and seismic moments*

[D, average displacement; L, rupture length; M_o, seismic moment; M, moment-magnitude; M, magnitude]

	D (m)	L (km)	M_o (dyne/cm × 10^{25})	M	M
1915, Scarps overall	2.03	59	61	7.2	7.5–7.8
China Mountain scarp	.93	10.0	4.7	6.4	—
Tobin scarp	1.86	8.5	8.1	6.6	—
Pearce scarp	2.81	30	42.8	7.1	—
Sou Hills scarp	.86	10.5	4.6	6.4	—
1872, Owens Valley, Calif.	—	—	[1]500	[3]7.8	—
1932, Cedar Mountain, Nev.	—	—	—	—	[2]7.3
1940, Imperial Valley, Calif.	—	—	[1]30	[3]7.0	[2]7.1
1954, Dixie Valley-Fairview Peak, Nev.	—	—	[1]90	—	[2]7.1

[1]Hanks and others, 1975

[2]Coffman and von Hake, 1973

[3]Hanks and Kanamori, 1979

lower than those derived from seismic-wave analysis. Many problems arise in obtaining mutually consistent magnitudes from the two methods. The argument can be made that surface faulting is neither a complete expression of the entire surface of displacement nor of the amount of displacement. For example, slip areas less than the depth of brittle behavior of the crust (approximately 15 km) may be contained completely below the ground surface. Slip may increase downward if strain is imparted at the base of the brittle layer and rupture is propagated upward. A slip surface may lengthen or shorten downward; however, the Pearce scarp coincides so closely with the flank of the Pearce mountain block that the 1915 scarp would seem to reflect fairly accurately the length of the block and its bounding fault plane.

The two large foreshocks may have been accompanied by the development of one of the four scarps or by a partial development of one or more of the scarps.

CHARACTERISTICS OF FAULTING AND SOME TECTONIC IMPLICATIONS

Characteristics of the 1915 faulting lead to some interpretations about regional tectonics and mechanisms of faulting. Two features, in particular, require discussion: (1) eastward tilting of the range blocks along which the 1915 scarps were formed, and (2) the right-stepping en echelon pattern of the four scarps.

EASTWARD TILTING OF RANGE BLOCKS

The China Mountain, Tobin, Pearce, and Sou Hills scarps all developed along the west flanks of mountain blocks (pl. 1; fig. 29). The youngest fault scarps bounding many other mountain blocks in the region, although prehistoric, also are on the west flanks of the mountains; the Humboldt and East ranges west of the 1915 scarps, and the Fish Creek Mountains, the Shoshone Range, and the Cortez Mountains to the east (fig. 29). To the north, a young fault scarp on the west flank of the Sonoma Range is in general alinement with part of the Tobin scarp (Wallace, 1979) (pl. 1).

The preponderance of the youngest fault scarps on the west margin of these ranges and the uplift of the ranges relative to the basins suggest that the range blocks have been tilting dominantly to the east in late Quaternary time. In addition, continental sediments of late Tertiary age that crop out on the east flanks of many of these ranges dip eastward at angles of as much as 35°. Basalt flows dipping eastward between 5° and 10° form erosional remnants on the east flanks of many

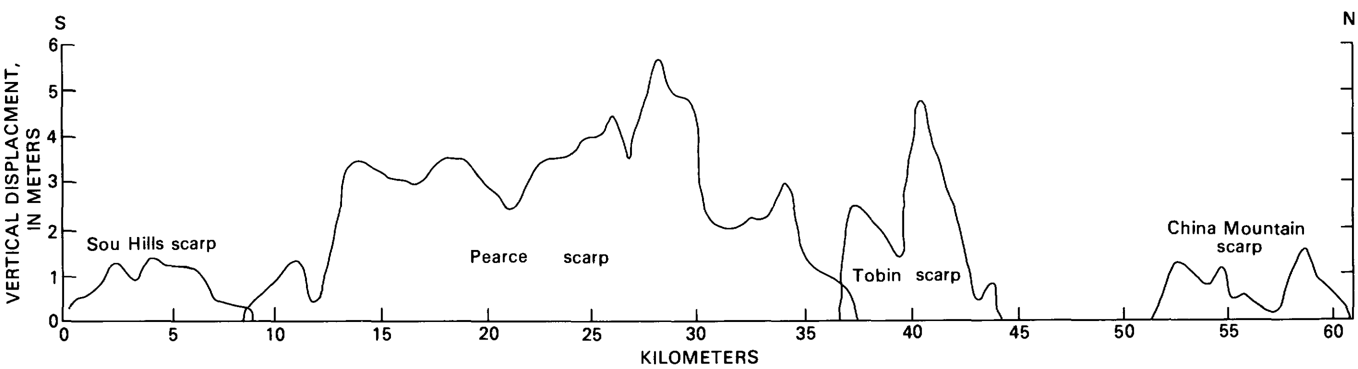

FIGURE 28.—Long profile of displacement on four main 1915 scarp segments.

ranges and in places lie unconformably across beveled edges of the older continental sediments. These relations further demonstrate the progressive eastward tilting of the range blocks.

Not all range blocks tilt simply to the east. The Buffalo Mountain block northeast of China Mountain, which has a young scarp on its southeast flank, appears to have been tilted to the northwest. Young fault scarps on the west and northwest flanks of the Battle Mountain block suggest tilting to the east and southeast. Volcanic flows in the Fish Creek Mountains are warped into a broad synclinal structure, which is broken into smaller blocks by faults. Although the western part dips eastward and is bounded on the west by a young scarp, some young scarps face east on the east side of the range and south on the south side of the range.

South of the 1915 scarps, and approximately along strike with the Sou Hills scarp, the east flank of the Stillwater Range is one of the most prominent, steep range fronts in the region, and it has an east-facing, young fault scarp at its base. Scarps produced during the 1954 earthquake in Dixie Valley lie along this same range front, but extend only to a point about 42 km south of the Sou Hills. Young scarps lie along parts of the west flank of the Stillwater Range. Within the Stillwater Range, basalt flows and other volcanic rocks, presumably of ages comparable to those dated as 10–14 m.y. old, are present in open folds and faulted blocks tilted a few degrees east or west to form a complex structural pattern. The change along strike, from west-facing scarps exemplified by the 1915 scarps to east-facing scarps exemplified by the east front of the Stillwater Range, takes place at about lat 40° N. A pronounced change in the tilt characteristics of other ranges north and south of this parallel in central Nevada suggests a boundary of domains of some tectonic significance (Stewart, 1980).

No mechanism is readily apparent to account for the consistent eastward tilt, between lat 40°–41° N. and about longitude 116°–118.5° W., of a series of range blocks. Stewart (1978, 1980) reviews several possible models. Regional extension might account for continued tilting once a direction of tilting has been established, but to initiate tilting

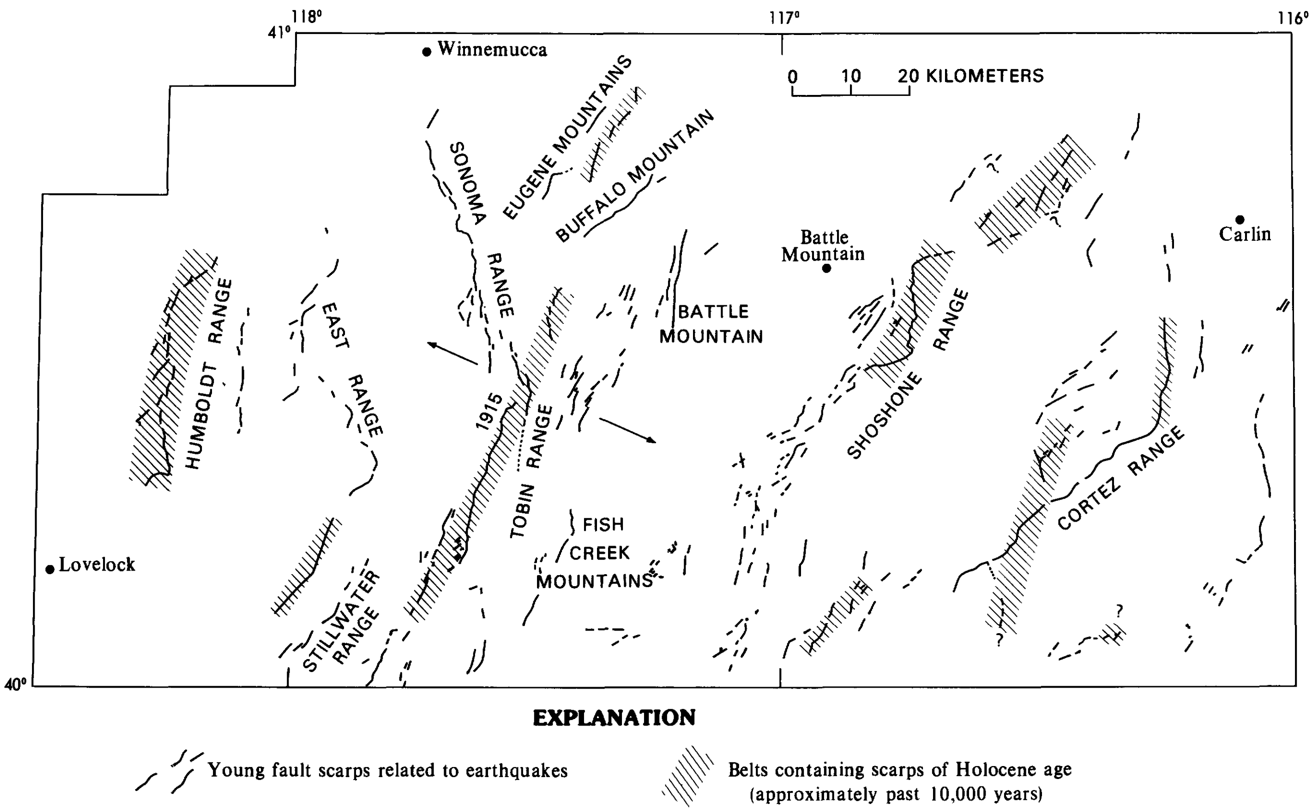

FIGURE 29.—Regional distribution of young fault scarps in north-central Nevada. Note three trends—north, northeast, and northwest. The 1915 scarps contain segments having the three trends. Scarps of Holocene age (past 10,000 yr) lie in northeast-trending belts. Arrows perpendicular to the 1915 belt of reactivation indicate orientation of regional extension.

in one direction would require some form of asymmetry, such as the master fractures postulated by Stewart. Moore (1960) suggests that the preferred direction of tilt might be related to gravity sliding from regional topographic highs, but no such relation to topography consistent with this explanation has been shown to pertain over the Great Basin.

At least some of the range blocks may have slid or slumped from other, larger adjacent range blocks in grossly landslidelike fashion, tilting toward the parent range block along curved fault surfaces. I refer to such blocks (fig. 32) as "second-order blocks."

A diagnostic feature of such blocks would be tilting of a small block toward a larger one. For example, Muller and others (1951) show that the Pearce block tilted progressively eastward; they state that "the dip of rhyolite is steeper than that of the overlying andesite" and it is small in comparison to the main Tobin Range block. The relation of the Sou Hills block to the Tobin Range block is similar, but not as clear.

Another range block in the region, for which the evidence of rotation toward a parent block is clearer, is the West Humboldt Range block (fig. 30) (Wallace, 1965). That the West Humboldt Range block has slumped or dropped relative to the Humboldt Range and has continued to rotate or tilt toward the Humboldt Range is evidenced by the following: Within the West Humboldt block, a thick section of fanglomerate of Tertiary age, clasts of which were derived from the main Humboldt Range block, now dips 30°–35° toward the Humboldt Range; basalt flows approximately 10 m.y. old lie unconformably across the beveled edges of the fanglomerate and dip 8°–10° toward the Humboldt Range; and above the basalt a surface on terrace gravels of late Quaternary age slopes 1°–2° toward the Humboldt Range.

Although the Pearce and Sou Hills blocks are relatively small, the West Humboldt Range block is comparable in size to most ranges in the Great Basin. So if the West Humboldt Range is a second-order structure, a similar relation might pertain to many other ranges in the region. It is tempting to apply the listric-fault model of a range the size of the West Humboldt Range to all the tilted ranges in the region, but such a step is difficult to support.

EN ECHELON PATTERN OF SCARPS AND REGIONAL EXTENSION

The four scarps, China Mountain, Tobin, Pearce, and Sou Hills, are arranged in a right-stepping, en echelon pattern confined to a belt approximately 6 km wide, 60 km long, and trending N. 25° E. The Tobin and Sou Hills scarps are segments of faults that extend many kilometers beyond the belt of 1915 reactivation. The belt of reactivation trends across the four range blocks and their bounding faults with no apparent relation to any conspicuous surficial structure (see fig. 29).

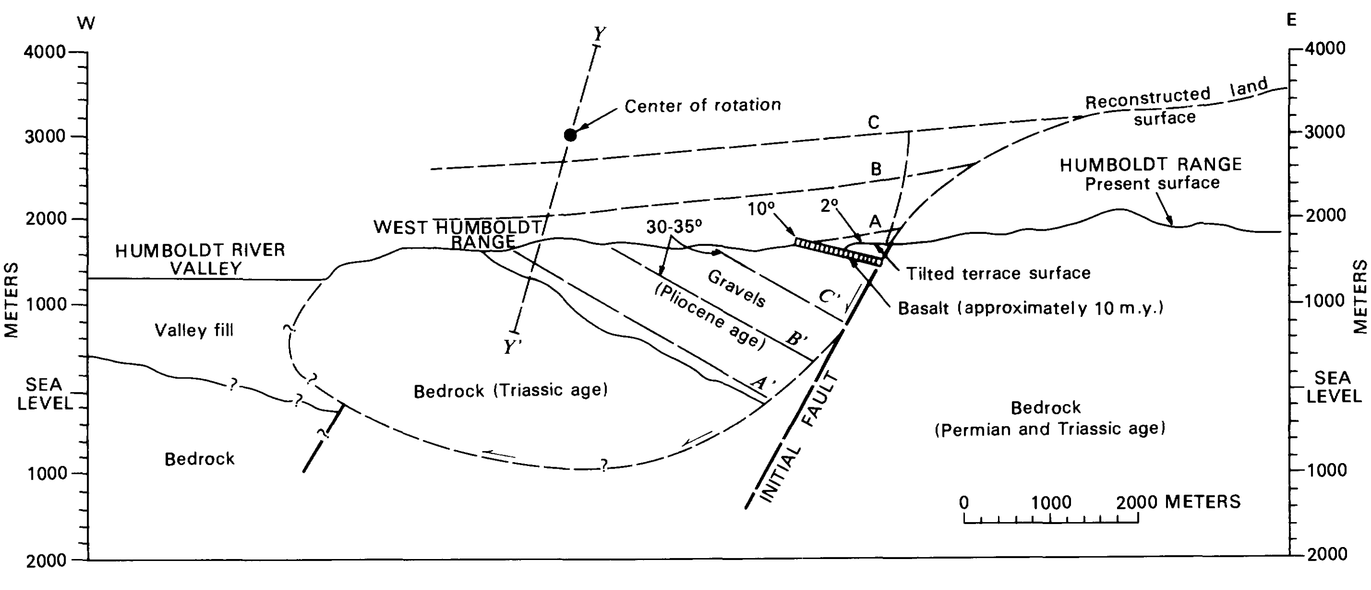

FIGURE 30.—Diagrammatic cross section of West Humboldt and Humboldt Ranges showing possible landslidelike slip on listric fault invoked to explain homoclinal structure in West Humboldt Range. *Y–Y'* is locus of points about which rotation could move fan gravel beds from reconstructed original positions A, B, and C to present positions A', B', and C' (after Wallace, 1965).

This independence from obvious surficial structure suggests that the belt relates to some deep structure and that the effects of extension across the belt are imposed on upper crustal blocks that originally formed in some other stress domain. The elongate belt of reactivation is characterized by extension normal to its long axis, as discussed below, but whether this linear zone of extension at depth is accommodated in a brittle mode, for example a fault zone, or in a ductile mode is unknown. The strike discordance of the reactivated faults and the trend of the zone of extension must result in a zone of readjustment, perhaps a subhorizontal zone of decoupling, between the extending material at depth and the shallower fault blocks being rotated.

Widely divergent strikes characterize major faults in the surrounding region (figure 29). Trends of faults in the region cluster in three principal orientations: northwest, north, and northeast. Each of these trends may have developed at a different time; the northwest trend, including the Oregon-Nevada lineament, is considered to have developed in late Miocene time (Stewart and others, 1975) and may be the earliest. The pattern of faults in several ranges indicates that these trends intersect. For example, the northern and southern parts of the fault along the west flank of the Humboldt Range, as well as a splaying fault near its midsection, strike northeast, whereas the major part of the fault along the range front strikes north. Similarly, faults bounding the East and Shoshone Ranges are made up of northeast-, north-, and northwest-striking segments. The different strikes of different segments of the 1915 scarp reflect these three major trends.

Regional extension can also be inferred from displacement vectors on the 1915 scarps. The few observed sets of slickensides plunge in directions that range from about N. 50° W. to N. 75° W. and average about N. 60° W. (fig. 31). North- and northwest-striking segments of the scarps generally display a right-lateral component of displacement, segments striking N. 20°–40° E. display simple dip slip, and one segment striking N. 70°–80° E. displays a left-lateral slip component. Regional extension normal to the N. 20°–25° E. trend of the belt of reactivation, that is, N. 65°–70° W., would be consistent with the detailed slip vectors described. The orientation, N. 55° W., of regional extension inferred in Dixie Valley by Thompson and Burke (1973) is within the limit of error of the slip-vector measurements made on the 1915 scarps. The orientation of two grabens near the south end of the Pearce scarp suggests a similar orientation, N. 60° W., of regional extension.

TECTONIC IMPLICATIONS

An attempt to synthesize some of the foregoing data and hypotheses into one model is shown diagrammatically in figure 32. Incorporated into this model are: (1) A predominantly eastward tilt of ranges at the latitude of the 1915 scarps; (2) a first- and second-order relation between some blocks; (3) a listric style of faulting bounding the ranges; (4) a limit of depth of seismic events, and thus of brittle behavior, to approximately 15 km; (5) presence of the Moho at a depth of about 25 km (Pakiser, 1963; Eaton, 1963); (6) a subhorizontal zone of decoupling at the base of the the listric faults (as in a similar structural setting in Utah, see McDonald, 1976); (7) a zone of extension at depth.

Although this model accounts for many of the observations, it raises many questions that await satisfactory answers. How do listric faults bottom, and why do they form in the first place? Is it plausible that listric faults be seismogenic? What is the nature of the deep zone of extension, and why should extension be confined to an elongate narrow belt? How can the effects of a narrow zone of

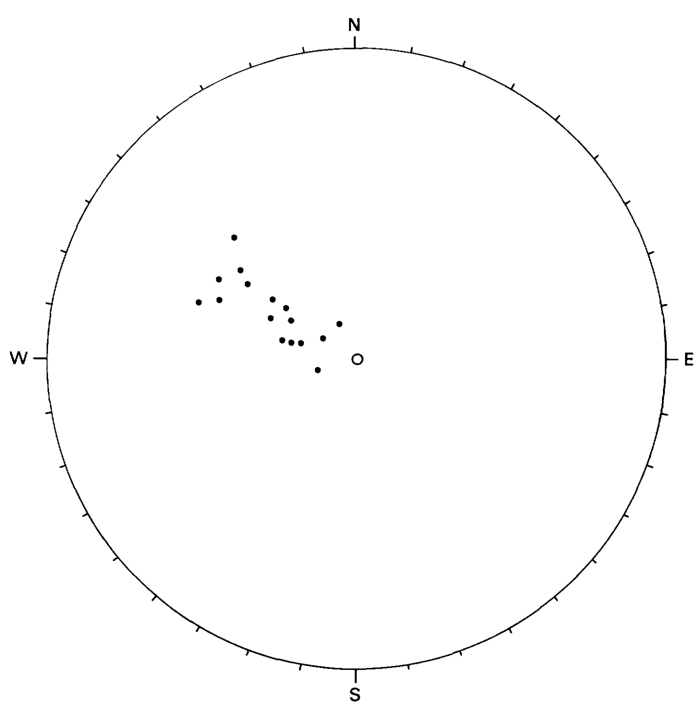

FIGURE 31.—Stereographic plot of orientation of plunge of slickensides on bedrock along Pleasant Valley scarp. Plotted on equal-area stereographic net, lower hemisphere.

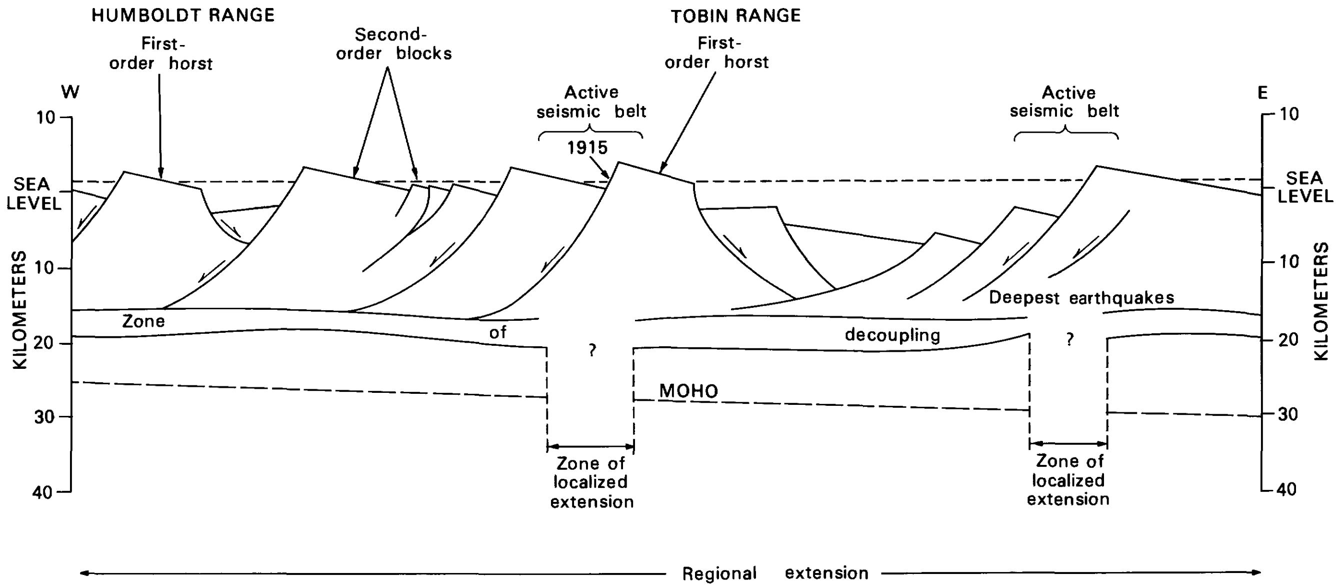

FIGURE 32.—Diagrammatic cross section of crustal structure near the 1915 scarps, presenting an interpretation of listric normal faults as a major structural feature.

extension be propagated upward through a zone of decoupling? Why would the results of extension at depth be expressed at the surface as a narrow band of reactivated fault segments, rather than be more widely distributed on listric faults that diverge upward from the vicinity of the deep zone of extension?

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Exploratory Trench Across the Pleasant Valley Fault, Nevada

By M. G. BONILLA, H. A. VILLALOBOS, *and* R. E. WALLACE

FAULTING RELATED TO THE 1915 EARTHQUAKES IN PLEASANT VALLEY, NEVADA

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EXPLORATORY TRENCH ACROSS THE PLEASANT VALLEY FAULT, NEVADA

By M. G. Bonilla, H. A. Villalobos, and R. E. Wallace

ABSTRACT

An exploratory trench was excavated across the 1915 trace of the Pleasant Valley fault, 60 km south of Winnemucca, Nevada, to study the history of recent displacements on a fault that had produced a major earthquake in historic time and to ascertain the appearance of such a fault in a trench cut in gravels, sands, and silts of an alluvial fan.

The trench exposed 16 mappable sedimentary units and four soils, including three buried paleosols. The ages of the mapped units could not be narrowly defined, but they are of late Quaternary age. Some rodent bones suggest a possible age of about 5,000 years for one of the higher stratigraphic units.

The fault zone is very clearly represented in the 4-m-deep trench, appearing as a zone of fault rubble as much as 1.5 m wide. Two fractures outside the fault rubble show no vertical displacement. In addition to the fault rubble, the fault is conspicuous because several of the mapped units terminate abruptly against the rubble zone and because the sediments southeast of the zone are coarser grained than the sediments northwest of the zone.

The maximum vertical component of the 1915 displacement is estimated to be 0.4-0.6 m on the basis of topography and 0.5-0.6 m on the basis of displacement of stratigraphic units, including soils. At least two episodes of vertical displacement, one of about 0.3 m and another of at least 0.2 m, occurred prior to 1915, perhaps during the last 5,000 years. These and other displacement events that happened before 1915 are poorly dated, but several certainly occurred in late Pleistocene and Holocene time.

The absence of wedge-shaped deposits or concentrations of large clasts adjacent to the fault suggests that all fault displacements at the site were small, probably less than 1 m each.

INTRODUCTION

An exploratory trench was excavated across the October 2, 1915, trace of the Pleasant Valley fault, 60 km south of Winnemucca, Nevada. This work was part of a broader study, sponsored by the U.S. Nuclear Regulatory Commission, of the use of trenching to evaluate active faults. The principal purpose of our work was to obtain information on the recent history of the fault and on the fault's appearance in the trench. A suitable site required young bedded sediments and fault displacements small enough that young displaced beds on the downthrown side could be reached by a trench about 4 m deep. A site meeting these criteria was found on the Pearce scarp segment of the fault, in the NW1/4 sec. 35, T. 30 N., R. 39 E., Mt. Diablo Base and Meridian. This site is 1.2 km N. 41.5° E. of the Siard Ranch house (fig. 1) where bedded alluvial-fan deposits were displaced less than 1 m in 1915 (Wallace, this volume, pl. 1); it is 3–4 km west of the front of the Tobin Range, from which the sediments in the trench were largely derived. Ground-surface elevation at the site is about 1,620 m; the local topography and the location of the trench can be seen in figure 2. The trench, perpendicular to the fault, was oriented about N. 40° W. and was about 30 m long, 1 m wide, and 2–4 m deep. Trench supports consisted of hydraulic shoring with a spacing of 1.4–1.8 m between sets. The trench was open from September 7 to September 22, 1977.

Acknowledgments—This investigation was partly supported by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. Mrs. T. A. Kaplan-Henry ably assisted in shoring and mapping the trench, Robert and Caesar Siard cooperated in various helpful ways, and D. G. Herd consulted on soil identification.

MAPPING OF THE TRENCH

The southwest wall of the trench was thoroughly cleaned with pick and brush (additional cleaning was needed during mapping, owing to the dry and dusty conditions), and mapping units were then selected primarily on the basis of lithology, soil development, and stratigraphic criteria. Once the unit boundaries were identified, they were marked with spray paint, nails, and flagging. Mapping was done by measuring vertical sections about 1 m apart and by taking supplemental measurements at critical points; horizontal control was by steel tape, and vertical control was by line level. The northeast wall was inspected but not mapped because the units and fault features were found to correlate closely across the trench. Cleaning of the walls and selection, marking, and mapping of the units was done in 11 days by H. A. Villalobos and T. A. Kaplan-Henry.

SEDIMENTARY UNITS MAPPED IN THE TRENCH

The sedimentary materials exposed in the trench were divided into 16 units. Except for the uppermost unit, which is primarily loess, all of the units are of types characteristic of an alluvial-fan environment; they include fan deposits, mud-flow deposits, and bajada deposits (table 1; pl. 1). The mapping units in plate 1 are designated by letters,

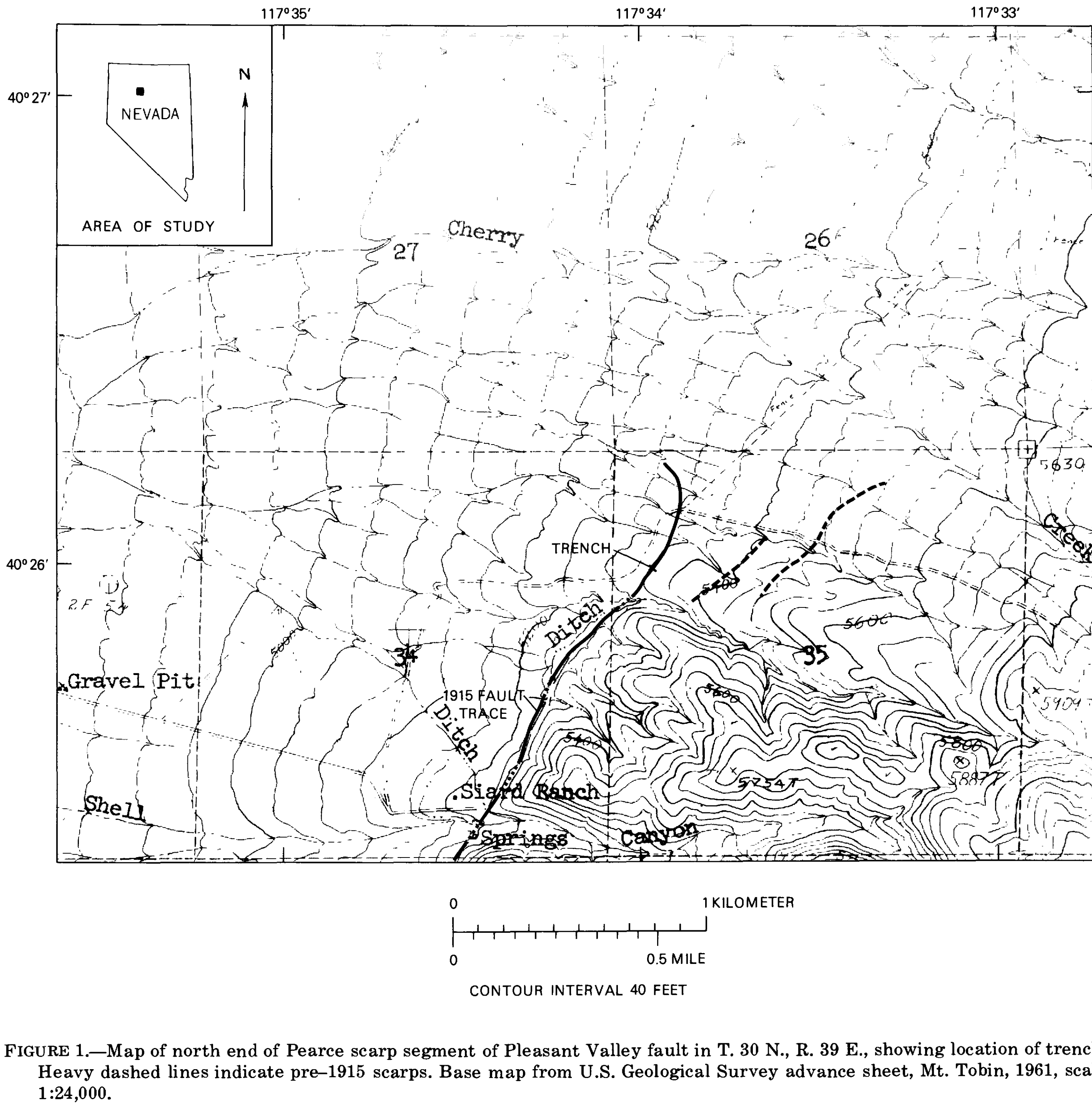

FIGURE 1.—Map of north end of Pearce scarp segment of Pleasant Valley fault in T. 30 N., R. 39 E., showing location of trench. Heavy dashed lines indicate pre–1915 scarps. Base map from U.S. Geological Survey advance sheet, Mt. Tobin, 1961, scale 1:24,000.

starting at the southeast end of the trench and proceeding generally northwestward and downward; reference to points is given in meters for the x (horizontal) and y (vertical) coordinates, in that order, separated by a comma: for example, (*26.60, 3.05*).

Stratigraphic units apparently do not correlate across the fault zone, except for units A and B, which were continuous across the fault zone before they were displaced in 1915. Correlations of other units across the fault zone cannot be unequivocally ruled out, however, because alluvial-fan deposition is so irregular that lithologic changes over short distances are the rule rather than the exception. If it is assumed that none of the units below B northwest of the fault are equivalent to units below B southeast of the fault, then it must be concluded, because of the down-on-the-northwest nature of fault displacement, that units L through P (a 2.5–m-thick set of sediments), and possibly additional units, once overlay units C through K on the southeast side of the fault but have been eroded off since the southeastern block was raised relative to the northwestern block.

FIGURE 2.—Aerial photograph looking south, showing oblique view of trench and its relation to the fault. Fault scarp is irregular dark line that crosses roads in foreground and follows base of hills in upper right. Spoil pile from trench forms the white band to left of parked car. Photograph by R. E. Wallace.

SOIL HORIZONS MAPPED IN THE TRENCH

The modern soil and three buried soils were divided into six soil units (table 2). Two modern soil horizons (mA and mB on plate 1) formed on the sediments of both the eastern and western blocks and are missing only where the 1915 rupture disturbed the ground surface. Buried paleosol b1B, a B horizon that developed on stratigraphic unit H, is now restricted to the block southeast of the fault and lies at a depth of about 1.5–2 m. Two paleosol B horizons, b2B and b2B_3, developed on stratigraphic unit L and are now restricted to the block northwest of the fault, where they lie at a depth of between 1 and 2 m. Paleosol b3B, a B horizon, is preserved in stratigraphic unit M at a depth of about 2–3 m on the northwest side of the fault.

Only the modern soil units can be traced across the fault zone with certainty. Buried paleosols b1B and b3B have some similarities, but are interpreted to represent distinctly different periods of soil formation.

DATING EVIDENCE

No materials suitable for radiocarbon or other radiometric dating were found in the trench. A sample of the silty clay of unit K, the oldest unit exposed in the trench, was examined for diatoms and pollen by J. P. Bradbury, but none were found. However, because of their close spatial association with modern alluvial fans, the sedimentary deposits cut by the trench are assumed to be of late Quaternary age. Some evidence presented below suggests that the surface that forms the base of unit B may have formed after middle-Holocene (about 5,000 years before present) time, but more than a few thousand years ago. Because much of the evidence for these dates is ambiguous, a discussion of the pertinent data and lines of arguments is provided below.

Rodent bones were found at two locations in the wall of the trench. A single bone, apparently deposited as a sedimentary clast, was found in unit L (*27.22, 2.95*) (pl. 1). A group of bones was found in a burrow 1.1 m below the ground surface in the buried paleosol $b2B_3$ (*26.60 3.05*) (pl. 1). The fossils were examined by C. A. Repenning, who found that two types of rodents are represented in the burrow: *Spermophilus townsendi* (Townsend ground squirrel) and *Peromyscus* sp.cf. *P. truei* (piñon mouse). Repenning (written commun., 1977) writes about these finds as follows:

> [In Pleasant Valley] the piñon mouse is somewhat north of its recorded range, but the difference does not seem significant; it is represented in the collection by a single first lower molar. The presence of the piñon mouse in a ground squirrel burrow is difficult to understand, but Townsend ground squirrels have been observed to carry dead rodents to places of safety and to eat them there.
>
> The Townsend ground squirrel is a resident in the area; it is represented in the collection by a large number of bones representing at least three individuals, two of which were very large and very old. The squirrel builds two types of burrows: home burrows with nests and auxiliary burrows without nests that are near feeding places. The auxiliary burrows are used for protective shelters and may or may not be well drained. Home burrows as deep as 1.5 m have been reported but auxiliary burrows are smaller and shallower, averaging less than 0.5 m in depth. The age grouping of the collection, its position on the downthrown side of the fault and the fine-grained material in which it was found suggest an auxiliary burrow and there seems to have been no evidence of a nest (T. A. Kaplan-Henry, oral commun., 1977). The suggestion thus would be that the burrow is auxiliary and related to a buried soil horizon rather than to the present land surface.
>
> Upon ignition, the bones clearly smell of 'burnt hair' indicating that considerable organic matter remains unleached within the bone. Experience has shown that this organic matter is leached out of bone under normal circumstances within about 10,000 years.

(See, for example, Quinn, 1957; Weston and others, 1973.) The sample from unit L (*27.22, 2.95*, pl. 1) "contains a fragment of a rodent radius that is indistinguishable from that of *Spermophilus townsendi* but is unidentifiable. It also smells of

TABLE 1.—*Sedimentary units mapped in the trench*

Unit	Description
A__	Grayish-orange unconsolidated laminated silt; laminations 0.5-1 mm thick. Contains flat-lying, scattered pebbles of low sphericity. Largely a loess deposit, but from x = 12.7 to x = 14.6 (at the fault zone) consists of loose silty debris containing pebbles and some cobbles; this part may have formed as slope deposits during degradation of the 1915 scarp.
B__	Very pale orange friable silty gravel. Clasts range from 4-64 mm in diameter, are coated with calcium carbonate, and are separated by a calcareous silty to sandy matrix containing voids <1 mm in diameter. Probably a mudflow deposit. A modern soil profile has developed on it.
C__	Yellowish-brown compact silty gravel. Most clasts are 8-32 mm in diameter, are subangular and have medium sphericity with long axis horizontal. Silt to sand matrix is slightly calcareous and has a crumbly texture. Some clasts are partially covered with a calcareous skin. Unit may be a mudflow deposit that has undergone some pedogenesis.
D__	Grayish-orange pebble gravel. Clasts range from fine pebbles to cobbles and are poorly sorted; most are flat lying but locally are imbricated, with long axes inclined downward to east; partially coated with calcareous skin <0.25 mm thick. Has irregular contacts; probably a channel deposit.
E__	Grayish-orange silt and very fine sand, well sorted. Unit is compact but has voids no more than 1 mm in diameter and discontinuous laminations 1-3 mm thick. Uneven fracture produces peds about 5 mm in diameter. Iron oxide marks most of basal contact. Contains scattered pebbles 8-16 mm in diameter. May be primarily loess that has undergone some pedogenesis.
F__	Moderate-reddish-brown to moderate-orange-pink pebble gravel. Moderately well sorted, not much matrix; most clasts are of fine to very coarse pebble size but range from coarse sand to cobbles. Clasts have low sphericity; most are randomly oriented, but some are flat lying. Probably a channel deposit.
G__	Very pale orange, somewhat indurated pebble gravel. Unit is poorly sorted; most clasts are of coarse pebble size but range from granules to cobbles. Most clasts have high sphericity and no apparent preferred orientation.

'burnt hair' when ignited and is caliche-coated." No caliche was noted on the bones from the burrow.

Uncertainties in the dating of the rodent bones and about the relations of the bones to the mapped units are important because of the significance of those factors to the history of displacement along the fault. The high proportion of unleached organic material suggests an age less than 10,000 years (C. A. Repenning, written commun., 1977) and possibly less than 5,000 years (C. A. Repenning, oral commun., 1980). These estimates do not imply a minimum age, but the caliche coating on the bone-fragment clast suggests that it is not modern. If the fragment in unit L is a sedimentary clast and not exotic, then unit L—and thus paleosol units b2B and $b2b_3$—is as young as the bone fragment; consequently, the bone fragment's identification as a sedimentary clast is critical, and supporting evidence would be helpful. More bones are found in the burrow, but the correlation of the bones' ages to the soil units is ambiguous.

Correlation of the bones in the burrow and the burrow itself with units L, b2B, and $b2B_3$ rests largely on the depth of the burrow. Hall (1946, p. 297) reports that Townsend ground squirrels near Fallon, Nevada, dig home burrows between 60 and 146.5 cm deep and auxiliary burrows between 30.6 and 45 cm deep. If the burrow in the trench wall is an auxiliary burrow, its depth of 1.1 m suggests

TABLE 1.—*Sedimentary units mapped in the trench*—Continued

Unit	Description
H--	Moderate-yellowish-brown friable silty pebble gravel. Clasts mostly of medium pebble size, have low to moderate sphericity, are randomly oriented, are floating in the matrix and do not touch one another. Matrix chiefly of silt but ranges from clay to fine sand size. Unit encloses a lens and beds of well-sorted pebble gravel that are designated unit I. Buried soil preserved over part of its extent.
I--	Loose pebble gravel. Iron oxide staining gives it a dark-yellowish-orange color. Pebbles mostly 4-16 mm in diameter, well sorted.
J--	Pale-yellowish-orange cobble gravel. Moderately well sorted; most clasts consist of very coarse pebbles and cobbles. Clasts touch one another; sand and silt fills most spaces between large clasts. Many clasts are flat lying and others are imbricated, inclined downward to southeast.
K--	Pale-olive pebbly silty clay. Scattered clasts, mostly of pebble size but including a few cobbles, are randomly oriented. Matrix breaks into uneven peds 5-10 mm in diameter with smooth shiny faces. No voids were seen in matrix. Probably a mudflow deposit.
L--	Grayish-orange loosely packed pebbly silt and sand. Poorly sorted; particles range from silt to granules and scattered pebbles. Coarse clasts are randomly oriented, with calcareous coatings 1-3 mm thick. Matrix calcareous; soil developed on part of unit.
M--	Grayish-orange pebbly silty clay. Contains scattered medium to coarse pebbles, randomly oriented, with partial calcareous coating (usually on bottom). Matrix has small (<1 mm) voids throughout, is highly calcareous. Buried soil preserved on top of this unit.
N--	Pebbly silty clay. Very similar to unit M but without well-developed soil.
O--	Very pale orange friable silty pebble gravel. Pebbles are in contact with one another, are mostly in coarse to very coarse size range, are randomly oriented, have partial calcareous coatings (usually on bottom). Matrix ranges from silt to sand, is highly calcareous.
P--	Moderate-yellowish-brown silty pebble gravel. Most larger clasts are 4-16 mm in diameter but a few are of cobble size; they are in contact with one another, and most have thin calcareous coatings. Matrix ranges from silt to very fine sand, is slightly calcareous, contains clumps of iron oxide cement. Unit has a crumbly fracture; pebble sizes seem to decrease upward; contact with overlying unit is gradational.

TABLE 2.—*Soils mapped in the trench*

Soil	Color (Munsell colors)	Texture	Structure	Other
		Modern		
mA	Very pale orange (10 YR 8/2) (dry) to moderate yellowish brown (10 YR 5/4) (wet).	Silty.	Uneven, earthy fracture.	Not calcareous. Many voids 0.1-0.5 mm in diameter.
mB	Moderate yellowish brown (10 YR 5/4) (dry) to dark yellowish brown (10 YR 4/2) (wet).	Clayey silt.	Peds not well developed, fracture uneven and crumbly, polygonal, 10-20 mm across.	Not calcareous. Clay skins poorly developed. Many voids 0.1-0.5 mm in diameter.
		Buried		
b1B	Moderate yellowish brown (10 YR 5/4) (dry) to moderate brown (5 YR 4/4) (wet).	Mostly silt.	Peds poorly developed, 3-15 mm across, crumbly fracture.	Mottled with veinlets of carbonate. Clay skins poorly developed.
b2B	Pale yellowish brown (10 YR 6/2) (dry) to dark yellowish brown (10 YR 4/2) (moist).	Clayey silt.	Peds well developed, especially west of $\underline{x} = \underline{26}$, break out easily, are 10-20 mm in diameter.	Mottled with carbonates. Has voids <0.5 mm in diameter.
$b2B_3$	Pale yellowish brown (10 YR 6/2) (dry) to dark yellowish brown (10 YR 4/2) (moist).	Clayey silt.	Peds poorly developed, about 5-10 mm across, crumbly fracture.	Mottled with carbonates. Clay skins poorly developed.
b3B	Moderate yellowish brown (10 YR 5/4) (northwest of $\underline{x} = \underline{18.7}$) to moderate brown (5 YR 4/4) (southeast of $\underline{x} = \underline{18.7}$).	Clayey silt.	Peds poorly developed, have crumbly polygonal fracture, about 2-10 mm across.	Extensively mottled with carbonates. Carbonate veinlets seem to have formed in ped fractures west of $\underline{x} = \underline{18.7}$.

that it was dug before the modern surface formed; if it is a home burrow, its depth does not rule out a modern age. The absence of caliche on these bones favors a modern age.

If, indeed, the rodent burrow and bones relate to unit L and the paleosol rather than to the modern surface, the burrow may have been dug either near the beginning or near the end of the soil-forming period, a period of time that could span thousands of years. Unit L must be older than the burrow, but how much older is unknown. It might be nearly contemporaneous, perhaps a few hundred years older, but it could be thousands of years older. Thus, the bones in the burrow are of limited use in dating, and we must rely on the isolated bone-fragment clast as evidence for the age of unit L.

At best, the above arguments can only suggest a possible maximum age (about 5,000 years) for the rodent bones, the paleosol, and unit L. Evidence for the possible minimum age is examined next.

After paleosol $b2B$-$b2B_3$ was formed, the following events took place: (a) Uplift of the southeastern block caused paleosol $b2B$-$b2B_3$, at least, to be eroded from the block east of the fault, forming a rather even surface as the base for unit B, (b) a probable mud flow (unit B) was deposited, (c) loess (unit A) was deposited, (d) older scarp facets above the 1915 scarp declined from steep angles to angles as low as 9°, and (e) modern soil horizons (mA and mB) were formed.

Deposition of the probable mud flow (unit B) could have occurred in one flash flood, but deposition of the loess (unit A) was probably a complex process, involving both periods of deposition and periods of deflation. Alternation of deposition and deflation of loess occurs today, but on the steeper slopes, which are remnants of pre-1915 scarps and which are cut by the trench, erosion by wash probably currently exceeds deposition from dust storms. The nearness of the site to the floor of prehistoric Lake Lahontan and the known deflation from the lake floor (Wallace, 1961) suggest that the loess was derived from there. Most of the deflation from the lake beds must have occurred after a large part of the lake had disappeared, a time considerably later than the last high stand of the lake (about 12,000 years ago). However, the loess at the trench site may not have been laid down during the period of major loess deposition at all. It may be relatively modern, and some may even be transported by sheet wash from higher on the slope. The age of the loess, therefore, is probably less than 12,000 years, but beyond that, it remains indeterminate.

The modern soil horizons (mA and mB) are not well developed but must have required more than a few hundred years to form. No soil has yet formed on the 1915 scarp. Considering that only 15 to 20 cm of precipitation falls each year, as much as a few thousand years may have been required for soil horizons mA and mB to form. Poor development of peds in the soil suggests an age of no more than a few thousand years (R. J. Janda, oral commun., 1980, and E. J. Bell, oral commun., 1980).

In summary, some of the data suggest that the surface that forms the base of unit B was formed after middle Holocene time (about 5,000 years ago), but more than a few thousand years ago. Much of the evidence is ambiguous or inconclusive.

FAULTS

FAULT ZONE

Within the trench, a fault zone sharply terminates several of the mapped units near $x = 14$. A band of fault rubble 1 to 1.5 m wide marks the fault zone. Southeast of the fault zone the sediments are predominantly of gravel (pebble size or larger) and have dips between horizontal and 5° northwest; the sediments northwest of the fault zone are predominantly of sand size or smaller and dip northwestward about 9° near the fault. The fault rubble can be divided into southeastern and northwestern parts. The southeastern part consists of pebbles and cobbles in a matrix of silt, sand, and caliche. Many of the clasts have calcareous skins about 1–3 mm thick and are similar to those in units G and F. Fractures cut this rubble, and many of them are highlighted by veinlets of calcareous material, particularly along the southeast side of the rubble zone. The northwestern part of the rubble is generally finer grained, consisting of a mixture of sand, silt, pebbles, and some cobbles. The northwestern part of the rubble is less consolidated than the southeastern part and tends to cave in where excavated. This difference in consolidation suggests that the most recent fault displacements were confined to the northwestern part of the fault zone; this hypothesis is further supported by the absence of displacement of unit B and the modern soil where they overlie the southeastern part of the fault rubble (pl. 1).

Fractures outside the fault zone were examined for signs of displacement. A fracture zone as much as 0.1 m near $x = 12$ is highlighted by caliche, which obscures the unit boundaries within the fracture zone. The units crossed by the fracture zone are not displaced. The fracture zone could not be traced to the surface or to the bottom of the trench. The absence of displacement and the limited vertical extent suggest that it might have formed by slumping, the block to the northwest having tilted toward an open face of a fault scarp. Such slump features are common along the 1915 scarp. No other evidence of an open face is apparent, however, and the fracture may have formed as an extension crack at depth, in response to tension across the whole zone.

A similar fracture appears at about $x = 17.5$. This fracture seems to offset the contact between units L and N, but other units, both above and below, are not offset. The apparent offset may be only an irregularity in the contact.

FAULT SCARPS

Almost the entire length of the trench was excavated on a degraded set of scarp facets that resulted from repeated displacements of the fault. The spur above the scarps has a slope of 5° to 6° and the bajada below has a slope of 4° to 5°, but the degraded fault scarps have slopes between 9° and 23° and at least two facets are identifiable above the 1915 break. The top member of this set of old scarps is at about $x = 1.3$ (pl. 1). Between $x = 1.3$ and $x = 10$ is a fairly regular slope of about 9° or 10°, from $x = 10$ to $x = 13$ is a slope of about 14°, and between $x = 13$ and $x = 14.5$ is a slope of approximately 23°. The top of the surface zone that was disturbed by faulting in 1915 and subsequent slope degradation is near $x = 13$ and extends west to about $x = 15.3$.

AMOUNT AND TIMING OF DISPLACEMENTS ON FAULTS

To estimate the amount and the timing of prehistoric displacements on the fault was one of the principal goals of this project. We find that the evidence for ages of the units offset is ambiguous or indeterminate and that only the modern soil units and two sedimentary units can be correlated with certainty across the fault. Nevertheless, some useful conclusions can be reached. As discussed below, the 1915 displacement at the trench site was about 0.5 to 0.6 m, unit B was displaced about 0.3 m prior to 1915, and at least 0.2 m of displacement occurred between the formation of paleosol b2B-b2B$_3$ and the deposition of unit B.

Furthermore, there is evidence that the displacements in these events as well as in all the late Pleistocene through Holocene events on this part of the Pleasant Valley fault were small, probably 1 m or less.

The positions of the modern soil horizons and unit B at the hypothetical fault plane within the fault rubble must be extrapolated from the bedding adjacent to the fault zone, and several extrapolations are possible (fig. 3). The inferred bedding relations at the fault zone indicate a range of vertical displacement during the 1915 motion of 0.49 to 0.86 m (table 3). Vertical displacements greater than about 0.65 m, however, are improbable. A restoration of that magnitude along the fault would place the top of unit B on the northwest (downhill) side of the fault above the ground surface on the southeast (uphill) side of the fault and it would place the base of mA higher on the downhill side of the fault than on the uphill side. Thus, the evidence from the bases of mA and mB, the top of unit B, and projection of the ground surface that lies southeast of the fault indicates that the 1915 displacement had a vertical component between 0.49 m and 0.65 m. This is a maximum because the evidence does not exclude possible

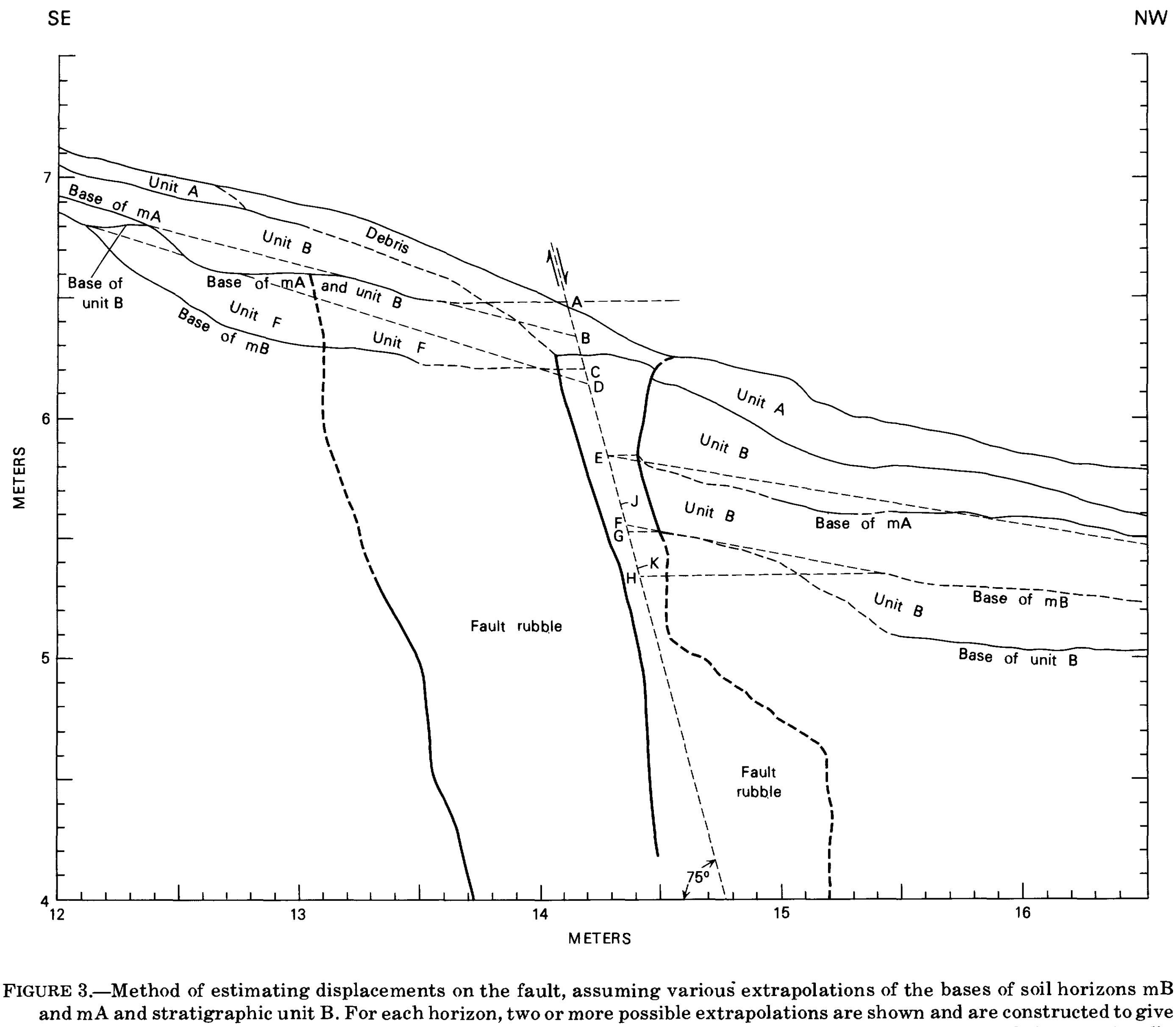

FIGURE 3.—Method of estimating displacements on the fault, assuming various extrapolations of the bases of soil horizons mB and mA and stratigraphic unit B. For each horizon, two or more possible extrapolations are shown and are constructed to give nearly a maximum value as well as an intermediate-to-small value of displacement. Inferred position of fault (assumed to dip 75°) and extrapolations of contacts are shown by light dashed lines; other line symbols are the same as on plate 1. See text and tables 3 and 4 for discussion of lettered points, and tables 1 and 2 for description of units and soils.

TABLE 3.—*Estimates of displacements without allowance for drag*

Match points	Displacement (m) Dip slip	Vertical component	Effect of relative movement of the two sides of the fault by the given displacements
		Base of mA	
A-E------	0.66	0.64	Acceptable join of base of mA and mB, but gives part of base of mA a flat slope. Top of unit B northwest of fault extends above ground surface projected from southeast of 1915 fault scarp, unless projections include an unlikely near-horizontal segment.
B-E------	.51	.49	Good join of base of mA, acceptable join of base mB; requires thin mB near fault, but acceptable. Top of unit B is near or above ground surface as projected from southeast.
		Base of mB	
C-F------	.67	.65	Effects similar to A-E above.
C-G------	.70	.68	Base of mA on northwest (downhill) side of fault slightly higher (0.04 m) than base of mA projected horizontally from southeast side. Top of unit B northwest of fault extends above projection of 14° slope from southeast of 1915 fault scarp.
C-H------	.89	.86	Base of mA on northwest side of fault is substantially higher (0.23 m) than base of mA projected horizontally from southeast side. Top of unit B extends far above projections of ground surface from southeast of 1915 fault scarp.
D-F------	.60	.58	Acceptable join of base of mA; other effects intermediate between A-E and B-E.
D-G------	.63	.61	Acceptable join of base mA; other effects similar to A-E.
D-H------	.82	.79	Base of mA on northwest side of fault is substantially higher (0.16 m) than base of mA projected horizontally from southeast side. Top of unit B extends above horizontal projection of ground surface from southeast side of 1915 fault scarp.
		Base of unit B	
A-F------	.96	.93	Top of unit B on northwest side of fault would have been higher than horizontal projection of unit B from southeast side of fault if unit B had its present thickness southeast of fault.
A-G------	.99	.96	Do.
B-F------	.81	.78	Do.
B-G------	.84	.81	Do.

TABLE 4.—*Estimates of displacements allowing for postulated drag*

Match points	Displacement (m) Dip slip	Vertical component	Effect of relative movement of the two sides of the fault by the given displacements
		Base of mA	
A-J---	0.86	0.83	Requires unlikely flat slope for top of unit B at the fault. Base of mB requires short flat slope.
B-J---	.71	.69	Top of unit B is above projection of 14° slope southeast of 1915 scarp but below horizontal projection. Base of mB about 0.07 m too low on northwest, but acceptable.
		Base of mB	
C-K---	.86	.83	Same as A-J.
D-K---	.79	.76	Top of unit B above projection of 14° slope southeast of 1915 scarp but below horizontal projection; base of mA makes good fit.
		Base of unit B	
A-K---	1.15	1.11	Top of unit B on northwest side of fault would have been higher than a horizontal projection of unit B from southeast side of fault if unit B had its present thickness southeast of fault.
B-K---	.99	.96	Do.

displacement after the formation of the bases of mA and mB but before 1915. As discussed below, the topography alone suggests a 1915 vertical component between 0.4 m and 0.6 m. Reasonable extrapolations of the base of unit B indicate a vertical component of displacement between 0.78 m and 0.96 m (fig. 3; table 3). The difference between these displacements and those indicated by bases of mA and mB suggests that a displacement of 0.14 m to 0.47 m occurred after the deposition of unit B but before 1915 and also before the formation of the bases of mA and mB.

So far, the discussion of displacement has assumed that no drag occurred during the 1915 faulting. Some of the sedimentary units and soils have a steeper dip just northwest of the fault ($x = 14.5$ to about $x = 15.2$) than they do farther northwest. Moreover, the more steeply dipping parts are underlain by fault rubble, and any distributed faulting in the rubble would be likely to flex the overlying units. To estimate the effects of such drag, the dip of unit B at the fault was adjusted to conform to the general dip that unit B has farther northwest, and then the other horizons were adjusted accordingly. On figure 3, the adjusted position of the base of mA is represented by point J, and the adjusted position of the bases of mB and unit B are represented by point K. The resulting estimates of displacement (table 4) are generally larger than the estimates listed in table 3. They also show a difference (0.13 m to 0.42 m of vertical component) between the displacements of the base of unit B and the bases of mA and mB, a difference suggesting a pre–1915 displacement of unit B.

Whether or not drag occurred at the trench site in 1915 is not clear; probably it did not. No obvious disruption of units was noted, but the postulated flexing is small (about 13°) and could have been accomplished by small intergranular movements. The best evidence on the question is the size of the 1915 displacement as inferred from the topography at the trench. Because of irregularities in the ground surface, the size of the 1915 displacement cannot be precisely determined by this method, but the indicated range is between 0.4 and 0.6 m. This range is closer to the 0.5 to 0.6 m estimated from the trench data for displacement without drag (table 3) than it is to the 0.7 to 0.8 m estimated for displacement with drag (table 4).

The evidence given above for a pre–1915 displacement of unit B is supported by the difference in thickness of unit B on the two sides of the fault. Except near the ends of the trench, unit B is generally thicker northwest of the fault than it is southeast of the fault (pl 1). Two possible explanations for the difference in thickness are: (1) Unit B was deposited across a fault scarp and has always been thicker on the northwest, or (2) unit B, initially of about the same thickness on both sides of the fault, has been uplifted and partly eroded southeast of the fault. However, if unit B was deposited across a fault scarp, it probably would have been thicker just below the scarp but of a more normal thickness farther downslope; in fact its thickness shows no notable changes about 12 m downslope from the fault. The hypothesis that unit B was deposited across a fault scarp is favored by the steeper dip of unit B just below the fault, although the steeper dip there could result from fault drag.

Under the second explanation, unit B was deposited with a nearly uniform thickness across the fault at a time when little or no topographic relief existed at the fault; later, after faulting occurred, the uplifted part of unit B was partly eroded. One difficulty with this explanation is the manner in which the erosion could be accomplished. The site is near the end of a flat-topped spur that is less than 150 m wide and has only a small catchment area, but the spur does have a few shallow channels that indicate some erosion. Although the present topography does not seem conducive to much erosion, the environment did permit transport of the silty gravel of unit B and could have permitted subsequent erosion of the unit, given different conditions of rainfall. Moreover, that unit B southeast of the fault was originally thicker than it is today is shown by the relative displacements required to match the base of unit B across the fault. All the reconstructions based on the postulated displacements place the top of unit B on the northwest side of the fault higher than the present top of unit B southeast of the fault (tables 3 and 4). Within about 8 m of each side of the fault, the average thickness of unit B to the southeast of the fault today is 0.26 m less than it is to the northwest of the fault. If the erosion was equal to the faulting, then for a fault dipping 75° a dip slip of 0.27 m and a vertical component of 0.26 m would be implied. These values are within the range of pre–1915 displacements of unit B inferred above. Thus, the 1915 vertical displacement at the trench site was most probably in the range of 0.5 to 0.6 m, and unit B probably has been displaced about 0.8 to 0.95 m, of which 0.2 to 0.35 m occurred prior to 1915.

The paleosol horizon b2B on unit L is well developed and it extends almost continuously from the northwest end of the trench to the fault. This soil probably extended southeastward across the fault originally, but its southeastern part has been faulted upward and removed by erosion in the vicinity of the trench. The absence of horizon b2B southeast of the fault gives a basis for estimating its minimum displacement (fig. 4). The paleosol horizon is not recognized southeast of the fault zone; therefore, southeast of the fault zone the base of the horizon must have been above the present altitude of the base of unit B, and so a minimum vertical displacement of 1.15 m is indicated. Therefore, during the interval between the cessation of the soil-forming processes responsible for b2B and the planation of units G, F, and L to form the base for unit B, one or more displacement events produced a vertical component of displacement of at least 0.2 m. (This value has been calculated by subtracting 0.95 m, which is the maximum offset of the base of unit B given in table 3, from 1.15 m, which is the minimum offset of b2B.)

The events discussed in this section are summarized by figure 5. That figure shows schematically the probable time relations of the various fault displacements to each other and to the formation of soils and sedimentary deposits.

Other variations in correlation and interpretation can be imagined, but quantification of other displacements older than the displacement of the base of unit B remains uncertain. Given the probability that the exposed sedimentary units southeast and northwest of the fault are not equivalent, at least 6 or 7 m of total vertical displacement across the fault is represented by the observable record in the trench.

Significantly, no unit northwest of the fault is wedge shaped, thick against the fault and thinning northwestward, nor do the units contain a concentration of large clasts near the fault and finer clasts away from the fault. Such sedimentary structures and lithologic variation would be present if scarps of a meter or more high had stood at the fault line. In other words, no sedimentary feature records the presence of a large fault scarp uphill of the sedimentary units L, M, N, O and P. Two interpretations are suggested: First, no scarps stood while L, M, N, O and P were being deposited. Perhaps no fault displacement extended into the sediments before paleosol horizon $b2B_3$ formed, the 6 or 7 m of displacement postulated above did not occur, and units C through K are correlatives of units L through P. This argument is contradicted by the width of the fault zone (1.5 m) and the generally coarser nature of the units southeast of the fault zone compared with units northwest of the fault zone, both of which argue for cumulative displacements measured in many meters. Second, and more likely, individual displacements were so small and relief along the scarps formed was so low that the perturbation of sedimentation downhill of the scarps is obscured in the general heterogeneity of fan deposits.

The degraded fault scarps across which the trench was cut provide additional evidence of both the number of past fault displacements and their ages (Wallace, 1977; Bucknam and Anderson, 1979). The different slopes of the degraded fault scarps give the surface a faceted appearance. The facet with a slope of 23° is interpreted as the local expression of the 1915 fault scarp, which in other places nearby has a free face. This facet has a height of about 0.6 m. The next higher facet slopes 14° and also has a height of 0.6 m; its slope/height ratio suggests an origin in the last half of the Holocene (Bucknam and Anderson, 1979). The highest facet, which slopes 9°-10°, has a height of 1.5 m. This slope/height ratio suggests an early Holocene or late Pleistocene age (Bucknam and Anderson, 1979), but the scarp may be composed of more than one facet. The scarp-facet evidence may indicate at least two displacement events prior to 1915, in the Holocene or late Pleistocene, but their exact timing cannot be determined from the data available. The interrelations of the processes of slope decline of the scarp facets, deposition and partial erosion of mudflow unit B, deposition of unit A, and development of the modern soil cannot be resolved on the basis of the present data.

SUMMARY

An exploratory trench about 30 m long and 2 to 4 m deep was excavated across the 1915 trace of the Pleasant Valley fault near the north end of the Pearce scarp segment. The trench revealed 16 mappable sedimentary units and 4 soils, including 3 buried paleosols. The mapped units are of late Quaternary age, and some rodent bones possibly 5,000 years old were found in one of the higher stratigraphic units.

Faulting is very clearly represented in the trench by the abrupt termination of several of the units where they abut a zone of fault rubble as

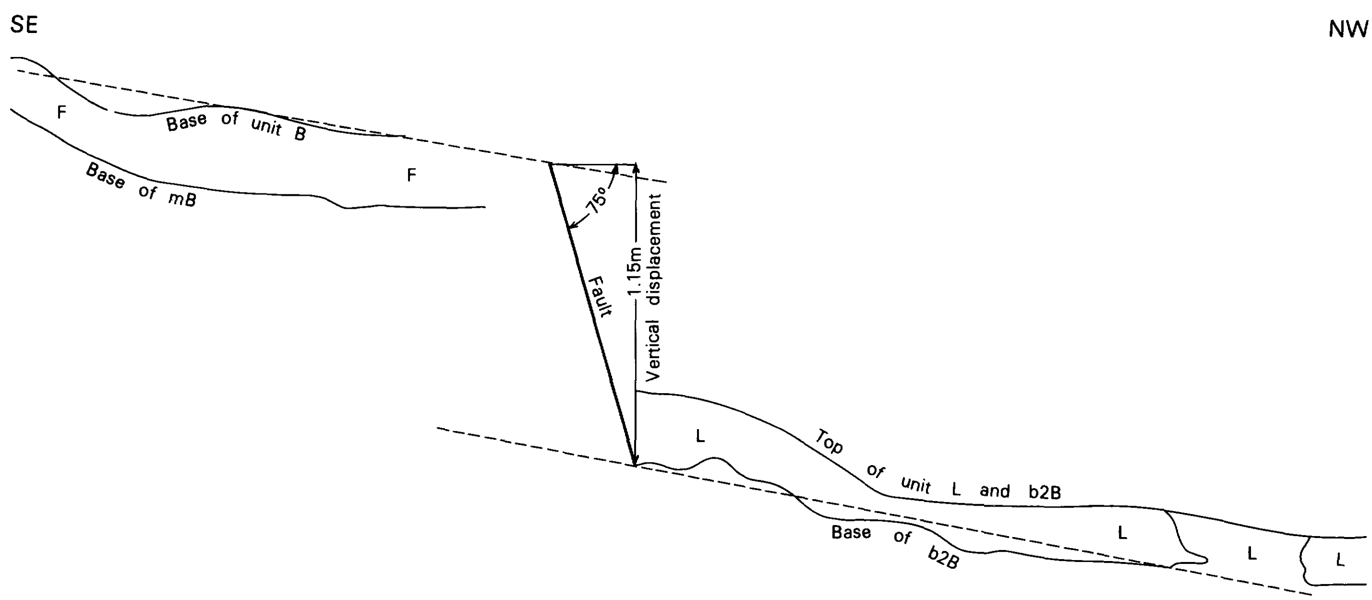

FIGURE 4—Method of estimating the minimum offset of the base of soil horizon b2B, present only west of the fault on unit L. The fault is assumed to dip 75°. See tables 1 and 2 for descriptions of units and soils.

much as 1.5 m wide. The fault rubble marks the fault zone as exposed in the trench; although fractures were noted outside the fault rubble, dip-slip fault displacements have not occurred on them. Southeast of the fault zone, the sediments are predominantly of gravel size or larger and have very low dips, whereas to the northwest they are predominantly of sand size or finer and dip northwestward about 9°. Only the uppermost units could be correlated across the fault.

Displacement of about 0.5 to 0.6 m (maximum vertical component) that occurred in 1915 is recorded by two sedimentary units and the modern soil; an earlier displacement of about 0.3 m at a time possibly less than 5,000 years ago is also represented. Additionally, a paleosol is displaced at least 1.15 m, of which at least 0.2 m occurred before the 0.3 m displacement, also possibly less than 5,000 years ago but probably before a few thousand years ago.

Most of the trench was located on a set of degraded fault scarps composed of four facets, three with slopes of 9°–10°, 14°, 23°, and one with an irregular surface. The lower two facets are believed to have been produced in 1915 and modified later. Topographic evidence suggests that about 0.4–0.6 m of the height of the two lower facets is the result of the 1915 displacement, and the heights of the facets above the 1915 scarps are 0.6 and 1.5 m, respectively. The number and ages of pre–1915

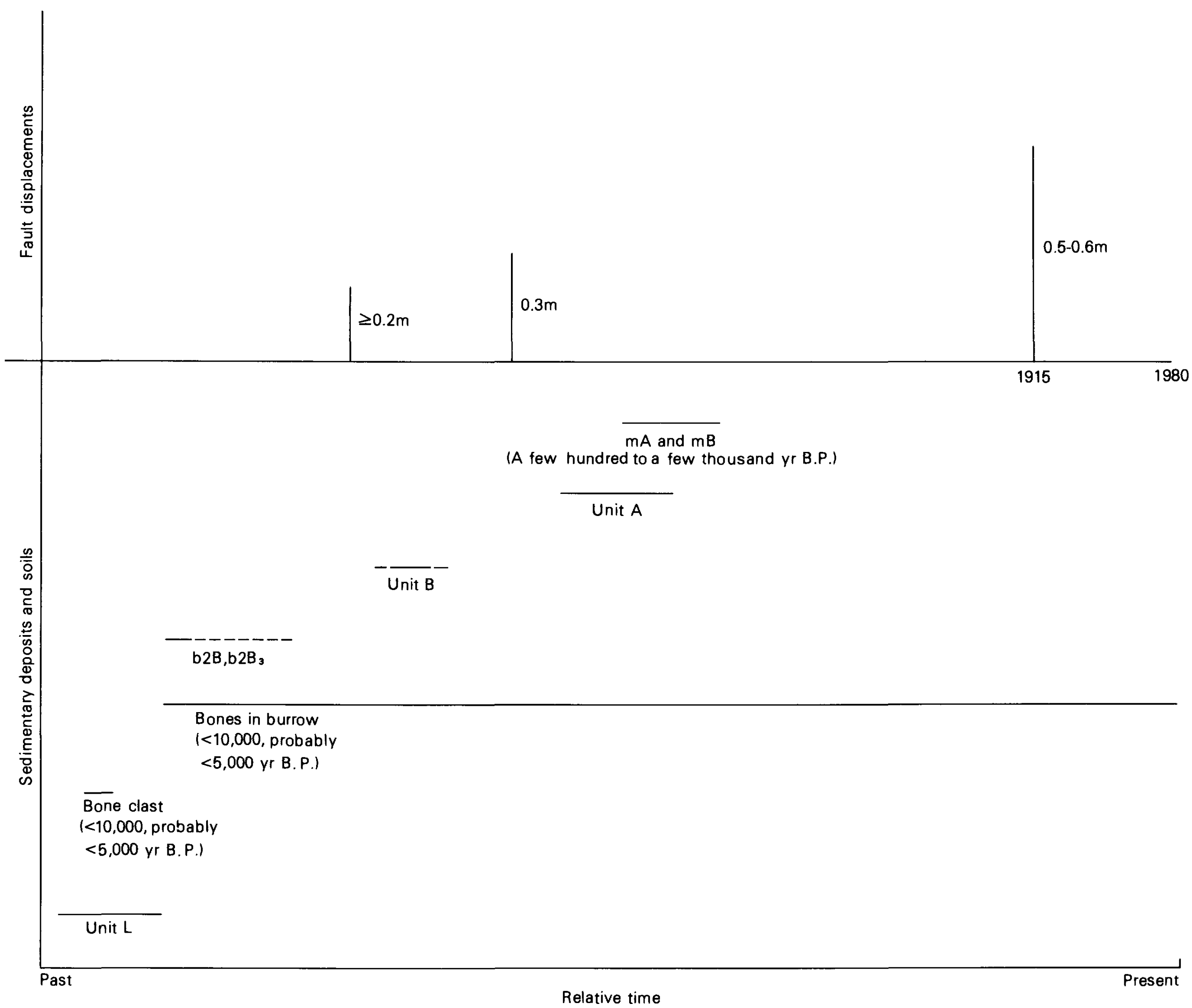

FIGURE 5.—Time relations of sedimentary deposits, soils, and fault displacements. Horizontal lines show possible time of formation of the deposits, soils, and ground squirrel bones. Heights of vertical lines are proportional to probable fault displacement. Time scale is schematic. See plate 1 and tables 1 and 2 for identification of units.

events associated with the facets are uncertain, but the slope/height ratios suggest a Holocene to late Pleistocene age for them.

Displacement events prior to 1915 cannot be dated accurately because of inconclusive evidence, but it is certain that several did occur in late Pleistocene and Holocene time. All of the fault displacements at this site were small, probably less than 1 m.

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